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Simulation and Analysis of Wildfire for Disaster Planning and Management

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Abstract: With climate change and the global population growth, the frequency and scope of wildfires are constantly increasing, which threatened people's lives and property. For example, according to California Department of Forestry and Fire Protection, in 2020, a total of 9,917 incidents related to wildfires were reported in California, with an estimated burned area of 4,257,863 acres, resulting in 33 fatalities and 10,488 structures damaged or destroyed. At the same time, the ongoing development of technology provides new tools to simulate and analyze the spread of wildfires. How to use new technology to reduce the losses caused by wildfire is an important research topic. A potentially feasible strategy is to simulate and analyze the spread of wildfires through computing technology to explore the impact of different factors (such as weather, terrain, etc.) on the spread of wildfires, figure out how to take preemptive/responsive measures to minimize potential losses caused by wildfires, and as a result achieve better management support of wildfires. In preparation for pursuing these goals, the authors used a powerful computing framework, Spark, developed by the Commonwealth Scientific and Industrial Research Organization (CSIRO), to study the effects of different weather factors (wind speed, wind direction, air temperature, and relative humidity) on the spread of wildfires. The test results showed that wind is a key factor in determining the spread of wildfires. A stable weather condition (stable wind and air conditions) is beneficial to limit the spread of wildfires. Joint consideration of weather factors and environmental obstacles can help limit the threat of wildfires.

Key words: simulation, analysis, wildfire, disaster planning, disaster management

1. INTRODUCTION

With the change of our climate and the significant increase of the world's population, the frequency and scope of wildfire have been increasing in recent years, causing serious damage to society and human lives. For example, the average duration of wildfires in Australia this century almost doubled that in the first half of the 20th century, and the wildfire in 2019 - 2020 caused 34 deaths and an estimated 100 billion AU$ of losses [1]. A similar trend exists in the U.S. According to California Department of Forestry and Fire Protection [2], in 2020, a total of 9,917 incidents related to wildfires were reported in California, resulting in 33 fatalities and 10,488 structures damaged or destroyed. The number of incidents, fatalities and damaged structures were all higher than the average of the past five years (2015 through 2019), which means the risk of fire and damage caused have shown an increasing trend. Why did wildfire cause such a dramatic loss? Could there be improvement in our response to and management of wildfire risks and events? In the current practice, some challenges in predicting and managing wildfires include: (1) wildfire usually occurs in remote wild areas, which makes it difficult to be found or detected at the early development stage; (2) the spread of wildfire is affected by geographical, weather, and human factors, which makes it difficult to predict and control; and (3) the wildfire spread area is generally very large, which increases the difficulty of potentially extinguishing it. Therefore, it is usually more feasible to control and manage the spread of a wildfire than to extinguish it.

The fast development of technology provides powerful and potentially effective tools for the management and control of wildfire. For example, drones are used to observe the spread of wildfires [3], [4], and geographic information system (GIS) is used to study the distribution of wildfires [5], [6]. On the other hand, because it is difficult to carry out real-world wildfire experiment, researchers use advanced computing technology to simulate the spread of wildfire [7]–[9], providing a basis for the prevention and management of wildfire. Spark, developed by the Commonwealth Scientific and Industrial Research Organization (CSIRO), is one of the cutting-edge computing frameworks focusing on wildfire spread prediction. It predicts the spread of wildfire by analyzing geospatial data, weather data and environmental information [10]–[12].

The authors in this study used the Spark computing framework to study the effects of weather factors, including wind speed, wind direction, air temperature, and relative humidity, on the spread of a wildfire to identify the dominating factor that affects the wildfire spread. The research in this paper helps address the second of the three challenges listed above in predicating and managing wildfire in the real world.

2. RESEARCH METHODOLOGY

This study focuses on the spread of a wildfire in the grassland of central Australia within 9 hours of initial ignition. Under European Petroleum Survey Group (EPSG): 3112 simulation projection (Well-Known Text format), the location of the fire resource is (150.379, -33.5723), and the time when the wildfire ignites is 13:00 local time. This study simulated the spread of fire for the next 9 hours to explore the effects of wind speed, wind direction, air temperature and relative humidity on wildfire. The data of these four factors was input into the computing framework in the form of comma-separated values (CSV) files [13]. We explored 6 different scenarios in this paper. Scenario 1 was set as the control group, during which the wildfire was simulated using original weather data as shown in Figures 1 through 4.

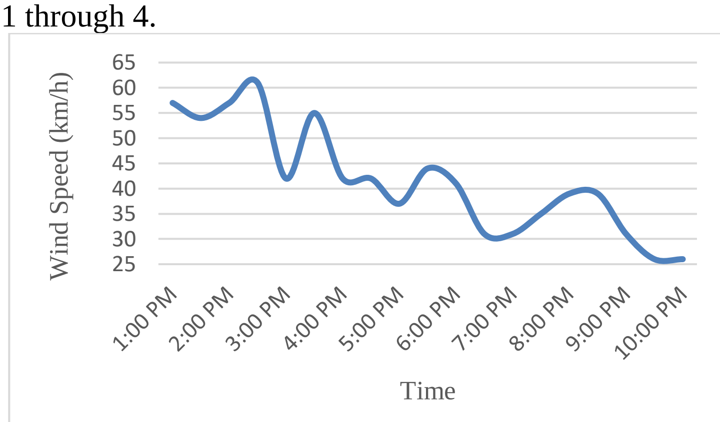

Figure 1. Wind speed (km/h) in Scenario 1

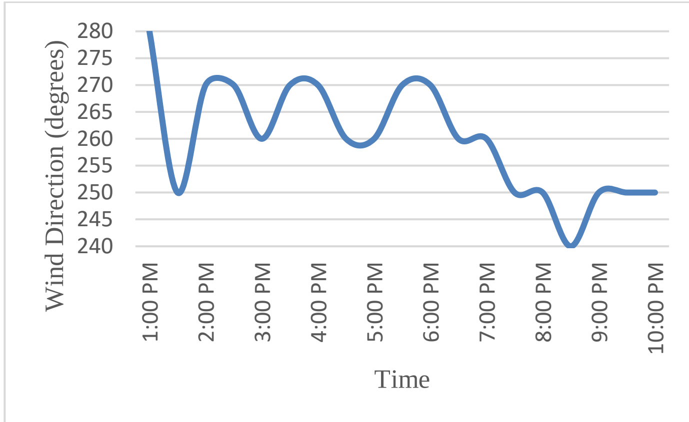

Figure 2. Wind direction (degrees) in Scenario 1

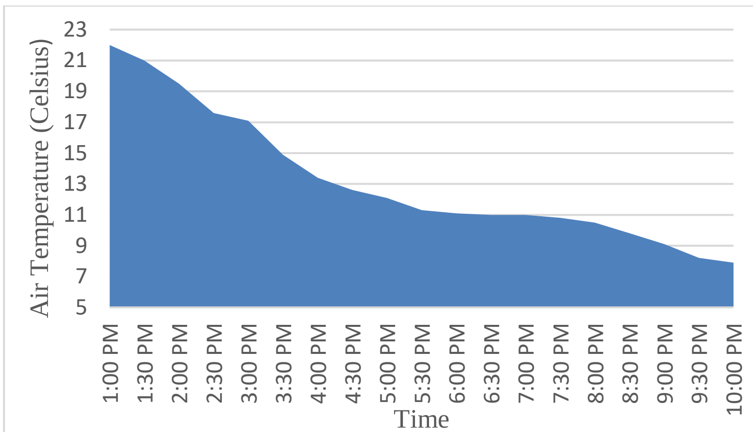

Figure 3. Air temperature (Degree Celsius) in Scenario 1

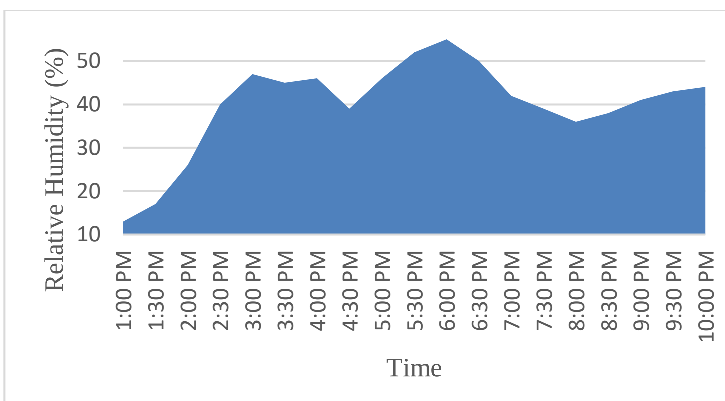

Figure 4. Relative humidity (%) in Scenario 1

Scenario 2 was used to study the effect of wind speed on wildfire spread. In Scenario 1, the wind speed varied from 26 km/h to 61 km/h within 9 hours. In Scenario 2, the average wind speed (42.27km/h) of Scenario 1 was used as a constant speed to explore the effect of the dispersion of wind speed on wildfire. Except for the wind speed, Scenario 2 had the same input data as Scenario 1.

Scenario 3 was used to study the influence of wind direction on the spread of wildfire. In Scenario 1, the wind direction changed from 240 degrees to 280 degrees within 9 hours. In contrast, an average wind direction (261.36 degrees) was adopted in Scenario 3. Except for the wind direction, Scenario 3 had the same input data as Scenario 1.

Scenario 4 used a combination of wind direction of 280 degrees in the first 4 hours and 240 degrees in the last 4.5 hours to study the effect of wind direction on wildfire. The wind direction was designed to change gradually over the half-an-hour transition period. The wind direction in Scenario 4 is shown in Figure 5.

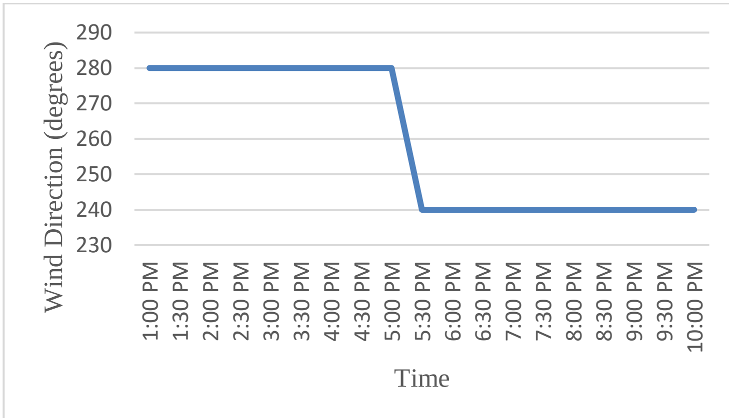

Figure 5. The wind direction in Scenario 4 (degrees)

Scenario 5 was used to study the effect of air temperature on wildfire spread. In Scenario 1, the air temperature varied from 22 Degrees Celsius to 9 Degrees Celsius within 9 hours. In Scenario 5, the average air temperature (13.71 Degrees Celsius) was used to explore the influence of the dispersion of air temperature on wildfire. Except for the air temperature, Scenario 5 had the same input data as Scenario 1.

Scenario 6 was used to study the effect of relative humidity on wildfire spread. In Scenario 1, the relative humidity varied from 13% to 55% within 9 hours. In contrast, the average relative humidity (38.27%) was used in Scenario 6. Except for the relative humidity, Scenario 6 had the same input data as Scenario 1. A summary of the factors used in different scenarios is presented in Table 1. In addition, all six scenarios were simulated in the same computer (i.e., a laptop with an Intel Core i7-5500U central processing unit (CPU) and an Advanced Micro Devices (AMD) Radeon R9 M375 (2 GB) graphics card) to obtain accurate experimental results.

Table 1. Summary of factors in different scenarios

Scenarios	Wind speed (km/h)	Wind direction (degrees)	Air temperature (Degree Celsius)	Relative humidity (%)
Scenario 1	26~61	240~280	22~9	13~55
Scenario 2	42.27	-	-	-
Scenario 3	-	261.36	-	-
Scenario 4	-	280 (4h) + 240 (4.5h)	-	-
Scenario 5	-	-	13.71	-
Scenario 6	-	-	-	38.27

***** “-” in the above table indicates that the factor is unchanged compared to Scenario 1.

3. RESULTS AND ANALYSIS

The simulation results of wildfire spread under 6 different scenarios are shown in Figures 6 through 11. The red dots in these figures indicate the fire source. The isochrones of different colors indicate the time it took for the wildfire to spread to the corresponding areas. The polygon with black and white stripes shows an incombustible obstacle when the wildfire spreads, such as a pond or a burned area. From these simulation results, we can directly observe the spread of wildfire within 9 hours under the different scenarios.

Figure 6 and Figure 7 show that the spread area of the wildfire in Scenario 2 within 9 hours was smaller than that in Scenario 1, which indicates that a relatively stable wind speed is beneficial to limit the spread of the wildfire. In other words, a wildfire is more dangerous under a changing wind speed than it is under a steady wind speed. It can be seen from Figure 6 and Figure 8 that a stable wind direction led the wildfire to spread farther in the wind blowing direction, but it reduced the spread of wildfire in all other directions. Therefore, the overall spread area of wildfire could be smaller. The results of Scenario 4 show that the direction of wildfire spread changed with the change of wind direction, and this change happened shortly after the change of wind direction, e.g., the wildfire spread direction changed at 4 hours and 12 mins, 12 minutes after the wind direction changed at 4 hours. Compared to Figure 6, the area of wildfires in Figure 10 increased, but this

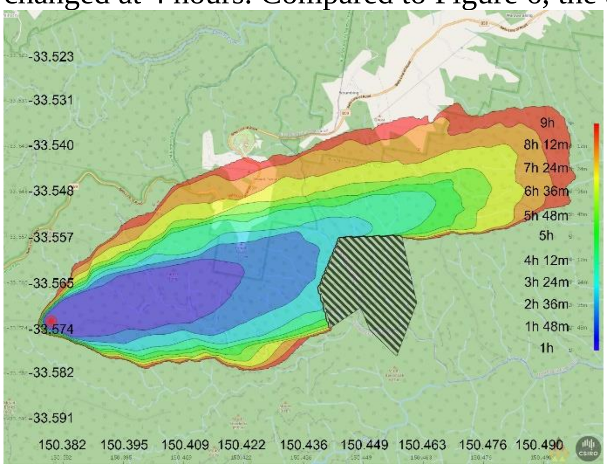

Figure 6. The wildfire spread in Scenario 1

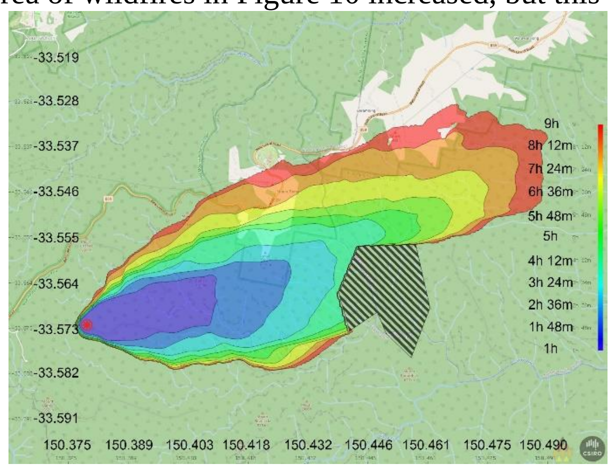

Figure 7. The wildfire spread in Scenario 2

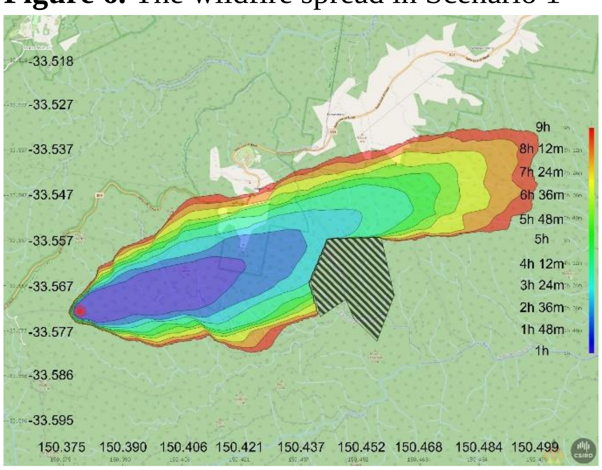

Figure 8. The wildfire spread in Scenario 3

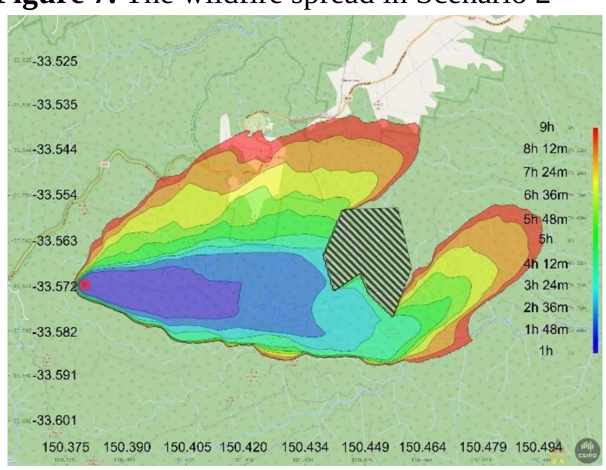

Figure 9. The wildfire spread in Scenario 4

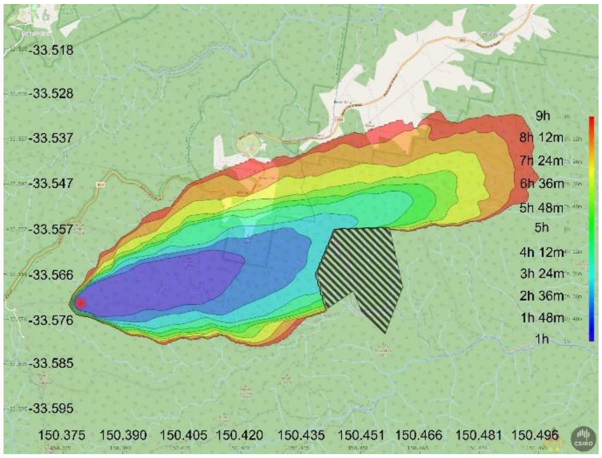

Figure 10. The wildfire spread in Scenario 5

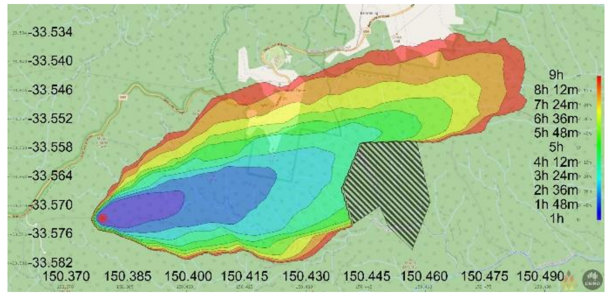

Figure 11. The wildfire spread in Scenario 6

increase was smaller compared to the effect of wind speed, indicating that changes in air temperature had a smaller contribution to the spread of wildfires. The effect of relative humidity on wildfire can be seen from the comparison between Figure 6 and Figure 11. The results show that the spread area of wildfire in Scenario 6 was smaller than that in Scenario 1, which indicates that a stable relative humidity is not conducive to the spread of wildfire.

The comparison from Figures 6 through 11 shows the influence of different weather factors on the spread of wildfire. Among them, wind direction was found to be the main factor that determines the direction of wildfire spread, and wind speed was the main factor that determines the speed of wildfire spread. A stable wind (with stable speed and direction) is conducive to limiting the spread of wildfire. Compared with wind, air temperature and relative humidity had a smaller influence on the spread of wildfires, but a stable air condition (with stable air temperature and relative humidity) could limit the spread of wildfires to a certain extent. Experimental results also show that the incombustible area, which can be a pond or a burned area, prevents the spread of wildfire. This provides a strategy to reduce the loss of wildfires to the built environment by establishing an incombustible zone around the housing plot and isolating it from grassland. In this way, if we consider the housing plot and the isolation zone around it as the non-combustible area, we can use this simulator in conjunction with building information modeling (BIM) to support the design and construction decisions of the built environment.

4. CONCLUSIONS

The spread of wildfires is affected by various factors, such as geological, weather and human factors. This research focuses on the effects of weather factors (i.e., wind speed, wind direction, air temperature, and relative humidity) and explores the dominating factor on the spread of wildfires. Based on the experiments in this paper, the following conclusions can be drawn:

(1) Wind speed and wind direction were the key factors that determined the speed and direction of wildfire spread, respectively. A wind with a stable speed and direction helped limit the spread of wildfires.

(2) Compared with the speed and direction of the wind, air temperature and relative humidity had a smaller effect on the spread of wildfires. Air condition with stable temperature and relative humidity helps control the spread of wildfires.

(3) Based on the above conclusions, joint consideration of weather factors and environmental obstacles (such as a burned area) can be used to reduce the threat of wildfires on the built environment to a large extent.

This study considers the impact of four weather factors on the spread of wildfires. Future research includes considering more weather factors such as precipitation, air pressure, etc. in simulation, exploring the effects of different types of geographic factors (e.g., grasslands and bushes) and environmental obstacles (e.g., ponds and burned areas) on wildfire progression, as well as cross validating results with real wildfire. These will provide useful knowledge for wildfire control and management in the context of protecting the built environment in the future.

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