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Calculating McArthur's Forest Fire Danger Index and the Keetch-Byram Drought Index

McArthur's Forest Fire Danger Index (FFDI) (McArthur 1967) requires measures of drought factor, air temperature, relative humidity, and wind speed. FFDI is calculated using the equation developed by Noble et al. (1980). FFDI is defined by Eq 1:

$$FFDI = 2.0 \times e^{(-0.450+0.987\ln(DF)-0.0345RH+0.0338T+0.0234V)}$$

where DF is the drought factor, RH is the relative humidity (%), T is the temperature (°C), and V is the wind speed (km h^{-1}).

Drought factor attempts to predict the availability of fine surface fuel for combustion in bushfires and is typically derived using either the Keetch-Byram Drought Index (KBDI) or Mount's Soil Dryness Index (SDI) (Holgate et al. 2017). Therefore, in order to calculate FFDI, drought factor must first be calculated. The KBDI and SDI are both representations of soil moisture deficit (SMD), a factor that represents dryness of the soil and the degree of drought present on the landscape (Lucas 2010). The index used to estimate soil moisture deficit varies between fire management agencies throughout Australia, however SMD was originally estimated by McArthur using the KBDI (Lucas 2010, Holgate 2017). Soil moisture balance is calculated as the difference between the amount of water infiltrating the soil, called effective precipitation, and the amount of water leaving the soil via transpiration or evaporation, called evapotranspiration (Finkele et al. 2006). Therefore, changes in SMD are calculated as:

$$SMD_t = SMD_{t-1} + ET - P_{eff}$$

where SMD_t is the SMD for the current day, SMD_{t-1} is the SMD for the day before, ET is the evapotranspiration for the current day, and P_{eff} is the effective precipitation for the current day.

Keetch and Byram (1968) define the KBDI as a number representing the net effect of evapotranspiration and precipitation in producing cumulative moisture deficiency in deep duff or upper soil layers. The index thus relates to the flammability of organic material on the ground (Keetch and Byram 1968). Keetch and Byram outline the theory and framework for the index with several assumptions. They assume 1) the rate of moisture loss in a forested area depends on the density of vegetation in that area and the density of vegetation is a function of the mean annual rainfall for that area, 2) the relationship between vegetation and rainfall is exponential where the rate of moisture removal is a function of mean annual rainfall, 3) the rate of moisture loss from the soil is determined by evapotranspiration relations, 4) the depletion of soil moisture with time is exponential in where the wilting point moisture is used as the lowest moisture level, and 5) the soil has a field capacity of 8 inches (203.2 mm) of available water. A mathematical description of the index was developed by Keetch and Byram based on these assumptions and supporting data.

Daily precipitation and temperature are the only variables needed to calculate KBDI. The KBDI represents moisture deficit in hundredths of an inch (millimeters). This means with a field capacity of 8.00 inches (203.2 mm) of available water in the soil for transpiration, the index is on a scale ranging from 0 to 800 (0 to 203.2) (Keetch and Byram 1968). A KBDI of zero indicates that there is no moisture deficiency while a KBDI of 800 (203.2) is the maximum drought possible. The KBDI also indicates the amount of net rainfall in hundredths of an inch (millimeters) required to reduce the index to zero. KBDI is incremented or decremented daily based on mean annual precipitation for the area, KBDI the day before, and the maximum temperature for the day. A reduction in KBDI occurs when net rainfall exceeds 0.20 inches (5.08 mm).

The KBDI can be calculated using the five tables of drought factors provided in Keetch and Byram (1968) or by using equations representing the net effect of evapotranspiration (ET) and precipitation. Keetch and Byram (1968) provide the table-based approach to simplify computations for field use. The values in the drought factor tables represent solutions of the ET equation but simplified for 3°F temperature increments at only five mean annual rainfall scenarios. The values presented in the tables are also rounded to the nearest whole number. Thus, values calculate using the table-based approach are approximations to the true values which should be calculated using the ET equation. ET for any given day is estimated as:

$$ET = 10^{-3} \times \frac{(203.2 - KBDI_{t-1}) \times (0.968 \times e^{(0.0875 \times T_{max} + 1.5552)} - 8.30)}{10.88 \times e^{(-0.001736 \times P_{annual})} + 1}$$

where ET is evapotranspiration, $KBDI_{t-1}$ is the Keetch-Byram Drought Index for the day before, T_{max} is the maximum temperature, and P_{annual} is the average annual precipitation.

The next term needed in calculating SMD is effective precipitation. This is daily precipitation decreased by an amount to account for interception by vegetation cover and/or runoff (Finkele et al. 2006). Finkele et al. (2006), Lucas (2010), and Holgate et al. (2017) all use 5 mm (0.19685 inches) as an approximation of interception and/or runoff while Keetch and Byram (1968) use 5.08 mm (0.20 inches). This software follows Keetch and Byram's specification of 5.08 mm. While several studies are ambiguous as to how effective precipitation is calculated, Lucas (2010) explains that effective precipitation is calculated by subtracting 5 mm from only precipitation events that exceed 5 mm. If there are consecutive precipitation days, these days are combined into a single precipitation event and 5 mm is only subtracted once for the single event. This indicates that effective precipitation is synonymous with what Keetch and Byram (1968) call "net rainfall". Though in the case of Keetch and Byram, they require that daily precipitation exceed 5.08 mm.

One should also notice the cumulative nature of calculating SMD. Daily SMD is partly determined by the SMD on the day prior and therefore special care should be taken in beginning a KBDI record. Keetch and Byram (1968) state that the drought index record cannot automatically begin at zero but instead should begin on a day when it is reasonably certain that the upper soil layers were saturated. Once SMD has been calculated, drought factor can be calculated. The drought factor (DF) is calculated using the formula given by Griffiths (1999) and is based on SMD (calculated using either KBDI or SDI) and the past 20 days' rainfall (Finkele et al. 2006). This formula more closely approximates McArthur's meter than the equation given by Noble et al. (1980) for drought factor. Drought factor is defined as:

$$DF = 10.5 \times \left(1 - e^{-\left(\frac{SMD+30}{40}\right)}\right) \times \frac{41x^2 + x}{40x^2 + x + 1}$$

where x expresses the influence of the past rainfall amount (P) and number of days since it fell (N) on the drought factor. It is calculated as:

$$x = \begin{cases} \dfrac{N^{1.3}}{N^{1.3} + P - 2} & N \geq 1 \; and \; P > 2 \\[2ex] \dfrac{0.8^{1.3}}{0.8^{1.3} + P - 2} & N = 0 \; and \; P > 2 \\[2ex] 1 & P \leq 2 \end{cases}$$

The function is evaluated for all previous rain events in the past 20 days. The minimum of all x values calculated is used as input for the drought factor equation and is considered the "most significant" rainfall event in the past 20 days. The drought factor is therefore reduced by the "most significant" rainfall event recorded in the previous 20 days (Finkele et al. 2006, Lucas 2010, Holgate et al. 2017). A rainfall event can be either a single rain day or a collection of consecutive rain days. In the case of consecutive rain days, P is the sum of all precipitation that has occurred over the event and N is the number of days since the largest daily precipitation event.

In operation use at the Australian Bureau of Meteorology, it was found that this procedure allowed the drought factor to increase too quickly during prolonged dry periods following a significant rain event (Finkele et al. 2006). Finkele et al. (2006) proposed that this can be resolved by substituting x with x_{lim} if x_{lim} is smaller than the previously calculated x. x_{lim} is calculated as:

$$x_{lim} = \begin{cases} \dfrac{1}{1 + 0.1135 \times SMD} & SMD < 20 \\[2ex] \dfrac{75}{270.525 - 1.267 \times SMD} & SMD \geq 20 \end{cases}$$

The smaller of the two values (x and x_{lim}) is used in calculating drought factor.

The drought factor equation can result in drought factors greater than the maximum allowed value of 10. Therefore, the final daily drought factor must be limited to be less than 10 in the final calculation. The final drought factor is calculated as:

$$DF = \min(10, DF)$$

References

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