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Theoretical Amounts of Water to Put Out Forest Fires

C.E. Van Wagner and S.W. Taylor

Canadian Forest Service
Pacific Forestry Centre

Information Report
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The Pacific Forestry Centre, Victoria, British Columbia

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2022

Cat. no. Fo143-2/458E-PDF
ISBN 978-0-660-44888-6
A pdf version of this publication is available through the Canadian Forest Service Publications website: http://cfs.nrcan.gc.ca/publications.

Cover photo: Darwin Lake experimental fire Unit 4, 1974. Head fire intensity 950 kW/m (227 kcal/s–m)

Contents

Tables

Figures

Preface

The majority of this paper was originally written in 1973 while the first author was at the Petawawa Forest Experiment Station but it has not been previously published. The research detailed in this paper was motivated by experimental work of Stechishen (1970) and Stechisen and Little (1971) who investigated depths of water needed to extinguish a fire as part of a larger study of water bombing. Despite the importance to fire suppression and to understanding the effects of precipitation on extinguishing free burning fires, there has been relatively little research on this topic (Pluckinski 2019). One earlier examination of the volume of water needed to cool a fire (King 1961) and two other more recent investigations by Hansen (2012) and Penney et al. (2018) are available. However, the different approach in the present paper provides a straightforward theoretical underpinning to the question of how much water is required to extinguish forest fires.

Since the original paper was written, the Systeme Internationale (SI) of physical measurement units has become the accepted scientific standard. The calorie (cal) has been replaced by the Joule (J) and the Watt (W) has become the new unit of power, namely the energy output rate. Rather than replace the units of every quantity in the original paper, which would not affect the theoretical argument, the following short list of equivalents can easily be applied if desired:

Energy: $1\ \text{cal} = 4.184\ \text{J}$

Fireline intensity: $1\ \text{kcal/s}-\text{m} = 4.184\ \text{kJ/s}-\text{m}$ or $4.184\ \text{kW/m}$

Radiation intensity: $1\ \text{kcal/m}^2-\text{s} = 4.184\ \text{kJ/m}^2-\text{s}$ or $4.184\ \text{kW/m}^2$

This revision includes a comparison of the theoretical water depths of water required to put out a fire with the amounts of water applied in Stechisen and Little’s (1971) test fires, as well as a summary of equations.

Abstract

A system of equations is presented to estimate the mass and depth of water required to extinguish forest fires for three different mechanisms: quenching the flame, cooling the hot fuel in the flaming zone, and wetting the fuel ahead of the flaming zone. A heat balance approach is used to equate the heat required for each mechanism with the amount and heat capacity of water (most of the 'cooling power' of water comes from conversion of water to steam). The equations provide a theoretical underpinning for understanding which fire characteristics influence the amounts of water needed, and the relative amounts needed for different fire extinguishing mechanisms. Examples are given for a range of fire intensities which illustrate that water requirements increase at a rate much less than the full power of line fire intensity. Comparing the amount of water applied with the theoretical requirements for a series of low intensity test fires in red pine needles and in slash fuel beds that were extinguished or not extinguished following the application of water confirmed that the theoretical estimates are plausible.

Résumé

Un système d'équations est présenté afin d'estimer la masse et la profondeur de l'eau requise pour éteindre un feu de forêt selon trois mécanismes : extinction des flammes, refroidissement du combustible chaud dans la zone de flammes, et mouillage du combustible avant la zone de flammes. Un bilan thermique sert à égaliser la chaleur requise pour chaque mécanisme à la quantité et à la capacité calorifique de l'eau (la majorité du « pouvoir réfrigérant » de l'eau vient de sa conversion en vapeur). Les équations fournissent une base théorique pour comprendre quelles caractéristiques du feu influent sur la quantité d'eau requise et quelles sont les quantités relatives nécessaires pour différents mécanismes d'extinction. Des exemples sont donnés pour un éventail d'intensités de feu; ils montrent que le besoin en eau augmente beaucoup moins rapidement que l'intensité maximale de la ligne de feu. La plausibilité des estimations théoriques est confirmée par une comparaison entre le besoin théorique en eau pour une série de feux d'essai de faible intensité sur des lits d'aiguilles de pin rouge et de rémanents, et la quantité d'eau utilisée ayant permis ou non de les éteindre.

1 Introduction

The actual mechanism by which water puts out fire is likely very complex from the viewpoint of fundamental physical chemistry. It is possible, however, to simplify the problem and to draw up heat balances relating fire behaviour, and the required amount of water based on some assumptions. Whether such an approach is valid enough to be useful is open to question; there are, at any rate, only a few treatments of this problem, and no harm can result from adding another.

There are three basic mechanisms dealt with in this report:

1) quenching the flame itself

2) cooling the hot fuel, and

3) wetting the fuel ahead of the fire.

Some quantities used are identified throughout the text, but the only formal complete description is in Table 1. This may be a small inconvenience, but it smooths the flow from one equation to the next.

Table 1. Symbols and quantities used in the calculation of water requirements

Symbol	Quantity	Units
c_s	heat capacity of steam	0.46 kcal/kg[a]
c_f	heat capacity of flame gas	0.264 kcal/kg[a]
c_l	heat capacity of hot fuel	0.35 kcal/kg[a]
d_f	density of flame gas	0.0328 kg/m^3 at 800°C
D	flame depth	m
D_w	depth of water	mm
H_w	heat absorbed by water	kcal/kg[a]
H_f	heat given up by flame gas	kcal/kg[a]
H_1	heat given up by hot fuel	kcal/kg[a]
i	radiant intensity from flame front	kcal/m^2−s[b]
I	fireline intensity	kcal/s−m of front[c]
L	flame length	m
Q	energy delivered to ground area ahead of fire	kcal/m^2 [d]
R	rate of advance	m/sec
V_f	volume of flame	m^3/m of front
W_f	weight of flame	kg/m of front
W_1	weight of fuel	kg/m^2 of ground area
W_w	weight of water	kg/m of front
T_a	air temperature	°C
T_e	equilibrium temperature	°C
T_f	flame temperature	°C

a 1 kcal = 4.184 kJ.

b 1 kcal/m^2−s = 4.184 kW/m^2.

c 1 kcal/s−m = 4.184 kW/m.

d 1 kcal/m^2 = 4.184 kJ/m^2.

2 Water Required by Fire Extinguishing Mechanism

Determining the amount of water required to extinguish a fire by the three mechanisms outlined above using an energy balance approach depends on calculating the amount of heat or energy that water can absorb from the flame or fuel as outlined in the following paragraph. It also relies on estimating the amount of heat emitted by the flame, the hot fuel in the flaming zone, and absorbed by the fuel in the pre-ignition zone which are considered separately in the following sub-sections, with fire line intensity as common link, where possible.

Heat absorbed per unit weight of water

H_w is the sum of the heat absorbed in the three steps from cool water to water vapour at equilibrium temperature.

$$H_w = (100 - T_a) + 540 + (T_e - 100)\,c_s \tag{1a}$$

If T_e is assumed to be 100°C and all water is vaporized, this reduces to

$$H_w = (100 - T_a) + 540 \tag{1b}$$

2.1 Quenching the Flame

The direct approach of calculating the amount of water required to put out a fire of a given intensity (as energy output rate) breaks down because intensity is a rate quantity, while water amount is not time-related; consequently, there is no link to make the equation dimensionally sound. However, intensity can be introduced through an empirical correlation, such as with flame length, which is then used to estimate the flame volume and weight, and the amount of heat produced per unit of flame weight.

Flame volume per unit length of fire front

Assume that the flame is reasonably vertical and triangular in cross-section (Figure 1). Then,

$$V_f = LD/2 \tag{2a}$$

Flame volume can be expressed in terms of fire intensity from correlations between L and burning rate given by Thomas (1963) at the same time assuming that flame depth, D, is just half of flame length L. The appropriate form of Thomas' correlation is, then,

$$L = 0.0792\ I^{2/3} \tag{2b}$$

in which the heat of combustion contribution to flame height is 3590 kcal/kg.[1] Combining these two equations and substituting L/2 for D gives:

$$V_f = L^2/4 = (0.0792)^2\ I^{4/3}/4, \text{ which simplifies to}$$

$$V_f = 0.00156\ I^{4/3} \tag{2c}$$

Flame gas density

Next, assume that flame gas density is equivalent to air. The density of air at STP is 0.129 kg/m^3. Density d_f at flame temperature is, then,

$$d_f = 0.129 \times 273/(T_f + 273) \tag{3}$$

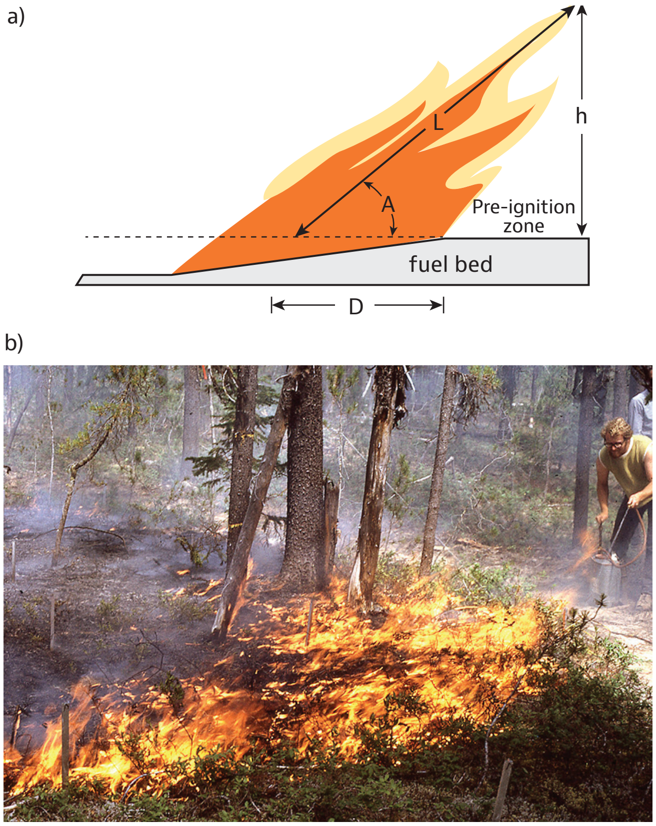

Figure 1. View of (a) flame dimensions perpendicular to the flame front (L = flame length, D = flame depth, A = flame angle, h = flame height), and (b) of a surface fire flame front (Darwin Lake experimental fire Unit 2, 1974. Head fire intensity 160 kcal/s–m (670 kW/m)).

Flame gas weight per unit length of fire front

This quantity (W_f) in terms of L and D is, from 2a,

$$W_f = d_f V_f = d_f LD/2 \qquad (4a)$$

In terms of fire intensity, assuming equation (2b) holds for L in terms of I,

$$W_f = 0.00156 I^{4/3} d_f \qquad (4b)$$

Heat released per unit weight of flame gas

H_f is the product of the temperature difference $T_f – T_e$ and the average heat capacity of the flame gas over the temperature range (100 – 540°C).

$$H_f = (T_f – T_e) c_f \qquad (5)$$

The value of each can be obtained from curves giving the heat capacities of gasses over varying temperature ranges (Walker et al. 1937). Flame gas is assumed to be equivalent to air in terms of heat capacity for present purposes.

Weight of water required per unit length of fire front

Finally, the weight of water W_w necessary to quench the flame is obtained by equating the heat absorbed by the water to the heat given up by the flame gas, all at equilibrium final temperature.

$$H_w W_w = H_f W_f \qquad (6a)$$

H_w comes from (1b), H_f from (5) and W_f from (4b); substituting in (6a) and supposing that all the water is vaporized, then,

$$W_w = \frac{0.00156 (T_f – T_e) c_f I^{4/3} d_f}{(100–T_a) + 540} \qquad (6b)$$

This result can be simplified if the following temperatures are assumed:

T_f = 800°C

T_e = 100°C

T_a = 20°C

In other words, if the heat balance is made at 100°C, then,

c_f = 0.264 (from Walker et al. 1937)

d_f = 0.0328 (from (3)), and

$$W_w = \frac{0.00156 \times 700 \times 0.264 \times 0.0328}{620} I^{4/3} = 1.52 I^{4/3} \times 10^{-5} \qquad (6c)$$

This result is in kg water per m of fire front, and assumes perfect efficiency with all water vaporized at 100°C.

Depth of water needed on the burning zone

This quantity (D_w) is readily obtained by dividing W_w by the depth of fire front D. The resulting value in kg/m^2 is numerically equal to depth in mm.

$$D_w = W_w/D \qquad (7a)$$

W_w comes from (6c). D has already been assumed to equal L/2; making this substitution in terms of $I^{2/3}$ (2b) gives

$$D_w = \frac{1.52 I^{4/3} \times 10^{-5} \times 2}{0.0792 I^{2/3}} = 3.84 I^{2/3} \times 10^{-4} \qquad (7b)$$

This result is in terms of mm of water applied on the burning zone and assumes that the water vaporizes completely while quenching the flame.

2.2. Cooling the Hot Fuel

The previous section considered the process of quenching the flame only. Suppose the mechanism of fire extinguishment is rather to cool the hot fuel within the burning zone. Assume as before that all water is vaporized and the final equilibrium temperature is 100°C.

Energy released per unit weight of hot fuel

The quantity (H_1) is found from the hot fuel temperature T_1 and its specific heat c_1

$$H_1 = (T_1 – T_e) c_1 \qquad (8)$$

Weight of water needed per unit length of fire front

The weight of water needed to cool the hot fuel in the burning zone to the equilibrium temperature (W_w) is found from the depth of the flaming zone, the weight of fuel consumed, the energy produced by the hot fuel, and the heat absorbed by water:

$$W_W = W_1 \, D \, H_1/H_W \qquad (9a)$$

H_1 comes from (8) and H_W comes from (1b). If T_e is 100ºC then

$$W_W = \frac{W_1 D (T_1 - 100) c_1}{(100 - T_a) + 540} \qquad (9b)$$

If D is assumed equal to L/2, and in turn proportional to $I^{2/3}$ then (2b) can be substituted in (9b). If T_1 is also assumed to be 500ºC, T_a equal to 20ºC, and c_1 to 0.35, then,

$$W_W = \frac{0.0792 \, I^{2/3} \, W_1 (500 - 100) 0.35/2}{(100 - 20) + 540} = 8.96 \, I^{2/3} \, W_1 \times 10^{-3} \qquad (9c)$$

Depth of water needed on the burning zone

This quantity (D_W) is obtained directly in mm by removing D from (9b) as:

$$D_W = \frac{W_1 (T_1 - 100) c_1}{(100 - T_a) + 540} \qquad (10a)$$

Making the same substitutions as for 9c,

$$D_W = 0.226 \, W_1 \qquad (10b)$$

2.3 Wetting Fuel ahead of the Fire

Suppose that enough water is added to the fuel ahead of the fire so that all the energy delivered to each unit of ground area by the fire is used up in cooling the fuel through evaporation, arresting fire spread such that the fire burns out. The width of the wet strip should presumably be equal to the depth of the burning zone, and the amount of water that is needed would be equivalent to the energy delivered to the pre-ignition zone by the flame front.

Radiant energy to be absorbed per unit ground area

This radiant energy delivered to the ground area ahead of the fire (Q) depends on the flame length, rate of advance, and the radiant intensity emitted by the flame (Van Wagner 1967),

$$Q = i \, L/2R \qquad (11a)$$

Substituting the $I^{2/3}$ correlation in (2b) for L,

$$Q = 0.0396 \, I^{2/3} \, i/R \qquad (11b)$$

Weight of water needed per unit length of fire front

The weight of water needed to cool a strip of unburned fuel ahead of the flame front of the same width as the flame depth to the equilibrium temperature (Ww) is obtained from the radiant energy delivered to the strip and the heat absorbed by water:

$$W_W = QD/H_W \qquad (12a)$$

Substitute (11b) for Q and L/2 in terms of $I^{2/3}$ for D (2b). H_W is from (1b); assume T_e is 100°C. T_a is 20ºC and all water is evaporated. Then,

$$W_W = 1.57 \, I^{4/3} \, i \times 10^{-3}/620R = 2.53 \, I^{4/3} \, i \times 10^{-6}/R \qquad (12b)$$

Depth of water needed on ground ahead of fire

This quantity (D_W) is obtained directly in mm by removing D from (12a),

$$D_W = Q/H_W \qquad (13a)$$

Again substituting (11b) for Q and (1b) for H_W with the assumptions in (12b), then,

$$D_W = 0.0396 \, I^{2/3} \, i/620R$$

$$D_W = 6.39 \, I^{2/3} \, i \times 10^{-5}/R \qquad (13b)$$

3 Examples and Validation

In order to compare these three tentative mechanisms of fire extinguishment by water and the equations that result, it is worthwhile calculating some examples. Let us choose three levels of fire intensity in kcal/sec-m:

100 – an easy fire to put out with water,

1000 – a difficult fire to put out with water, and

10 000 – a probably impossible fire to put out with water.

Before all the equations can be used, it is necessary to assume values for the rate of advance, R, and the weight of fuel, W_1, all consistent with an effective heat of combustion of 3590 kcal/kg. The intensities, in other words, represent sensible convective heat only, not total energy. Also chosen were some reasonable values for i, the average intensity emitted by the fire front. All these data appear in Table 2. Probably the two most pertinent parameters for comparison are the weight of water needed per unit length of front (W_W) and the depth of water required on the wetted strip (D_W). These results are given in Table 3 for each mechanism along with the equations used to derive the quantities. The Rate of advance or spread, R, appears as m/min in Table 2, but must be divided by 60 for use in the equations.

Stechisen and Little's (1971) work remains one of the few validation datasets. They applied varying depths of water with a spray apparatus to 77 low intensity test fires (15–155 kcal/s−m) in red pine needle and slash fuel beds, and assessed whether the fires:

a) were extinguished in less than 3 minutes;
b) were extinguished in 3–20 minutes;
c) exhibited delayed reigntion within 20 minutes; or
d) were rekindled within 3 minutes (additional details are in Hansen, 2012).

The theoretical amounts of water required to put out the test fires by quenching the flame, cooling the hot fuel, and wetting the fuel ahead of the fire were calculated using Equations 7b, 10b, and 13b in this report and are given in Appendix 2. For the fires that were extinguished, more water, on average, was applied than the average theoretical requirements to either quench the flame, cool the hot fuel, or wet the fuel (it is difficult to separate which mechanism was responsible). For the fires that were not extinguished, the average amount of water applied was less than the average total theoretical requirements for all three mechanisms.

Table 2. Nominal fire characteristics for three fire intensities

Intensity (kcal/s–m)	Weight of fuel (kg/m^2)	Rate of spread[a] (m/min)	Radiant intensity (kcal/m^2–s)	Flame length[b] (m)	Flame depth (m)
100	1.25	1.33	5	1.7	0.85
1 000	2.5	6.67	10	7.9	3.9
10 000	5	33.3	20	36.7	18.4

a R must be divided by 60 for use in equations 12b and 13b.

b From (2b).

Table 3. Amounts of water needed to extinguish the three fires in Table 2 by three different mechanisms, assuming 100% efficiency

	W_w – weight of water (kg/m fire front)			D_w – depth of water (mm/m fire front)		
	Extinguishing mechanisms					
Intensity (kcal/s–m)	**Quenching flame (Eqn. 6c)[a]**	**Cooling hot fuel (Eqn. 9c)**	**Wetting unburned fuel (Eqn. 12b)**	**Quenching flame (Eqn. 7b)**	**Cooling hot fuel (Eqn.10b)**	**Wetting unburned fuel (Eqn.13b)**
100	0.007	0.24	0.26	0.008	0.28	0.31
1 000	0.15	2.24	2.28	0.038	0.56	0.57
10 000	3.27	20.8	19.64	0.18	1.13	1.07

a The equations used to calculate each quantity are listed by mechanism. See summary of equations in Appendix 1.

4 Discussion

If the amounts of water needed to put out the fires in Table 3 appear rather small, the main reason is probably the assumption of perfect efficiency—all water being vaporized. Equation 1a for H_W shows clearly why this is so. The cooling power of liquid water is limited to a mere 80 kcal/kg at a T_a of 20°C, while 540 kcal is contributed by evaporation. Assuming a T_e of much above 100°C helps relatively little since the heat capacity of steam is less than half that of water. Of the three mechanisms considered, flame quenching apparently requires much less water than the other two. This is because the flame envelope at any instant contains only a small fraction of the heat associated with the total fuel weight that is eventually consumed. Actually, although flame quenching and hot fuel cooling are treated separately, it makes sense to combine them, since one could hardly succeed without the other.

We are left then with two distinct choices: put the water either on the fire or ahead of it. When these two are compared, it is surprising how similar the required amounts of water are across the intensity range (Figure 2). Note that the water requirements increase at a rate much less than the full power of line fire intensity, in part because the amount of water required to cool the fuel is proportional to the weight of hot fuel.

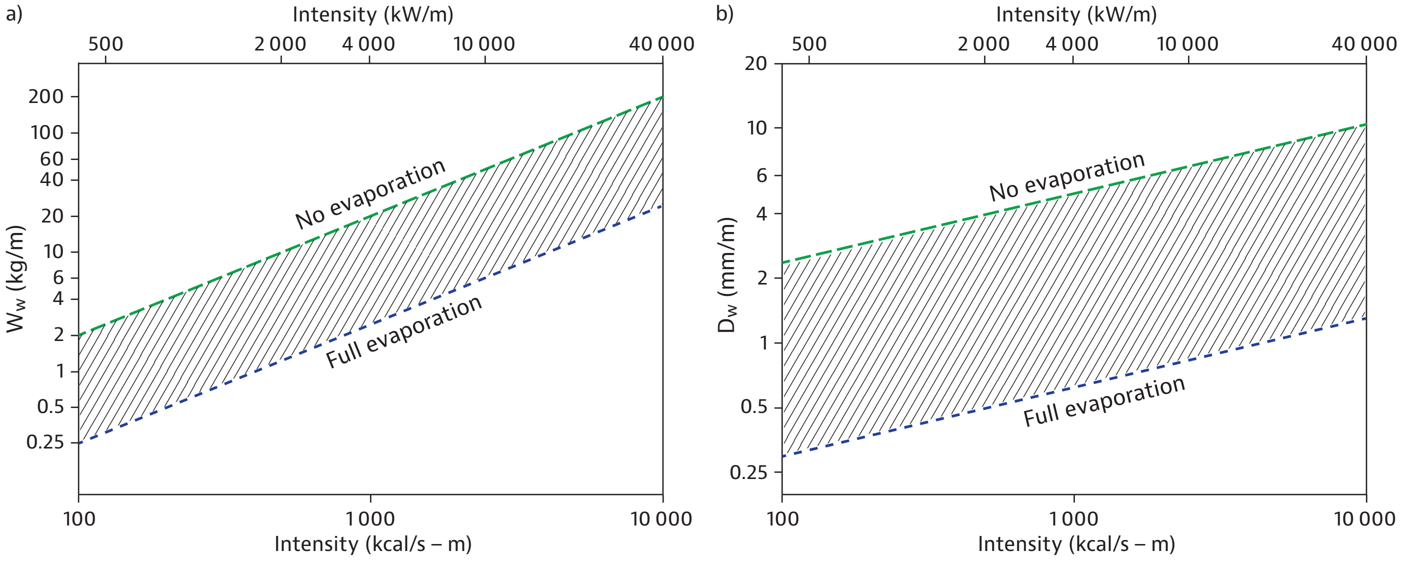

Figure 2. (a) Weight (W_w) and (b) depth (D_w) of water to put out a fire by extinguishing the flame and cooling the hot fuel for the fire characteristics in Table 2, showing a range of efficiency.

The many assumptions made during these calculations raise an equal number of questions. A really rigorous analysis of how water extinguishes fire would be a very complex undertaking. The heat balance approach is the simplest one, but interference with the ideal blend of air and flammable pyrolysis products by the addition of water vapour might be important, especially when water is added ahead of the fire. However, no matter how the problem is tackled, the main stumbling block is probably the question of efficiency. How much water evaporates? As noted previously, the limits of efficiency are nearly eight-fold in the required amount of water. Liquid water escaping into the ground without contacting the fuel would further increase this range.

Fuel characteristics, including particle size and packing ratio, likely also affect water application efficiency. In Stechisen and Little's (1971) test fires, more water was required to extinguish fires in slash than in red pine needle fuel beds relative to the theoretical requirements for quenching the flame + cooling the hot fuel, and cooling fuel ahead of the fire (Table 4). As would be expected, the ratios of water applied/theoretical requirements were lower for fires that were not extinguished, in the range of 1–2 times. Allowing for loss of efficiency, the theoretical requirements to extinguish these fires are plausible.

Table 4. Water application efficiency[a] (Mean + S.E.(n)) by fuel type and extinguishing mechanism for 77 test fires in Stechishen and Little (1971); Appendix 2

Fuel Bed	Extinguishing Mechanism	Fire Not Extinguished	Fire Extinguished
Red pine needles	Quenching flame + Cooling fuel	1.2 ± 0.12 (12)	2.4 ± 0.21 (21)
	Wetting fuel	1.0 ± 0.14 (12)	1.4 ± 0.15 (21)
Slash	Quenching flame + Cooling fuel	1.9 ± 0.19 (17)	2.8 ± 0.15 (27)
	Wetting fuel	1.5 ± 0.19 (17)	2.0 ± 0.15 (27)

[a] Ratio of amount of water applied/theoretical requirement.

The main objective of this report was to provide a theoretical framework to estimate the amounts of water required to put out a fire; many assumptions were made and complicating factors disregarded for simplicity sake. While several other relationships between flame length and intensity have appeared since 1963 (e.g., Alexander and Cruz 2021, Table S1), Thomas' expression for fires in the open, backed by his maths and physics, remains valid today. Further empirical evaluation of water application efficiency over a wider range of fire intensites and fuel types would be needed for practical application.

Endnote

1. Thomas (1963, eqn. 18) correlated flame length L with m_W, the mass flow rate of fuel per length of fire front as

$$L = 400\, m_W^{2/3} \text{ (in cgs units)} \tag{S1}$$

which equates (Van Wagner 1967) to

$$L = 18.566\, (W_1 R)^{2/3} \tag{S2}$$

converting from cgs to mks units and in the terms used in this report. Given that $I = H W_1 R$, assume the heat of combustion H = 3590 kcal/kg, and substitute I/H for $W_1 R$ in (S2), then,

$$L = 0.0792\, I^{2/3} \tag{S3}$$

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Appendix 1 – Summary of fire extinguishment mechanisms and equations

(following the units in Table 1 and assumptions in the text).[1]

Heat absorbed per unit weight of water

$$H_w = (100 - T_a) + 540 \qquad (1b)$$

I. QUENCHING THE FLAME

Flame volume per unit length of fire front

$$V_f = 0.00156\, I^{4/3} \qquad (2c)^1$$

Flame gas density

$$d_f = 0.129 \times 273/(T_f + 273) \qquad (3)$$

Flame gas weight per unit length of fire front

$$W_f = 0.00156\, I^{4/3}\, d_f \qquad (4b)^1$$

Heat given upper unit weight of flame

$$H_f = (T_f - T_e)\, c_f \qquad (5)$$

Weight of water required per unit length of fire front

$$W_w = 1.52\, I^{4/3} \times 10^{-5} \qquad (6c)^1$$

Depth of water needed on the burning zone

$$D_w = 3.84\, I^{2/3} \times 10^{-4} \qquad (7b)$$

II. COOLING THE HOT FUEL

Energy given upper unit weight of hot fuel

$$H_1 = (T_1 - T_e)\, c_1 \qquad (8)$$

Weight of water needed per unit length of fire front

$$W_w = 8.96\, I^{2/3}\, W_1 \times 10^{-3} \qquad (9c)^1$$

Depth of water on the burning zone

$$D_w = 0.226\, W_1 \qquad (10b)$$

III. WETTING FUEL AHEAD OF THE FIRE

Radiant energy to be absorbed per unit ground area

$$Q = 0.0396\, I^{2/3}\, i/R \qquad (11b)^1$$

Weight of water needed per unit length of fire front

$$W_w = 2.53\, I^{4/3}\, i \times 10^{-6}/R \qquad (12b)^1$$

Depth of water needed on ground ahead of the fire

$$D_w = 6.39\, I^{2/3}\, i \times 10^{-5}/R \qquad (13b)^1$$

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[1] To convert fireline intensity (I) in kcal/s–m to kw/m, multiply by 4.184.

Appendix 2 – Comparison of actual and theoretical amounts of water to extinguish test fires (adapted from Stechisen and Little (1971) Appendix C).

Table A2.1 Fire characteristics and water depths applied to test fires in red pine needle beds

	Fire characteristics					Water depth (mm)					Water application efficiency[d]	
		I	W_1	R	i[b]	Applied	Theoretical requirement[c]					
No.	**Status[a]**	**(kcal/s–m)**	**(kg/m^2)**	**(m/min)**	**(kcal/m^2–s)**		**Q**	**C**	**Q+C**	**W**	**Q+C**	**W**
						Not extinguished						
14	DR	62	2.8	0.60	5	0.8	0.006	0.63	0.64	0.50	1.3	1.6
16	DR	105	3.0	0.60	5	1.5	0.009	0.68	0.69	0.70	2.2	2.1
21	DR	105	1.6	0.62	5	0.3	0.009	0.36	0.37	0.69	0.8	0.4
12	DR	125	2.1	0.63	5	0.6	0.010	0.47	0.48	0.76	1.2	0.8
30	R	36	1.3	0.65	5	0.3	0.004	0.29	0.30	0.32	1.0	0.9
4	R	84	1.6	0.66	5	0.6	0.007	0.36	0.37	0.55	1.6	1.1
8	R	88	2.4	0.68	5	0.6	0.008	0.54	0.55	0.56	1.1	1.1
20	R	126	2.0	0.69	5	0.5	0.010	0.45	0.46	0.70	1.1	0.7
12	R	130	2.2	0.71	5	0.6	0.010	0.50	0.51	0.69	1.2	0.9
34	R	138	3.1	0.71	5	0.6	0.010	0.70	0.71	0.72	0.8	0.8
28	R	145	1.3	0.73	5	0.2	0.011	0.29	0.30	0.73	0.7	0.3
35	R	318	3.0	0.72	5	1.2	0.018	0.68	0.70	1.24	1.7	1.0
	Mean	**122**	**2.2**	**0.67**	**5**	**0.7**	**0.009**	**0.50**	**0.51**	**0.68**	**1.2**	**1.0**
						Extinguished						
2	O	15	1.0	0.19	5	0.6	0.002	0.23	0.23	0.63	2.6	0.9
3	O	24	1.0	0.29	5	0.6	0.003	0.23	0.23	0.54	2.6	1.1
1	O	26	0.7	0.47	5	0.6	0.003	0.16	0.16	0.35	3.7	1.7
134	O	30	1.3	0.28	5	5.8	0.004	0.29	0.30	0.66	NI[e]	NI
136	O	41	1.4	0.37	5	0.8	0.005	0.32	0.32	0.61	2.5	1.3
19	O	44	1.8	0.29	5	0.7	0.005	0.41	0.41	0.81	1.7	0.9
137	O	46	1.7	0.34	5	1.2	0.005	0.38	0.39	0.73	3.1	1.6
23	O	54	1.7	0.38	5	0.3	0.005	0.38	0.39	0.71	0.8	0.4
148	O	58	1.8	0.39	5	1.6	0.006	0.41	0.41	0.74	3.9	2.2
149	O	58	2.4	0.29	5	1.8	0.006	0.54	0.55	0.98	3.3	1.8
11	O	67	1.1	0.75	5	0.4	0.006	0.25	0.25	0.42	1.6	1.0
32	O	72	2.2	0.40	5	0.5	0.007	0.50	0.50	0.82	1.0	0.6
6	O	77	1.1	0.89	5	0.6	0.007	0.25	0.26	0.39	2.3	1.5
7	O	87	1.0	1.03	5	0.6	0.008	0.23	0.23	0.37	2.6	1.6
27	O	121	1.8	0.80	5	1.5	0.009	0.41	0.42	0.58	3.6	2.6
15	GO	41	0.8	0.62	5	0.2	0.005	0.18	0.19	0.36	1.1	0.6
10	GO	68	1.7	0.49	5	0.5	0.006	0.38	0.39	0.65	1.3	0.8
9	GO	71	1.2	0.71	5	0.5	0.007	0.27	0.28	0.46	1.8	1.1
5	GO	85	0.9	1.22	5	0.6	0.007	0.20	0.21	0.30	2.8	2.0
17	GO	150	3.0	0.62	5	2.2	0.011	0.68	0.69	0.87	3.2	2.5
36	GO	238	3.0	1.01	5	1.9	0.015	0.68	0.69	0.73	2.7	2.6
	Mean	**70**	**1.6**	**0.56**	**5**	**1.1**	**0.006**	**0.35**	**0.36**	**0.58**	**2.4**	**1.8**

a DR = delayed reignition lasting >20 mins; R = rekindles within 3 mins; O = out in <3 min; GO = out in 3–20 min.

b i is assumed to be 5 kcal/m^2–s.

c Theoretical requirement by mechanism: Q = quenching flame; C = cooling hot fuel; W = wetting fuel ahead of the fire.

d Water applied/theoretical requirement for quenching flame + cooling hot fuel or wetting fuel ahead of the fire.

e Not included. Applied water depth is extreme.

Table A2.2 Fire characteristics and water depths applied to test fires in slash fuel beds

	Fire characteristics						Water depth (mm)					Water application efficiency[e]	
							Actual	Theoretical requirement[d]					
No.	**Spp.[a]**	**Status[b]**	**I (kcal/s–m)**	**W_1 (kg/m^2)**	**R (m/min)**	**i[c] (kcal/m^2–s)**		**Q**	**C**	**Q+C**	**W**	**Q+C**	**W**
							Not extinguished						
133	Ab	DR	154	1.9	1.03	5	1.1	0.011	0.43	0.44	0.54	2.5	2.1
109	Ab	R	43	1	0.57	5	0.4	0.005	0.23	0.23	0.42	1.7	1.0
126	Ab	R	75	1.5	0.64	5	0.6	0.007	0.34	0.35	0.53	1.7	1.1
116	Ab	R	106	1.7	0.82	5	0.9	0.009	0.38	0.39	0.53	2.3	1.7
119	Ab	R	110	1.3	1.06	5	0.4	0.009	0.29	0.30	0.41	1.3	1.0
128	Ab	R	116	1.6	0.94	5	0.7	0.009	0.36	0.37	0.48	1.9	1.4
115	Ab	R	126	1.7	0.97	5	0.8	0.010	0.38	0.39	0.49	2.0	1.6
130	Ab	R	159	1.9	1.10	5	0.9	0.011	0.43	0.44	0.51	2.0	1.8
142	Ab	R	161	2	1.01	5	1.0	0.011	0.45	0.46	0.56	2.2	1.8
107	Ab	R	182	1.9	1.22	5	1.4	0.012	0.43	0.44	0.51	3.2	2.8
101	Ab	R	190	1.7	1.43	5	0.7	0.013	0.38	0.40	0.44	1.8	1.6
140	Ab	R	195	1.9	1.33	5	1.5	0.013	0.43	0.44	0.49	3.4	3.1
144	Ab	R	199	2.2	1.16	5	1.5	0.013	0.50	0.51	0.56	2.9	2.7
155	Pm	R	75	3.1	0.32	5	0.8	0.007	0.70	0.71	1.07	1.1	0.7
157	Pm	R	110	3.3	0.44	5	1.0	0.009	0.75	0.75	1.01	1.3	1.0
145	Pg	R	46	1.9	0.32	5	0.04	0.005	0.43	0.43	0.76	0.1	0.1
146	Pg	R	56	2.3	0.32	5	0.74	0.006	0.52	0.53	0.86	1.4	0.9
		Mean	**124**	**1.9**	**0.86**	**5**	**0.90**	**0.009**	**0.40**	**0.40**	**0.60**	**1.9**	**1.5**
							Extinguished						
125	Ab	O	63	1.4	0.59	5	1.0	0.006	0.32	0.32	0.51	3.1	1.9
108	Ab	O	71	1	0.87	5	0.8	0.007	0.23	0.23	0.38	3.4	2.1
105	Ab	O	155	1.2	1.73	5	1.1	0.011	0.27	0.28	0.32	3.9	3.4
152	Pm	O	33	1.7	0.24	5	0.8	0.004	0.38	0.39	0.81	2.1	1.0
151	Pm	O	43	2.8	0.25	5	1.3	0.005	0.63	0.64	0.93	2.0	1.4
110	Ab	GO	45	0.9	0.61	5	0.6	0.005	0.20	0.21	0.39	2.9	1.5
124	Ab	GO	65	1.1	0.75	5	1.0	0.006	0.25	0.25	0.41	3.9	2.4
120	Ab	GO	67	1.4	0.62	5	0.6	0.006	0.32	0.32	0.51	1.9	1.2
118	Ab	GO	80	1.1	0.89	5	0.4	0.007	0.25	0.26	0.40	1.6	1.0
112	Ab	GO	82	1.4	0.76	5	0.8	0.007	0.32	0.32	0.48	2.5	1.7
103	Ab	GO	86	1.3	0.85	5	0.9	0.007	0.29	0.30	0.44	3.0	2.0
111	Ab	GO	100	1.2	1.10	5	0.6	0.008	0.27	0.28	0.37	2.1	1.6
112	Ab	GO	101	1.4	0.91	5	0.9	0.008	0.32	0.32	0.46	2.8	2.0
106	Ab	GO	111	1.6	0.89	5	1.2	0.009	0.36	0.37	0.50	3.2	2.4
122	Ab	GO	122	1.8	0.86	5	1.0	0.009	0.41	0.42	0.55	2.4	1.8
129	Ab	GO	126	1.6	0.98	5	0.9	0.010	0.36	0.37	0.49	2.4	1.8
132	Ab	GO	129	1.9	0.85	5	1.3	0.010	0.43	0.44	0.58	3.0	2.3
114	Ab	GO	134	1.7	1.04	5	1.0	0.010	0.38	0.39	0.48	2.5	2.1
127	Ab	GO	143	1.7	1.02	5	1.2	0.010	0.38	0.39	0.51	3.0	2.3
102	Ab	GO	151	1.6	1.22	5	1.4	0.011	0.36	0.37	0.45	3.8	3.1
139	Ab	GO	166	1.8	1.17	5	1.5	0.012	0.41	0.42	0.49	3.6	3.0
141	Ab	GO	183	2	1.16	5	1.8	0.012	0.45	0.46	0.53	3.9	3.4
117	Ab	GO	195	1.9	1.34	5	1.3	0.013	0.43	0.44	0.48	2.9	2.7
143	Ab	GO	213	2.2	1.27	5	2.0	0.014	0.50	0.51	0.54	3.9	3.7
153	Pm	GO	50	2.3	0.28	5	0.8	0.005	0.52	0.53	0.94	1.5	0.8
154	Pm	GO	78	2.5	0.41	5	0.8	0.007	0.57	0.57	0.86	1.4	0.9
156	Pm	GO	102	3.3	0.40	5	1.4	0.008	0.75	0.75	1.04	1.9	1.3
		Mean	**107**	**1.7**	**0.85**	**5**	**1.1**	**0.008**	**0.38**	**0.39**	**0.55**	**2.8**	**2.0**

[a] Ab = balsam fir; Pm = black spruce; Pg = white spruce.

[b] DR = delayed reignition lasting >20 mins; R = rekindles within 3 mins; O = out in <3 min; GO = out in 3–20 min.

[c] i is assumed to be 5 kcal/m^2–s.

[d] Theoretical requirement by mechanism: Q = quenching flame; C = cooling hot fuel; W = wetting fuel ahead of the fire.

[e] Water applied/theoretical requirements for quenching flame + cooling hot fuel or wetting fuel ahead of the fire.

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