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Three Different Fire Suppression Approaches Used by Fire and Rescue Services

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Abstract. This paper describes the relationship between the water flow rate applied by the Fire and Rescue Services (FRS) and the area of a fire; the limitations of the FRS in terms of water flow rate; and the most effective use of firefighting water across a broad range of fire areas. The paper is based on five sets of data gained by the FRS at the fire scene, in total almost 6000 fires. It shows a fundamental difference in fighting a small fire compared to fighting a large one. It also shows that the relationship between applied water flow rate and fire area is not best described by a continuous power function. It distinguishes between three different approaches or modes of firefighting: a standard nozzle approach (fires up to 20–50 m^2, depending on context), a perimeter approach (fires up to 200–500 m^2, depending on context) and a maximum flow approach (fires larger than 200–500 m^2, depending on context). The transition between the approaches varies between the five data sets and can be distinguished using the optimum flow density (5.4–6.0 l/m^2 min) or the water flow density giving the smallest total volume and the critical water flow density (3.5–4.0 l/m^2 min). The two transitions vary with the context; they are not physical constants (the numbers corresponds to the most recent studies of Metro and County FRS). The study validates the strategic considerations that attack is more demanding than containment, that one should ensure containment and then attack; and that the earlier response, the better result.

Keywords: Fire and Rescue Service, Fire suppression, Firefighting flow rate, Firefighting strategy, Water flow rate

1. Introduction

There is empirical knowledge saying that for the FRS attending to fires, exposure control has higher priority than to suppress the fire. At least as long as the fire has a potential to spread, e.g. in many wooden buildings. In most brick and concrete buildings, passive fire prevention measures solve the containment issue. Fredholm [1] formulates four basic rules or strategic considerations of priority: The first is that saving life goes before saving property. Secondly, that attack is more

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demanding than containment. The third is to contain first, then attack. Fourth is that the earlier response, the better result. These considerations are empirical with their roots in ancient warfare, e.g. von Clausewitz discusses the relation between attack and defence [2]. They are also normative, i.e. implying what the FRS is supposed to do but there are no studies discussing practical application of the considerations. The first one concerns the relation between life and property and is not the topic of this paper. It will not be further mentioned although life might be saved by putting out fires. The other three will be addressed further.

For design purposes, i.e. in the normative situation, there are several methods available [3, 4]. A power function normally describes the relation between the water flow rate (q) and the fire area (A): $q = kA^n$. The exponent (n) is usually in the range 0.5–1.0. The Insurance Services Office use the method, and add a minimum and maximum level [5]. In sprinkler design, there is also a minimum level, when a single head is operating, and a maximum area [6]. In contrast, this paper gives a descriptive study of the water flow rates actually applied by the FRS.

In firefighting operations, it may be easiest to employ the same intervention method at a big fire as at a small one. Traditionally, the concept of 'small fire—small water; and big fire—big water' is regularly promoted in fire tactics literature [7]. Fire experiments and fire tests referred to in studies of fire attack are usually in small scale, where firefighters are able to employ water in an efficient way. This is also the case for firefighting training. However, no known studies shows the limits within which small-scale fire suppression tests can be extrapolated into a larger context. Therefore, suppression methods and equipment validated for one scale of fire may fail to perform well in a different scale.

In 1999, Särdqvist [4] presented a descriptive comparison of the FRS water flow rate from three different studies of fires, ranging from small fire areas to very large. In the comparison, he showed that a continuous power function does not give a good representation of the relation between the applied water flow rate and the fire area. Rather, he suggested that fires of different size have different correlation between applied water flow and fire area due to the applied methods of the FRS. The hypothesis was not possible to validate at that time due to lack of data. This has changed with the recent study by Grimwood and Sanderson [8] consisting of 4173 fires from a metropolitan area FRS and 1146 fires from a county FRS.

2. Method

Four studies consisting of five data sets were examined, according to Table 1. All studies were based on information gained by the FRS at the fire scene. The Grimwood and Sanderson [8] Metro FRS data set is the largest of the available ones. Therefore, we used this to identify patterns in the relation between applied water flow rate and fire area. The remaining four data sets were for validation and comparison.

Table 1
Four FRS Studies with Five Sets of Water Flow Data were Included in the Study

Study	Year of publication	Number of fires	Type of fires
Grimwood and Sanderson [8]	2015	4173 + 1146	UK, Metro FRS + UK, County FRS
Särdqvist [9, 10]	1998	307	UK, Greater London Non-residential
Baldwin [11]	1972	134	USA, Illinois, > 20 m^2
Thomas [12]	1959	48	UK, > 5 jets, > 200 m^2

We studied two variables: the fire area and the maximum water flow rate applied by the FRS. A bigger picture might have included the building conditions and the development of smoke, air, heat and flames, together with a more comprehensive description of how and where the water was applied together with ventilation procedures. Data on this is not available.

We defined fire area here as the post fire horizontal foot print of the fire, i.e. the total area damaged by fire as reported by the officer in command or the fire investigator after the fire. The area measure does not take into account the variation in energy load per area unit (MJ/m^2) or the variation in heat release per area unit (kW/m^2) as measured in test situations by oxygen consumption calorimetry or by measuring the fuel mass loss. Both require measurement equipment to be in place before the fire. This is possible at fire tests but not at real fires. At a real post fire investigation, you have either to reconstruct the fire development or to measure the remains. Reconstructing fires is time consuming and coupled with great uncertainties. Therefore, the common way to measure real fires and the data available for studies is the geometric measure of the remains.

We used the area data from the Särdqvist [9, 10], Baldwin [11] and Thomas [12] studies as actually reported, converted to SI units when necessary. Grimwood and Sanderson [8] used an interval scale: 1–5 m^2, 6–10 m^2, 11–20 m^2 and so on up to 20,000 m^2, as shown in Fig. 1. There are many more small fires than large fires. The two largest area intervals were put together due to a small number of fires. In the following, a representative area of each fire in this study was determined. As the fire area was log normally distributed rather than uniformly, we calculated a representative area as the average of the log values of the interval boundaries.

The calculation process was identical for the County FRS data set as for the Metro FRS. In the Thomas, Baldwin and Särdqvist data sets, the fires were clustered depending on the fire area with an equal number of fires in each cluster. For each cluster, a median fire area and a median water flow rate was determined.

The flow rate as described here is an estimation of the maximum flow rate applied at any time during the fire suppression, where the majority of the data was derived from the maximum number of simultaneously applied nozzles, as reported by the officer in command or the fire investigator after the operation. At around 10% of the metro fires, flow data was recorded by computer programmes

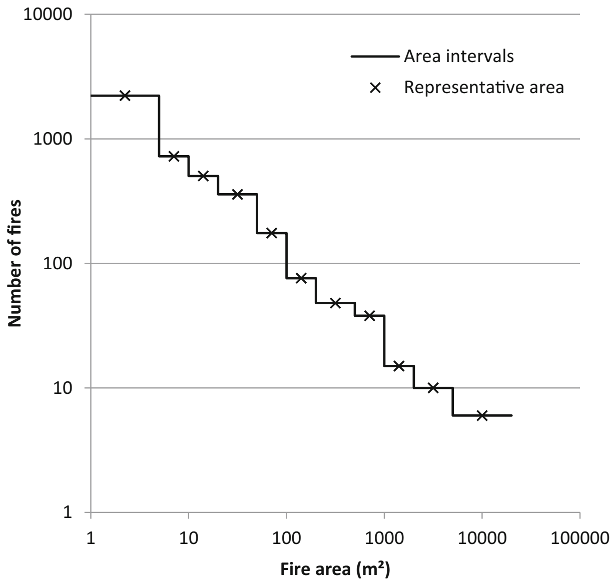

Figure 1. Area distribution of the 4173 fires in the Metro FRS study [8].

linked wirelessly to the fire engines flowing water onto the fires. The reports include information on the maximum number of e.g. nozzles connected to high-pressure hose reels, jets or monitors, together with an estimation of the maximum flow rate when fully open. Differences in flow rate depending on e.g. differences in pump pressure, or pressure losses due to different hose length or type were not taken into account. These differences may have caused great variations in the estimated flow rates, but it may be compensated by the fact that all studies were performed within their context: nozzles connected to high-pressure hose reels within the same organization at the same time are in general comparable. The systematic error may be greater between the studies. Therefore, the actual water flow numbers have uncertainties, but the general trends are more valid.

Because of the skewness in the data, we choose to study the median value of the maximum applied water flow rates. An average value would have been better with normally distributed data, but they were closer to log normally distributed.

It may seem risky to compare studies of such difference in age. A UL study [13] showed a great difference in fire performance in modern fires compared to legacy fires. In addition, Grimwood and Sanderson [8] concluded that the 1800 l of water carried by a fire engine was sufficient in 86% of all fires attended in 1960–1961 but only in 64% of 'working' fires in 2009–2012. From that perspective, the Thomas [12] and Baldwin [11] studies are quite similar: both conducted before the use of modern protective equipment including a breathing apparatus on a regular basis in the FRS. The Särdqvist [9, 10] and the Grimwood and Sanderson [8] studies are also quite similar, since the UK FRS is using essentially the same type of equipment during both periods. In spite of this, nothing suggests a fundamental difference in the kind of relation between the fire area and applied water flow rate. The transition points may differ with a similar overall layout.

2.1. Results from the Metro Data

In Fig. 2, one can see a maximum level at which all or most resources are employed. For the Metro FRS the level was a few thousand litres per minute, occasionally higher at the largest fires. The maximum water flow rate was sometimes applied at individual small fires but most commonly at the larger ones.

We identified a standard tool, used at a large number of fires. For the Metro FRS it was the 100 l/min high-pressure hose reel. If this was not sufficient, a doubling of the flow by use of a second nozzle was common. This tool was used in 50% of the fires smaller than 50 m^2 and occasionally up to 500 m^2. It is impossible to see in Fig. 2, but the smallest area interval contains 2220 data points.

If you study the relation between applied water flow rate (q) and fire area (A) separately in different area intervals, you can retrieve more information than if you determine a single correlation over the whole area range, see Fig. 2.

The correlation $q = kA^n$, where n is the correlation power can represent each segment of the median curve, calculated using regression analysis. Figure 3 shows the correlation power as a function of the fire area. A correlation power of 1 means a direct proportionality; if the fire area is doubled, the water flow rate is also doubled. A correlation power of 0.5 means that the water flow rate is propor-

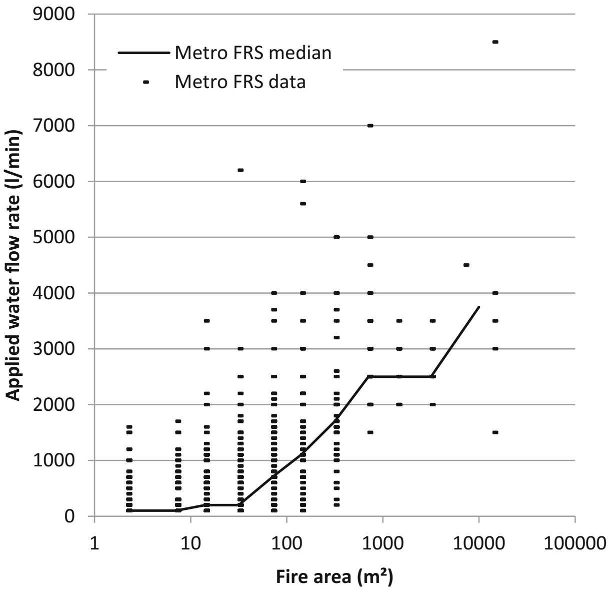

Figure 2. Metro FRS data of the relation between applied water flow rate and fire area together with median values. Note that a large number of data points overlap.

tional to the square root of the area or the perimeter of most fires. A correlation power of 0 means that the applied water flow rate is not correlated to the area of the fire.

In Fig. 3 three different area intervals can be distinguished, corresponding to three different firefighting approaches.

At small fires, with an area up to 50 m^2 in the Metro FRS case, a standard nozzle approach can be identified. Two different standard attacks were used, marked as 1a and 1b. First, a single 100 l/min high-pressure nozzle up to 10 m^2, then a combination of two nozzles up to 50 m^2. The correlation power goes from low to high, down again and then up to high, even above 1. A correlation power above 1 is not a mathematical problem, it just means that the FRS increase the water flow rate more than the fire area grows.

The correlation power decreases to around 0.5 for the second area interval marked as 2 in the figure, at fire areas 50–500 m^2 in the Metro FRS case. The water flow rate is roughly proportional to the square root of the fire area, as $q = kA^{0.5}$. The square root of an area is directly proportional to the area perimeter and we can therefore describe this approach as a perimeter approach.

At the third area interval, at fire areas 500 m^2 and above in the Metro FRS case, the correlation power decreases further and the correlation becomes significantly weak. Here, a high flow is applied, regardless how large the fire is. This

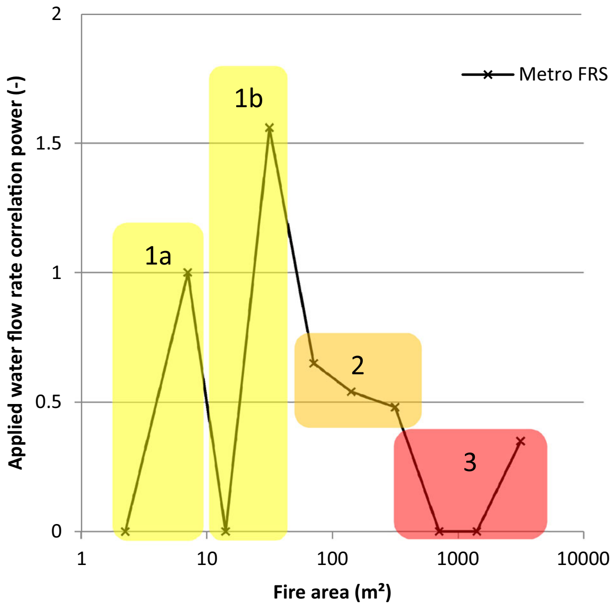

Figure 3. Correlation power, derived from the median water flow rate for the Metro FRS, depending on the fire area, with three identified different intervals. The figure identify a (1) standard nozzle approach, (2) perimeter approach and (3) maximum flow approach.

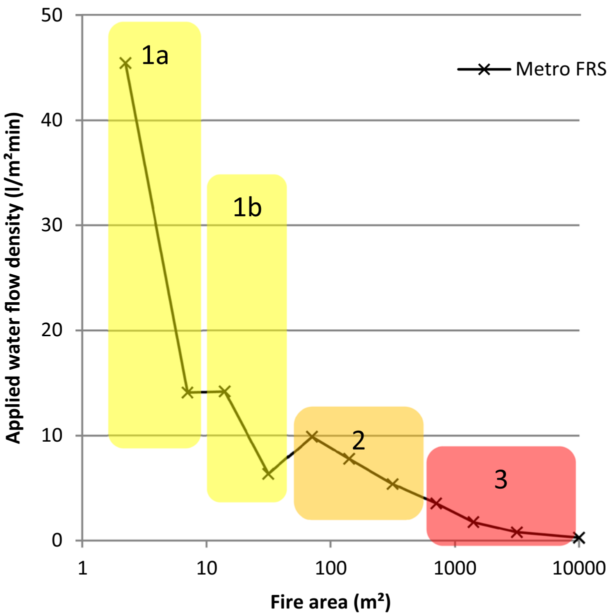

Figure 4. Metro FRS applied water flow density, depending on the fire area.

may be identified as a maximum flow approach. The maximum water flow potential is applied regardless the size of the fire. The precision in data decreases with area since there is a small number of fires in the third interval.

Figure 4 shows the median water flow rate divided by the fire area, giving the applied water flow density. At the transition from a standard nozzle approach to a perimeter approach, at the area of 50 m^2 in the Metro FRS case, the applied water flow density was 6.3 l/m^2 min. Särdqvist [14] described this as the optimum flow rate because it results in the smallest total amount of water applied per unit fire area (l/m^2).

Similarly, the transition from a perimeter approach to a maximum flow approach can be distinguished by the critical water flow density, e.g. as studied by Rasbach [15]. For the Metro FRS it was identified at 500 m^2, with an applied water flow density of 5.4 l/m^2 min. More than two nozzles applied this flow.

This is a descriptive study: we use empirical data to retrieve the water flow density giving the smallest total volume and the critical water flow density. This is in contrast e.g. to Grimwood and Sanderson [16] who used the terms critical flow-rates and optimum (adequate) flow-rates in a normative way, to specify the water flow rate boundaries, below which firefighters are faced with extended extinguishing times and increasing amounts of heat exposure, requiring more on-scene staffing and resulting in greater amounts of building damage.

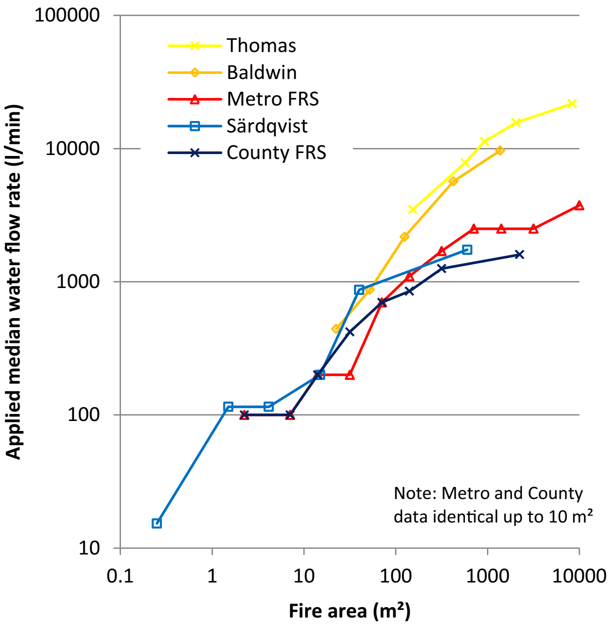

Figure 5. Applied median water flow rates in relation to the fire area for the five different data sets.

2.2. Validation by Comparing Metro Data with Data from Other Studies

Since four additional sets of data were available, according to Table 1, similar calculations was made from them. Figure 5 shows the relation between applied water flow rate and fire area. At fires larger than around 100 m^2, water flow rates applied at recent fires (1990–) were lower than at older ones (–1970) where firefighters in the earlier period used up to 5–6 times higher water flow rates. This decrease in flow rate coincide with changes in the FRS, e.g. a change from solid streams or jets to spray nozzles, and the development of protective equipment including breathing apparatus enabling firefighters to approach the fire.

The correlation power for each pair of data points were calculated in the same way as for the Metro FRS data, as shown in Fig. 6. Figure 7 displays the water flow density in a similar way. All four data sets showed the same pattern, with different modes of firefighting, as for the previously shown Metro FRS data.

The fire area for the transition from one approach to another varied between the five data sets as seen in Fig. 6 and Table 2. The area at this transition varied between the data sets. It may depend on e.g. organization, type of equipment and resources or on systematic differences in the fires facing the FRS in different studies. Unfortunately, the data sets do not contain comparable information on these topics.

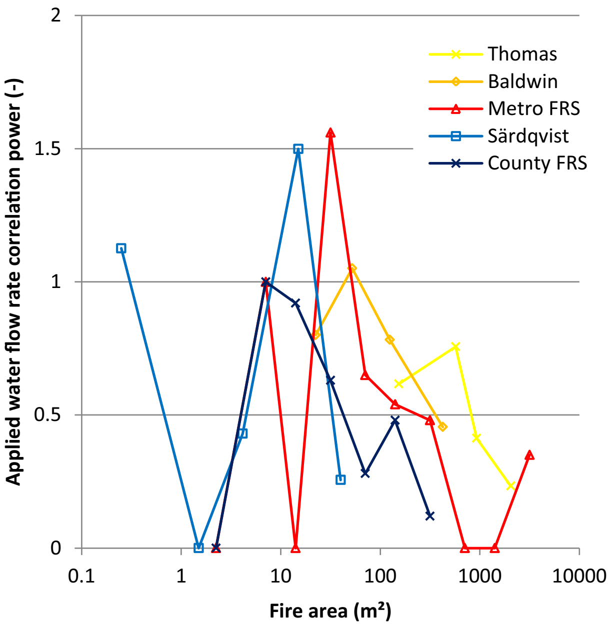

Figure 6. Correlation power depending on the fire area for the five different data sets.

Table 2
Area Estimations for Transition Between Different Approaches for the Five Data Sets, Together with the Fraction of Fires that Falls into the Different Approaches

Study	Fraction of fires with a standard nozzle approach	Upper limit for the standard nozzle approach (m^2)	Fraction of fires with a perimeter approach	Upper limit for the perimeter approach (m^2)	Fraction of fires with a maximum flow approach
Thomas	–	NA	–	750	–
Baldwin	–	50–100	–	500	–
Särdqvist	–	30	–	NA	–
Metro	0.91	50	0.072	500	0.015
County	0.82	20	0.16	200	0.023

2.3. Extinguishing Duration and Total Water Volume

Grimwood and Sanderson [8] compared the water flow rates used by firefighters from two different fire response areas (County FRS and Metro FRS), on fires occurring in three main groups of occupancies (dwellings, non-dwellings and industrial). They showed how the applied water flow rates increase in accordance

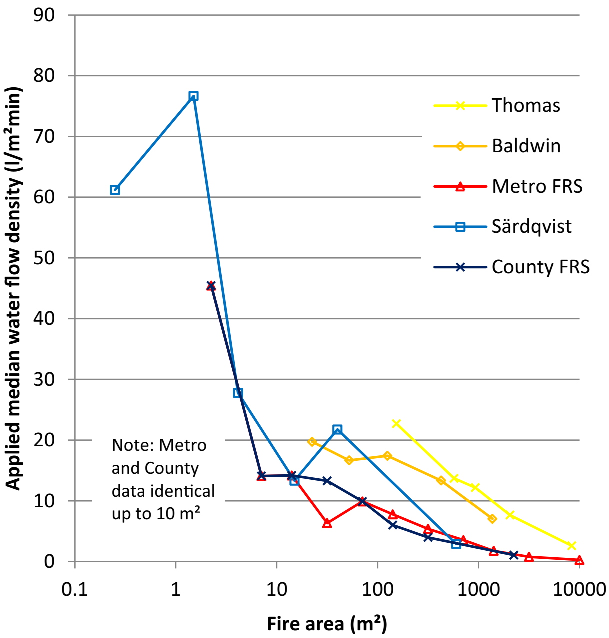

Figure 7. Applied water flow density depending on the fire area for the five different data sets.

with higher fire load and larger compartment size. They also suggested a link between the quantity of water applied within the first few minutes of arrival on-scene and subsequent building fire damage. Higher water flows applied during the early stages of dwelling fires resulted in notably less fire area.

This is in accordance with the Särdqvist [9, 10] study, with data on the extinguishing duration. Figure 8 shows the correlation between the extinguishing duration and the applied water flow density. The study included 307 fires, whereof 238 had a complete data set. As noted in the previous section, a standard nozzle approach gives a poor correlation between flow rate and area. Figures 8 and 9 shows therefore only the 71 fires with flows larger than this.

The applied water flow density varied, but the extinguishing duration was usually less than 30 min. In the other cases, an applied water flow density below 8.8 l/m^2 min resulted in a long extinguishing duration, in particular for fires larger than 150 m^2.

Figure 9 shows the total applied water volume per unit fire area as a function of the applied water flow density from the Särdqvist study [9, 10]. The fishhook shape indicates two categories of fires that resulted in a large water volume per unit fire area. The first category is the large fires, in this study larger than 150 m^2. These had a subcritical water flow density and subsequent long duration giving a large total volume. They fit into the description of a maximum flow approach, even though they are hidden by the statistical method in Fig. 6. The subcritical flow density may even be the very reason for these fires to grow big.

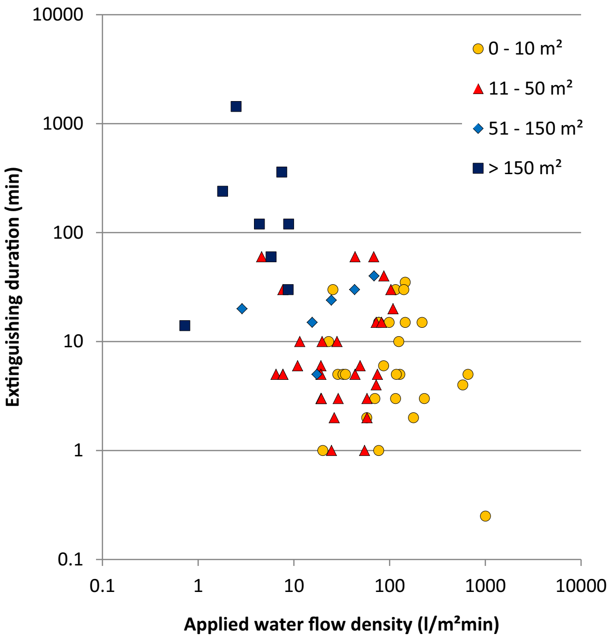

Figure 8. Extinguishing duration correlated to the applied water flow density in the Särdqvist data [9, 10].

The second category is the small fires with a high water flow density, resulting in a short extinguishing duration. They may fit into the description of the perimeter approach. The volume per unit fire area may be large, but the fire area was limited due to a quick suppression which resulted in a limited total applied water volume.

3. Discussion

In the previous section, we showed that the relation between firefighting water flow rate and fire area is not best described by a single correlation. Here, we interpret this and translate it into practical firefighting.

3.1. The Standard Nozzle Approach

A standard nozzle approach does in fact not relate to any standard. The wording rather describes a method of selecting a nozzle with the result that the FRS choose the same nozzle at most of the fires. At the Metro and County studies, nozzles connected to a high-pressure hose reel were the standard choice, but this may vary from organisation to organisation.

For the smallest fires, the correlation power increases. Thus, the correlation between applied water flow rate and fire area gets stronger with increasing area. A standard nozzle equipped on the fire engine normally provides a generous water

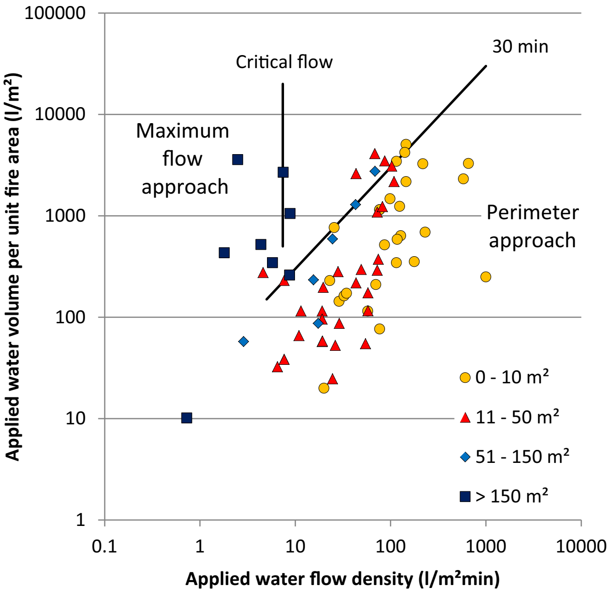

Figure 9. Total applied water volume per unit fire area in relation to the applied water flow density in the Särdqvist data [9, 10].

flow rate for small fires, regardless the fire area. Here, you have a large margin of safety for a growing fire. The smaller the fire, the shorter time you have to have the nozzle open. Facing bigger fires, the over-power of the water gradually decreases and at the upper end of this area interval, the water flow rate is directly proportional to the fire area. This indicates a nozzle used at its full capacity.

The Metro FRS uses two standard nozzles. The first peak in Fig. 6 comes at 5–10 m^2 fires with the corresponding applied flow of 100 l/min from a single high-pressure nozzle. A second peak comes at 20–50 m^2 with the water flow rate 200 l/min. This usually means two high-pressure nozzles at work. The water flow density is above 6.3 l/m^2 min at this area.

The County FRS uses a standard nozzle approach at around 5–20 m^2 with a corresponding flow of 100 l/min and a water flow density of 14 l/m^2 min, i.e. the same approach as for the Metro FRS but with smaller means to get additional resources. An observation is that the Metro FRS handle 91% of their fires using this approach, but the County FRS only 82% of their fires, see Table 2.

The Särdqvist data also contain fires suppressed by the FRS using fire extinguishers. These give the first peak at small fires, 0.25 m^2 with a corresponding water flow rate from a fire extinguisher. A second peak is seen at 15 m^2 with a 200 l/min flow rate and a 13 l/m^2 min density. This is the same peak as observed in the Metro data.

In the Baldwin data, the peak appears in the interval 50–100 m^2 with the flow rate of 870 l/min. This is a notably large area and a high flow standard nozzle approach.

The Thomas data explicitly include fires with five or more jets (streams). Therefore, the standard nozzle approach is not applicable for this data set.

3.2. The Perimeter Approach

From the point with a very strong correlation between applied water flow rate and fire area, the correlation in Fig. 6 decreases with increasing fire area. At a certain point, the water flow rate is proportional to the square root of the fire area: $q = kA^{0.5}$. This means an applied water flow rate directly proportional to the perimeter of the fire: Firefighters surrounding the fire with one nozzle each at suitable access points. The number of access or attack points to the fire is a restricting factor in any building fire, but in particular in fires in e.g. high-rise buildings or tunnels.

The Metro FRS use a perimeter approach at 50–500 m^2 with an applied flow of 700–1700 l/min. This is 5.4 l/m^2 min at the upper limit.

The County FRS use the approach at 20–200 m^2 with the applied flow of 400–850 l/min or 6.0 l/m^2 min at the upper limit. This means that the perimeter approach appears at smaller areas and involves lower flows at the County FRS than at the Metro FRS. The water flow density differs only 10%, which is less than significant.

In the Särdqvist data, the data points are few in this region, but the perimeter approach can be identified at 40 m^2, with a flow of 870 l/min.

The Baldwin data are few, but the approach can be identified at two fires with the area of 125 and 425 m^2. For these two fires, the water flow rates are 2200 and 5700 l/min respectively. The highest of these gives a water flow density of 13 l/m^2 min.

The number of fires in the Thomas data are small, but the approach can be observed for two fires with the area of 150 and 570 m^2, with corresponding flow rates of 3500 and 7800 l/min, giving a water flow density of 14 l/m^2 min for the bigger one.

There are explanations to why the firefighting efficiency is decreasing with increasing fire area. The throw of the nozzle is one parameter. Most fires in this interval are so small that you can reach the centre of the fire from the perimeter, the square root of the area is much smaller than the throw of most nozzles. However, there may be access difficulties and obstacles that prevent the water from reaching the fire. One stack of pallets is sufficient to protect fire from the water from a spray nozzle with 30° cone angle and 375 l/min [17]. This is mostly from pure geometrical reasons: a large number of the droplet trajectories are blocked.

The optimum flow density was identified in the Metro and County data as 5.4–6.0 l/m^2 min. Notably, both water flow rates and water flow densities are higher in the Baldwin and Thomas studies: The water flow density 13–14 l/m^2 min in the old studies is twice as high as in the recent ones. The critical water flow rate is not purely a physical parameter; it varies with the context. Still, the difference is large enough to state that modern firefighters use the water flow more effectively than in the earlier periods, although this work does not answer the question of which of the previously mentioned changes in the FRS system that is the cause of the change.

3.3. The Maximum Flow Approach

At the upper part of Fig. 5, we find a median water flow rate that is relatively constant or that is only slightly increasing with increasing fire area. This water flow rate represents the maximum deployment of resources of the FRS, available at the time. The fires where a maximum flow approach is applied are few but commonly large.

Metro data for the 1.5% of fires that are larger than 500 m^2 give water flow rates from 2500 to 3800 l/min, according to Table 2 and Fig. 5. The lowest of these flow rates, 2500 l/min, gives the limiting value and correspond to a water flow density of 3.5 l/m^2 min, Fig. 7. Note that although speaking about maximum flow rates, it is the maximum of the median flows. Half of the individual fires have a higher flow rate, and half of them have a lower, according to Fig. 2.

Similar analysis regarding the County FRS shows that 2.3% of the fires are larger than 200 m^2, where the County FRS applies from 1200 l/min (4.0 l/m^2 min) to 1600 l/min. The fire area where the critical water flow density is applied is smaller for the County FRS than for the Metro FRS. However, the water flow density is only 14% higher, a non-significant difference.

The Särdqvist study contains few large fires. The only data point is 600 m^2 with 1700 l/min applied, speaking in the same direction as the other data. In the Baldwin study the maximum flow approach concerns fires larger than 1400 m^2 with water flow rates greater than 9700 l/min (7.0 l/m^2 min). The Thomas study covers fires larger than 900 m^2 with water flow rates above 11,000 l/min (12 l/m^2 min). Since there is a small number of large fires, there is some uncertainty but all three studies point in the same direction.

At this maximum flow approach, there is a very poor correlation between the fire area and the applied water flow rate. The water flow density is low in spite of using high flow rates. Most likely, these fires are not extinguished, but rather contained until they run out of fuel. The area vary between the data sets but is in all cases, the area is smaller than the maximum compartment area normally accepted. English authorities normally accept 2000 m^2 for many non-sprinklered commercial multi-storey buildings [18].

The critical flow density is 3.5 and 4.0 l/m^2 min in the Metro and County data. This is lower than the earlier described conservative 7.2–8.4 l/m^2 min [14], but higher than the critical flow density around 2 l/m^2 min from Grimwood's previous work [19], below which the fire could not be extinguished without first having entered the decay stage. Corresponding values from the Baldwin and Thomas studies are higher, 7.0 and 12 l/m^2 min.

3.4. Tactical Considerations

This paper describes how the FRS bring what they have at small fires, thus being over-powerful. It also describes how the FRS bring what they have at the huge fires even if the demand from the fire is greater. This poses a problem if you design water flow rates in a normative way from studies of real operations: At small fires, the water flow demand will be over-predicted and at large fires, it will be under-predicted.

The data presented here validates three out of four of the previously mentioned considerations of priority, given that the demand is measured using the applied water flow density (l/m^2 min): [1] Small fires are usually suppressed by an offensive direct attack using a standard nozzle approach with a high water flow density. Large fires are suppressed using much lower water flow density. Here, the suppression time is long implying it is either about a defensive attack concerning exposure control or an offensive attack where the water cannot reach its target e.g. due to physical obstacles. This is the explanation of rule number two, *attack is more demanding than containment*: Even if the water flow rate is lower, the water flow density is higher at the offensive attack using a standard nozzle approach and thus more demanding than at the maximum flow approach using a defensive attack.

Rule number three, *contain first and then attack*, is derived from rule number two: One has to ensure that the resources are sufficient and thus start with the less demanding task, to contain first, and then attack. A standard nozzle can suppress most fires, and there is little need to reflect on this in most cases where you suppress the fire in the initial attack. In addition, fire prevention measures may already have contained the fire. In the remaining fraction of fires, containment may pose less demand for resources.

The fourth and last rule, *the earlier response the better result*, is obvious. Fires are usually growing with time, sometimes according to the simplified t^2 design fire, and the applied water flow rate increases with the fire area. A small fire can be suppressed more effectively than a big fire. Also, as fires are growing and spreading, the earlier the fire is suppressed, the smaller the area of fire damage. Thereby, the earlier response, the better result.

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