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Designing Buildings and Building Environments for Greater Resilience against the Encroachment of Seasonal Forest Fires

Projektowanie budynków i ich otoczenia ukierunkowane na zwiększenie ich odporności na oddziaływanie sezonowych pożarów lasów

ABSTRACT

Purpose: The threat of forest fires in residential communities close to the urban-wildland interface is a big concern in the face of limited manpower for firefighting operations. The paper seeks to answer the question of, 'how to design buildings to withstand the threats from seasonal forest fires. To encourage further research on automatic fire detection and suppression, the following questions are asked:
1. Can we develop a simulation system to manage water in reservoirs for fire suppression efforts while reducing the toll on firefighters in various communities?
2. What are the factors that we need to consider in establishing a minimum distance between the forest and residential communities?
3. How can we reduce fire hazards in various residential communities?
Project and methods: A site visit was carried out at local fire station to have a better understanding of the equipment used in firefighting operations. To examine the feasibility of having an adequate water supply for automatic sprinkler operations for firefighting purposes in exterior portions of buildings, simulation processes were used to evaluate how long the water in a reservoir will be available for firefighting.
Results: The results showed that water in reservoirs can be successfully managed for automatic fire suppression efforts. This indicates that automatic fire suppression systems would be a good complement to the human response to the encroachment of forest fires in residential communities. This would be helpful to reduce the toll on firefighters while reducing losses in various communities.
Conclusions: This study describes a conceptual framework on how buildings can be designed to better withstand the threats from seasonal forest fires. An adequate application of the water sprinkler technology for the exterior part of buildings is recommended. Simulation systems were used to evaluate how long water from various sources may be available for firefighting purposes. Rather than waiting for firefighters to come and help extinguish the fire in residential communities, the design of our buildings can be such that it would not only put a major focus on the automatic deployment of the water sprinkler effect for the interior sections of the buildings, but the improved designs for residential buildings should be such that automatic water sprinklers are available to cover all the exterior portions of buildings for a pre-determined length of time, to mitigate the effect of seasonal forest fires. Field testing and validation of the proposed process are recommended.
Keywords: forest fires; firefighting; building designs; automation; simulations
Type of article: original scientific article

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ABSTRAKT

Cel: Zagrożenie pożarami lasów w zabudowie mieszkaniowej znajdującej się na styku obszarów miejskich oraz leśnych stanowi poważny problem w obliczu ograniczonej liczby sił możliwych do zadysponowania do działań gaśniczych. W artykule podjęto próbę odpowiedzi na pytanie, jak projektować budynki, aby były odporne na zagrożenia wynikające z sezonowych pożarów lasów. W celu przeprowadzenia badań nad środkami automatycznego systemu detekcji i gaszenia pożaru postawiono następujące pytania:
1. Czy można opracować symulator do zarządzania wodą w zbiornikach zapasu wody gaśniczej, jednocześnie zmniejszając liczbę ofiar śmiertelnych wśród strażaków w akcjach prowadzonych w różnych zabudowach mieszkaniowych?
2. Jakie czynniki należy wziąć pod uwagę przy ustalaniu minimalnej odległości pomiędzy lasem a zabudową mieszkaniową?
3. Jak możemy zmniejszyć zagrożenie pożarowe dla zabudowy mieszkaniowej?

Projekt i metody: W lokalnej jednostce ochrony przeciwpożarowej przeprowadzono wizytację, która miała pozwolić na lepsze poznanie wyposażenia używanego w akcjach gaśniczych. Aby zweryfikować możliwość zapewnienia wystarczającego zaopatrzenia w wodę w automatycznych systemach tryskaczowych w zewnętrznych częściach budynków, zastosowano symulację pozwalającą ocenić, na jaki czas gaszenia wystarcza dostępna w zbiorniku woda gaśnicza.
Wyniki: Wyniki wykazały, że do celów automatycznego gaszenia pożaru wodą w zbiornikach można skutecznie zarządzać. Oznacza to, że automatyczne systemy gaśnicze byłyby dobrym uzupełnieniem akcji w odpowiedzi na wkraczanie pożarów lasów do obszarów z zabudową mieszkaniową. Byłoby to pomocne w zmniejszeniu liczby ofiar wśród strażaków, a także strat w różnych zespołach budynków mieszkalnych.
Wnioski: Niniejsze badanie opisuje ramy koncepcyjne tego, w jaki sposób można projektować budynki, aby lepiej przeciwstawiały się zagrożeniom związanym z sezonowymi pożarami lasów. Zaleca się zastosowanie technologii tryskaczowej na zewnątrz budynków. Do oceny czasu, w jakim woda z różnych źródeł pozostanie dostępna do celów gaśniczych, wykorzystano systemy symulacyjne. Zamiast czekać na przybycie strażaków i ugaszenie pożaru w zabudowie mieszkaniowej, już sam projekt budynków może pozwolić na automatyczne uruchomienie zraszania wodą. Automatyczne zraszacze powinny być dostępne nie tylko w wewnętrznych częściach budynków, ale również obejmować swoim zasięgiem wszystkie zewnętrzne partie budynków, przez z góry określony czas, tak aby złagodzić skutki sezonowych pożarów lasów. Zalecane są badania terenowe oraz walidacja proponowanego procesu.
Słowa kluczowe: pożary lasów; gaszenie pożarów; projekty budowlane; automatyzacja; symulacje
Typ artykułu: oryginalny artykuł naukowy

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Introduction

Forest fires have been a serious problem for humanity in various communities. Encroachment of forest fires in residential neighbourhoods has led to the loss of lives and destruction of properties in various places. Fire hazards can be caused by both natural factors and human negligence. Fire disasters result in serious tragedy for cities. Disasters from fire can negatively affect a nation as they affect national productivity and can cause a reduction in people's welfare. Fire occurrences often occur in high-activity-level regions [1]. According to the National Fire Protection Association (NFPA), in 2021, in the United States alone, 3,800 civilian deaths and 14,700 civilian injuries were caused by fires. The property damage that came with the fire is estimated at $15.9 billion. The local fire departments responded to about 1.35 million fires. $648 billion in direct property damage was caused by the major fire in the Colorado wildland/urban interface, WUI [2]. Aydin et al.[3], cited a previous work that stated that 4.5 million U.S. homes are identified as being at a high or extreme-high risk of wildfire.

Associated Press reported that in Greece, six days after Europe's deadliest forest fire in more than a century, fire officials raised the death toll from the wildfire that raged through a coastal area of Athens to 91, and 25 people were reported as missing [4]. In May 2016, the Horse River wildfire shifted towards the communities of Regional Municipalities of Wood Buffalo (RMWB) and resulted in the evacuation of almost 88,000 people. Sadly, 2 lives were lost in a motor vehicle accident on Highway 881. However, miraculously, no life was lost in the actual fire. The estimated damage to insured properties was $3.6 billion. Further impacts of the wildfire were also estimated to be about $8.9 billion. The Insurance Bureau of Canada noted that this wildfire was the costliest insured natural disaster in Canadian history [5]. Wildfires have become a fairly common scene in California. Shoot [6] noted that historically, fires in California cost billions in state and federal suppression costs with insurance claims.

Coogab et al.[7], also reported that the financial costs that are associated with health and safety evacuations and losses that result from wildfires are significant. Techniques to prevent the negative impacts of big wildfires continue to be an important research area in fire suppression, forest and land-use planning, and civil protection research [8]. Huge demand for the construction of new housing, commercial buildings and associated infrastructure is anticipated with the growth and urbanization of the global population over the next several decades [9]. This brings many communities close to urban-wildland interface areas. In addition to substantial losses to societies, economies and ecologies globally, forest fires have resulted in considerable losses in global forest resources, people's lives and property [10]. The high cost of wildfires has called for a need for improved research and efforts to evaluate innovative ways of reducing the potential impact of seasonal wildfires.

Present firefighting systems for communities and their impact on firefighters

Presently, the protocol in some places is that when a fire is detected in a community, the emergency services are called. Firefighters respond quickly to put out the fire. However, it can be overwhelming if the degree of fire is beyond the available human resources, materials and equipment to fight the fire. For example, when the massive, out-of-control Chuckegg Creek wildfire crept to within 3 kilometres of High-level Alberta, an evacuation order was issued. It was reported that the fire grew to 92,000 hectares. The exhausted firefighters and support staff received help both from the weather and from the inflow of new firefighters that came from other provinces [11]. Given the huge amount of dollars that are recorded as suppression costs in various places, it is wise to further evaluate how additional investment in automatic firefighting technologies (incorporation of firefighting automation systems into the design and construction of buildings) can help to reduce the loss of life and properties, as well as reduce the amount that may have been spent to suppress fire encroachment. It is known that water extinguishes fire (in a reasonable number of circumstances), and we have an abundance of water on earth (from the oceans, rivers, lakes, streams, rain, underground aquifers, etc.). Hence, we have enough water around us to help prevent the damaging effects of seasonal forest fires. Where the amount of water in the community can be of concern, water runoff during heavy rains can be collected and stored in evaporation-controlled reservoirs. Rather than waiting for firefighters to come and help extinguish the fire in residential communities, (if firefighters are going to use water to fight fires in exterior sections of buildings) our building designs can be such that they will not only automatically deploy water sprinkler effects for the interior sections of the buildings, but the improved building designs for residential construction should be such that automatic water sprinklers are available to cover all the exterior sections of residential buildings for a pre-determined length of time, to mitigate the effects of seasonal forest fires (especially in urban-wildland interface regions). At this time, water sprinklers are mostly used for fire protection for interior sections of buildings. Innovations in fire management and fire safety have seen the introduction of automatic fire detection and fire suppression systems for industrial operations. For example, Innovfoam [12] has developed 'plug and play roof monitors' (a fire extinguishing monitor) that are installed in a standard roof opening. During a fire event, the fire extinguishing system is activated to put out the hotspot of the fire. Innovfoam [13] also developed an extinguishing robot that can be operated remotely and can access hard-to-reach areas. While a water screen protects the robot from the heat, the robot can cast a blanket of foam in its path, allowing it to safely move forward. The robot can also work with hoses for extinguishing water that is supplied by a fire-extinguishing vehicle. These innovations can be adapted for use in new community designs and existing communities that are at risk of forest fire encroachments. Fleming [14] stated that although water is not a perfect extinguishing agent (it is mostly used in fire extinguishing work because of its wide availability), the structural elements of a building can be protected by the cooling abilities of water until the fire can be extinguished through other means. Like the efforts in traditional firefighting, it is hoped that when applied in the right quantity, water discharged through automatic water nozzles/sprinklers for exterior firefighting work will help make buildings more resilient to the damaging potential of seasonal forest fires, reducing the economic, social and environmental impact. Water to be stored in a reservoir for emergency firefighting may be obtained from harvesting rainwater, pump actions from underground aquifers, or other means as stated above. More research is recommended to ascertain whether water will be a perfect extinguishing agent for specific materials used for the exterior finishing of various buildings.

In the effort to answer the question, 'How can we design buildings and building environments to better withstand the threats from seasonal forest fires?' and also develop a sustainable automatic fire suppression plan to minimize property loss during encroachment of forest fires, this study presents:

– A discussion on the present firefighting systems for communities and their impacts on firefighters.
– A discussion aimed at evaluating the effectiveness of the present firefighting system on the achievement of sustainability goals.
– A discussion aimed at describing how to incorporate reliable autonomous fire suppression systems into the engineering design of infrastructures to better protect the occupants in episodes of normal forest fires until greater intervention is available.
– A discussion on why the use of materials with high fire ratings alone would not be sufficient to guard against the encroachment of seasonal forest fires.
– A discussion on basic infrastructures that are needed to better withstand the effects of seasonal forest fires.
– A description of a simulation approach to evaluate how long water in a reservoir can last during automatic fire suppression episodes (while using multiple water discharge outlets/sprinklers).
– Questions for further research on how to design buildings and building environments for greater resilience against the encroachment of seasonal forest fires.

These discussions aim to highlight the fact that the present approach to fire suppression during wildfire episodes brings a high toll on firefighters. Meanwhile, it still comes with heavy losses to society at large. However, the adoption of technological innovations (as described) can help reduce the heavy toll on firefighters while reducing the loss to society at large. The process description of the 'evaluation of how long water in a reservoir for fire suppression' can last is important to encourage further research and adequate planning on water management during fire episodes. If there is not enough water in a reservoir to consistently mitigate against the risk of the fire until the end of the fire episode, the infrastructure may eventually burn. Hence, adequate planning, management and supply of water for fire suppression at places where they are needed during fire episodes is important.

Can we achieve sustainability goals with the present firefighting systems for residential communities?

Cities are surrounded by forests, open areas, or agricultural land where fire incidence can occur, threatening human life and causing many resources to become extinct [15]. Sustainability, a term that evaluates whether the approach of doing things can be continued without adverse effects is important in resource management. The United Nations report of the World Commission on Environment and Development [16] stated that sustainable development seeks to meet the aspirations and needs of the present without compromising the ability to meet those of the future and that this is a goal that is not only for developing nations, but also for industrialized nations. When it comes to the impact of seasonal forest fires on residential communities in various places (especially when residential buildings are burnt and people have to explore new resources for reconstruction), there is a need to evaluate whether the present system is sustainable. (i.e., are we making a judicious use of resources if we keep the status quo?). Can we say that we have sustainable community designs if our communities and buildings are not designed to be resilient to the impact of natural disasters such as forest fires?

Purvis et al.[17], stated that the three-pillar (economic, social and environmental) conception of sustainability has become ubiquitous. The economic impact of seasonal forest fires on residential communities includes the cost to rebuild after the destruction of houses, loss of potential revenue for companies that are affected, cost of insurance to provide temporary accommodation and compensation for lost properties, and an increase in insurance premiums for people contributing to the house insurance pool in the community. The social impacts include interruption in people's daily living, the inconvenience that comes with sudden and mandatory evacuations, loss of personal belongings and loss of things that create some cherished memories. The environmental impact on residential communities includes the effects of the seasonal forest fires on the immediate environment in residential areas, and the impact on air quality for people in various other communities (including communities in distant places), etc. It cannot be said that we are sustainability conscious if we do not fully explore the means to avoid the unnecessary waste of resources (including waste of resources that come from the impact of forest fires on residential communities). If allowing seasonal forest fires to destroy residential communities cannot be seen as a sustainable way of living, it will be good to further explore opportunities to minimize the impacts of these events on people.

How can we design and incorporate a reliable autonomous system into the engineering design of infrastructures to ensure better protection for the occupants in episodes of normal forest fires until greater intervention (and rescue effort) is available?

One of the concerns with firefighting efforts is that in some instances, resources that are available locally for fire suppression activities are not enough. Gonzalez-Olabarria et al.[8], described management areas for fire suppression support (MASSs) as areas in the landscape that change fire behaviour, reducing the size of the wildfire and greatly improving the capacity/effectiveness of fire suppression. It is expected that a careful design, construction and utilization of automatic water sprinklers to cover entire exterior areas of buildings will also help reduce the toll on firefighters and improve the effectiveness/capacity of fire suppression activities. Design and construction of residential buildings to make buildings more resilient to the threats from seasonal forest fires may require some changes to building codes in various communities. The national strategy (Forest and range lands) [18] stated that changes in building codes are likely to be more effective in counties with increasing wildland-urban interface, places that can be regarded as high-hazards etc. Focus on home defensive actions is one of the management options that was specified in the national strategy.

In planning for a good irrigation system for the lawn of a building, a good designer will ensure that the sprinklers are positioned to adequately cover all the green areas of the properties that need to be watered. In improving building designs to ensure that automatic water sprinklers can cover the entire exterior parts of the building (similar to the sprinkler designs for in-door fire-fighting), it will be desirable to know the extent to which each exterior water sprinkler can adequately reach. A good design will ensure that the installation of the exterior water sprinklers adequately covers the entire building. Exterior water sprinklers to prevent the encroachment of seasonal forest fires to residential buildings should not only cover the building, it will be a good idea to ensure that the water sprinklers can also reach a good height and cover areas that are at a considerable distance from the residential buildings. Various creative design approaches can be used for this. While it will not be a bad idea for all buildings to have automatic exterior fire prevention and firefighting systems, if the cost of incorporating a new design on buildings will be a lot for some homeowners, it will be a wise idea to incorporate automatic fire fighting systems in important buildings in the communities (such as hospitals, schools, and other buildings that people access for essential services) and for buildings that are close to wildland-urban interface, to mitigate against encroachment of seasonal forest fires on residential communities. Note that the proposed automatic exterior firefighting systems for buildings do not mean that buildings should not be equipped with lightning spikes (to collect electrical charges from the lightning and safely dissipate them to the ground) in jurisdictions where lightning is rampant.

Why will the use of materials with high fire protection ratings in traditional construction not be enough to guard against the encroachment of seasonal forest fire?

Fire protection ratings of construction materials vary. The fact that a material has a high fire rating does not mean that the material will not fail at some point. Eventually, the materials used in traditional construction will fail if a certain temperature is maintained for a particular length of time. The 2018 International Fire Code defines fire protection ratings as "the period that an opening protective assembly will maintain the ability to confine a fire as determined by tests prescribed in Section 716 of the International Building Code". Fire protection ratings are stated in hours or minutes [19] (International Code Council). Because even buildings that have some of their components made up of materials with high fire protection ratings will eventually fail if the fire in the environment is maintained for a considerable length of time, there is a need to ensure that other systems exist that can retard the possibility of ignition of the building materials. To employ a holistic approach in the effort to mitigate the negative impact of seasonal forest fires in residential communities, it will be good to combine various wildfire management strategies including adequate vegetation and fuel management and fire-smart construction practices.

What basic infrastructure do we need to re-design our communities to better withstand the effects of seasonal forest fires?

Fleming [14] noted that a single gallon of water can absorb 2,586.5 KJ of heat as it moves from a room temperature of 21°C to steam at 100°C. For situations when water is a good fire extinguishing agent (when water alone is used during a firefighting operation) if the quantity of water discharged during the firefighting operations is not enough, the fire may not be extinguished. Materials, equipment and infrastructure that are needed for the installation of water sprinklers for building exteriors may include individual water reservoirs, water supply from community reserves or other sources (such as boreholes, ocean, river, lakes etc.), water pumps where needed, piping systems for automatic sprinklers (for exterior sections of buildings), and the sprinklers.

It is known that various localities have community water supply systems. In some places, boreholes (to get water from underground aquifers) are not uncommon. In the effort to re-design our communities to better withstand the threat from seasonal forest fires, basic questions that needs to be asked in various communities include:

On the community level:

- Do we want to make the water reserved to fight seasonal forest fires independent of the general water supply for the community or do we want to link the water reserve for seasonal forest fires with the community water supply?
- If we are to build new infrastructure for water storage to fight seasonal forest fires, what is the capacity of water tanks/reservoirs that we want to build?
- What technology do we have to put in place to activate the operation of the water reservoir for fire-fighting?

On the individual building level:

- What is the number of sprinklers that are needed to cover the entire house?
- What locations on the building do we need to install the water sprinklers?

On the community level, to ensure that people can still have a reasonable level of water supply for domestic use, it will be a good idea to have a separate reserve for emergency fire-fighting during seasonal forest fires. The capacity of water reservoirs to be built in every community will be dependent on the expected water discharge rate from the sprinklers and the time that the community want the automatic fire fighting system to last before the need for an external intervention. Determining how long the water in a reservoir will last before an external intervention is required can be done through simple mathematical calculations. In this study, simple simulation processes are used to illustrate this. The intensity of water sprinkling operations and testing to ensure the safe deployment of the system is a subject for more research. From small buildings to wide forest areas, surveillance system applications are growing drastically [20]. As regards the technology that is needed to activate the system, a technology that is similar to the technology used in the interior water sprinkling system may be used. Alternatively, a technology in which the water sprinkling system will be automatically deployed when the temperature reaches a certain limit (coupled with evidence from video surveillance) may be designed to ensure automatic deployment of the water sprinkling system. It is advisable that the system still has a manual component to ensure that people can physically operate the system in case there is a failure of the automatic water deployment system. Cui [20] discussed fire detection using a wireless sensor network (WSN) with similar functional properties. The sensors are used to sense gas, smoke, heat, and other atmospheric parameters that can cause fire accidents. Once an abnormal condition is detected the nearest or linked administrative device in the network is alerted. A method like this can be further developed to activate automated fire suppression and extinguishing systems for various municipalities on the urban-wildland interface.

If we will design automatic fire fighting systems to extinguish fires that are encroaching on a building from the exterior sections, it is essential that important questions such as the ones below be addressed.

- How many kilojoules of heat will be released from the combustion of different construction materials?
- For the construction materials in which water is a suitable fire extinguishing agent, how many gallons of water are required to extinguish the fire from varied quantities of materials?
- To create a condition that is not favourable for fire, how much water needs to be continually sprayed on a building for a specified period during the encroachment of a forest fire to prevent the building from being engulfed in fire?
- How often and at what rate do we need to refill the community reservoir that is designed to prevent fire disasters in Urban-Wildland Interface regions to prevent property loss due to forest fire encroachment on residential communities?

Some of the above questions are posed to encourage further studies on this topic.

Objectives, research questions and justification for the study

Fire suppression efforts are crucial during the encroachment of fire to a building. Oftentimes, the available resources are not sufficient to respond to the fire issue, resulting in fatalities and property loss. Sometimes, various communities receive help from firefighters from distant places, but the firefighting efforts can still be limited by the available resources for fire suppression. Hence, to mitigate the negative consequences of fire encroachment on life and property, it is important to review the global approach to fire management. With the knowledge of the fire triangle, bushfires and forest fires are not meant to be a threat to humanity at large. Rather, there is a need to improve research and development efforts to keep the fires away from residential communities. In this line, this study evaluates what can be done to encourage research and development in innovative fire management to reduce the negative impacts on residential communities in various parts of the globe. An innovative fire management system will involve the automatic identification of a fire and the conditions that favour the fire, and the automatic deployment of fire suppression mechanisms (not only for interior parts of buildings but also for the exterior parts). To encourage further research on automatic fire detection and suppression, the following questions are asked:

1. Can we develop a simulation system to manage water in reservoirs for fire suppression efforts while reducing the toll on firefighters in various communities?

2. What are the factors that we need to consider to establish a minimum distance between the forest and residential communities?
3. How can we reduce fire hazards in various residential communities?

Experimental design

Fire trucks and hoses with different nozzle discharge capabilities are often used for traditional fire suppression and fire extinguishing operations. In the course of this project, a fire station was visited to learn more about the operations. The firefighters use water for traditional firefighting. However, it is known that different types of fires may require a specialized approach rather than water only for fire extinguishing. Hence, each fire episode needs to be duly evaluated to establish an appropriate response from the firefighters. Water is the main extinguishing agent that is used by firefighters for common house fires. Different nozzles that can be operated with a fire truck include a 44 mm fog nozzle with a discharge capability of 550 litres per minute (LPM) (0.0092 m^3/s), a 65 mm fog nozzle with a discharge capacity of 950 LPM (0.0158 m^3/s), a quick attack monitor with varied discharge capability of 950 LPM (0.0158 m^3/s), 1400 LPM (0.0233 m^3/s), 1900 LPM (0.0317 m^3/s) etc., a Saber master deck gun with a flow rate of 4800 LPM (0.08 m^3/s), or a Smeal ladder waterway with a varied flow rate of 1900-5700/1900-7600 LPM (0.0317-0.095/0.0317-0.1267 m^3/s). Information on the different discharge capabilities of the different water discharge nozzles above was obtained during a visit to a fire station. Figure 1 shows an example of a fire truck and some accessories for fire suppression systems.

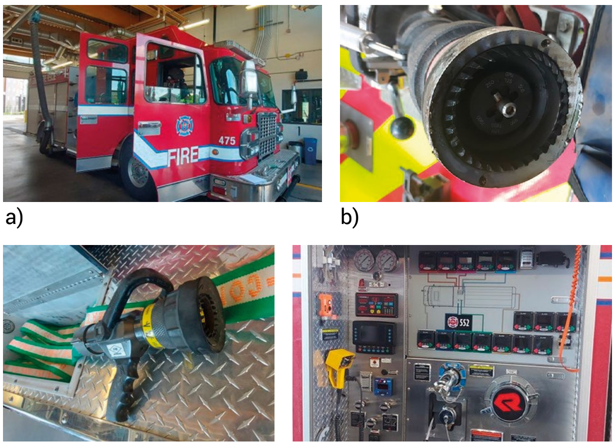


Figure 1. Traditional firefighting systems: a) traditional fire truck, b) water discharge nozzle (quick attack monitor), c) water hose with discharge nozzle (44 mm fog nozzle with 550 LPM discharge capacity), d) control point for the fire truck
Source: Author's own archive.

To examine the feasibility of having an adequate water supply for automatic water sprinkler operations for firefighting purposes in exterior sections of buildings, simulation processes were used to evaluate how long the water in a reservoir will be available for firefighting works. The simulations were done at an inflow of 100 gallons per minute (gpm) (0.0063 m^3/s) both for scenarios where there is no outflow and for scenarios when there is an outflow of water from the reservoir. The simulations were categorized into 2 major sections (depletion and filling of water in a reservoir when there is an inflow of water into the reservoir at a specified rate and when there is no external inflow). The outflow rate of water for firefighting works was varied. For water depletion when water outflow is greater than water inflow, the outflow rates for the 100,000-gallon (378.5 m^3) water reservoir were varied between 200 gpm (0.0126 m^3/s) to 400 gpm (0.0252 m^3/s) at an increment of 10 gpm (0.00063 m^3/s). To illustrate the situation when the reservoir will be filled up while the sprinklers are in operation, the evaluation was done at a constant inflow of 100 gpm (0.0063 m^3/s) and outflow rates between 0–90 gpm (0-0.00568m^3/s) at an increment of 5 gpm (0.000315 m3/s), and an increment of 2.5 gpm (0.000158 m^3/s) between 90–95 gpm (0.00568-0.00599 m^3/s). The times to fill a 100,000-gallon (378.5 m^3) reservoir using varied outflow and inflow rates were also compared. In addition to evaluating the feasibility of water management using Excel analysis, models were developed using Vensim system dynamics software. Field testing to determine the outflow rate of water from sprinklers for fire suppression and extinguishing is recommended for efficient planning of autonomous fire suppression systems. It is important that the water reservoir has an adequate water supply to maintain the right pressure that is required to achieve the desirable amount of discharge. The simulation technique that is presented here can be helpful in estimating the time that the water in the reservoir for firefighting works will reach a specified threshold and eventually reach a point of total depletion. The simulation model has the capacity to allow for an increased number of inflows and outflows with different rates. This could help with forecasting the time that various reservoirs may require an additional supply at varied water supply rates.

Thus far, many buildings are designed with indoor fire suppression systems (e.g. fire sprinklers). However, few buildings are designed with systems for external fire suppression systems. The devastating effects of fire encroachment on different communities and the loss of various precious and memorable belongings that people have accumulated over the years calls for further action and research on how we can better design our buildings to be able to withstand the threat of the encroachment of external fires.

Results and discussion

Some discharge nozzles for firefighting now come with automatic (programmable) head adjustments. In addition, the world now has autonomous firefighting equipment. All these can be very helpful in firefighting operations, as long as the equipment has an adequate supply of fire extinguishing material, which may be water or some other chemicals.

If we are going to reduce the toll on firefighters during forest fire encroachment on a city, it is important that we have an adequate plan for automatic fire detection and firefighting systems. In addition, it is important that we continue with more research on the amount of water (or other fire extinguishing agents) that will be enough to prevent as well as to extinguish fire on combustible structures. This will help in the design of external fire extinguishing systems that will be made available (on standby), and ready for use in areas that are susceptible to the encroachment of forest fires.

How long will the water in the reservoir last during automatic water sprinkler operation to fight seasonal forest fires?

AbouRizk et al.[21], gave an illustration of the law that governs the physical flow of fluids and developed a simulation software (Symphony) that can be used to simulate continuous flow. For continuity of flow in a tank having a cross-sectional area A_{c1} and a drawn-down velocity V_{d1} to another tank having a cross-section area A_{c2} and a drawn-down velocity V_{d2}:

$$A_{c1} * V_{d1} = A_{c2} * V_{d2} \tag{1}$$

Given a water reservoir with capacity V_{total} and Sprinklers with discharge rate R_1, R_2, R_3...R_n, at the end of the water sprinkling operation, (i.e. by the time the reservoir is empty,) the total volume of water used will be equal to the volume of water that is discharged through each sprinkler (i.e. $V_1+V_2+V_3+...V_n$).

The total volume of water discharged = Rate of discharge•Time of discharge

The time (t_{emp}) it will take to empty the reservoir can be illustrated as follows:

$$t_{emp} = \frac{V_{total}}{\sum_{i=1}^{n}(R_1 + R_2 + R_3 + ...R_n)} \tag{2}$$

For example, assuming the water reservoir/tank has a capacity of 100,000 gallons (378.5 m^3) of water, and the summation of the discharge rate for all the sprinklers is 200 gpm (0.0126 m^3/s), there will be no more water for automatic sprinkler operation after 500 minutes (30,000 s). Given that naturally, fire will not burn in pure water, and also wet wood (with a high moisture content) is not expected to be ignited except when it has dried considerably, it is expected that water sprinkling operations will be effective to prevent a building from being ignited by fire (under normal circumstances). The amount of water that is needed for fire prevention in this way is subject to further research. Note that in the presence of some material, even wet wood may be eventually ignited. For example, if a considerable amount of oil is present in wet wood, the wood may burn. The heat released from the burning oil may eventually create a condition that is suitable for the ignition of the wood. If in some situations, wet wood does not have oil in it, and this creates a condition that is not suitable for ignition, an introduction of materials like petrol or kerosene may create a condition for wet wood to be ignited. In situations such as that of a forest fire, it is not expected that anyone will introduce materials that can aid the fire. Hence, it is expected that the adequate application of water sprinklers that can cover the entire exterior sections of buildings will help prevent the spread of fire in residential communities. For neighbourhoods that have a central gas supply to various houses in the community, to minimize the possibility that the central gas supply will aid the spread of the fire, it is expected that such communities will have automatic gas shut-off systems that can be remotely turned off for all houses in the community during an emergency such as the encroachment of seasonal forest fires. Figure 2 shows a figurative illustration of water flow from reservoirs to discharge nozzles/sprinklers for automatic fire suppression.

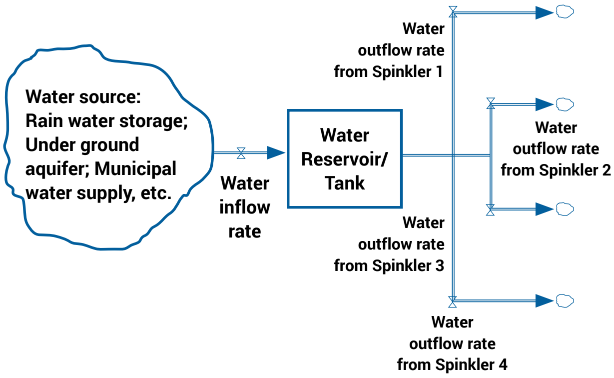
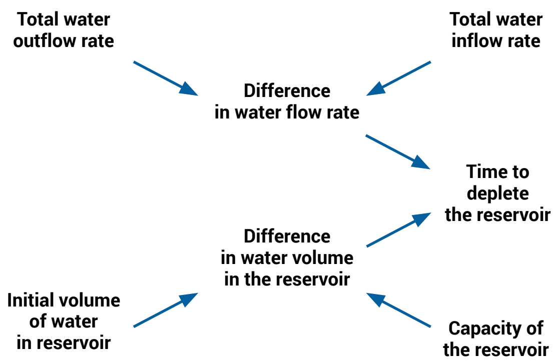
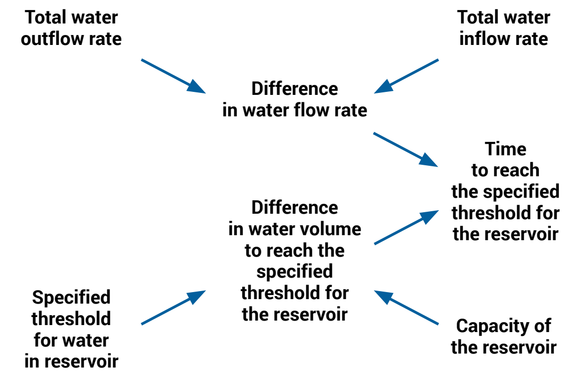


Figure 2. Figurative illustration of water flow paths for fire suppression
Source: Own elaboration.

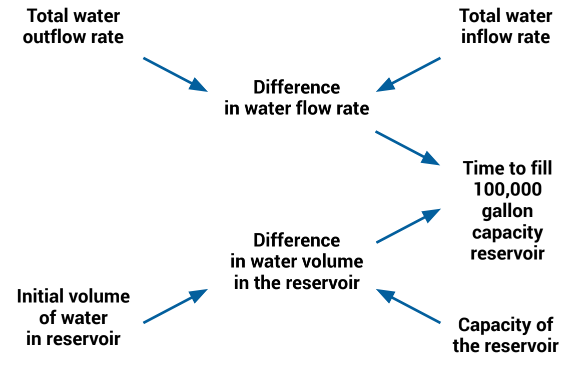
The water that is reserved for emergency seasonal firefighting can be replenished from an underground aquifer by a pump. This is expected to generate a more lasting water source for the firefighting work. However, if the rate of outflow (from the sprinklers) exceeds the rate of inflow from the underground aquifer, the water in the reservoir will be depleted at some point. Hence, for situations like this, it is important to know the expected time that the water reserve (including the inflow from the underground aquifer) for automatic firefighting purposes will not be sufficient to hold back the fire from destroying the property. It is also important to have a good knowledge of the water reserve in the underground aquifer to have a good estimate of the quantity of water that can be accessed at the desired rate during a fire episode at different times of the year. Other potential water sources for firefighting include rainwater storage, municipal water supply, etc.



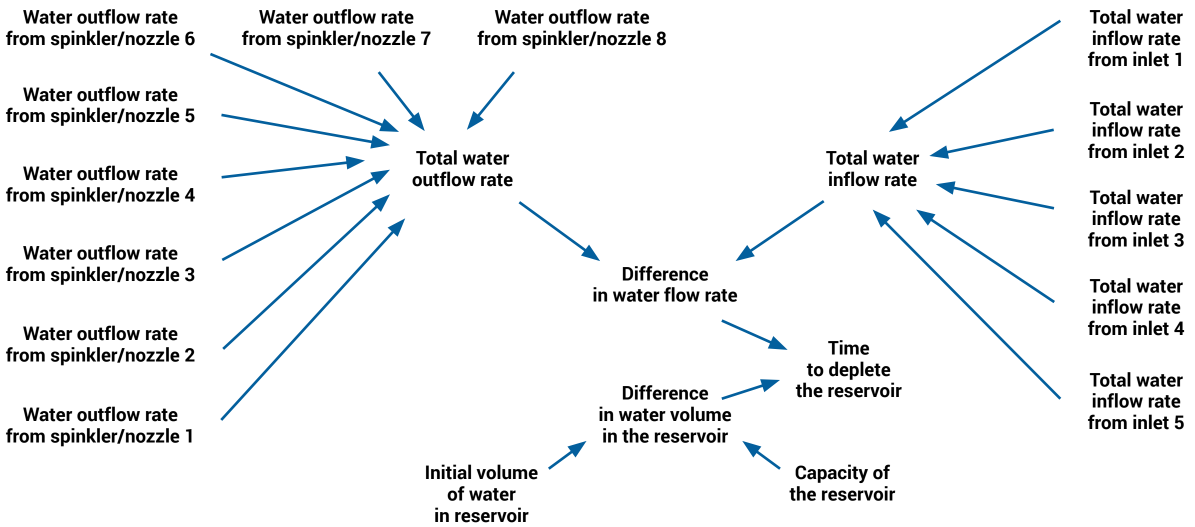
a) Simulation of time to deplete the reservoir



b) Simulation of time to reach a specified threshold



c) Simulation of time to fill a reservoir



d) Simulation of effect of multiple inflow and outflow rates on depletion of water in a reservoir

Figure 3. Figurative illustration of simulation interphase for planning of water management for fire suppression using Vensim software
Source: Own elaboration.

Figure 3 shows the simulation interphase for the time to fill, reach a specified threshold and deplete the water in a reservoir of specified capacity for the simulation.

The simulation results showed the expected trend. When the capacity of the reservoir increases, the time to fill the reservoir increases. As the capacity of the reservoir reduces, the time to fill the reservoir reduces. The models can also show how changes in various parameters will affect the time to deplete the water in the reservoir, facilitating a means to ensure adequate water management during automatic fire suppression processes. By careful design of the capacity of the reservoir and careful design of fire suppression systems, it is possible to design a building that has enough water supply to withstand the encroachment of traditional forest fires. Figure 4 shows an illustrative simulation interphase for water management during automatic fire suppression efforts.

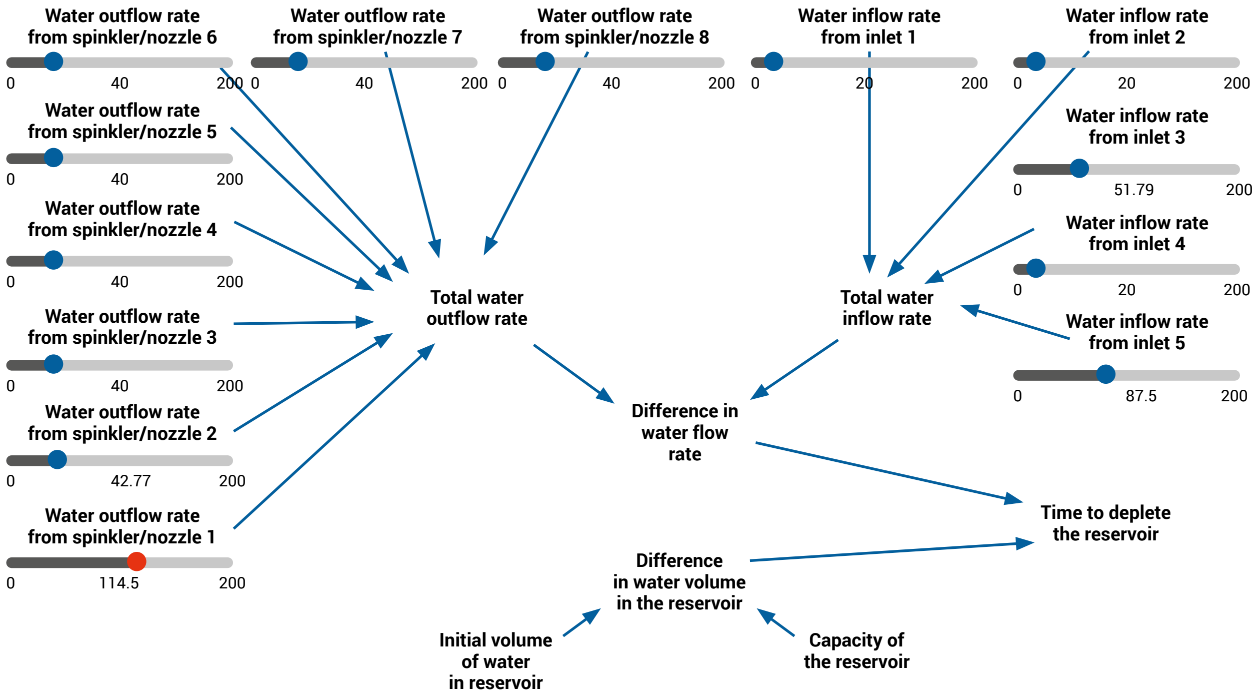


Figure 4. Illustrative simulation for water management for automatic fire suppression efforts
Source: Own elaboration.

$$t_{threshold} = \frac{V_{total} - V_{threshold}}{\sum_{i=1}^{n}(R_1 + R_2 + R_3 + \ldots R_n)} \tag{3}$$

$$t_{threshold\_w\_inf} = \frac{V_{total} - V_{threshold}}{[\sum_{i=1}^{n}(R_1 + R_2 + R_3 + \ldots R_n) - (\sum_{j=1}^{k}(R_{\text{inf}\ \_1} + R_{\text{inf}\ \_2} + R_{\text{inf}\ \_3} + \ldots R_{\text{inf}\ \_k}))]} \tag{4}$$

A simulation like the one presented in Figure 4 can automatically capture how the difference in water outflow from any sprinkler/nozzle will affect the time to deplete the reservoir. The simulation interphase for the management of water during automatic fire suppression efforts can also be designed to easily calculate the time it will take the water level in a reservoir to reach a specified threshold. This will give good information on prioritizing which reservoir may require additional replenishment efforts.

Where $t_{threshold}$ is the expected time to reach the specified threshold, V_{total} is the initial volume of water in the tank and $V_{threshold}$ is the expected volume of water at the specified threshold level, the time it will take to reach the threshold can be illustrated as in equation 3.

The equation for the time to reach the specified threshold and the time to empty the tank as indicated above are for scenarios in which the water level in the tank is at a fixed initial rate and is gradually depleted without the introduction of additional water. Knowledge of the time to reach a specified threshold will help with planning on managing the water reserves and replenishment efforts. Note that in the designs above, although the water sprinkled is not designed to return to the reservoir if desired in real life, it is possible to have a landscape design in which some of the excess water used during the water sprinkling operations may flow back to the reservoir and be re-used for the water sprinkling operations.

For situations in which the water reservoir accepts water from various sources during automatic water sprinkling operations for fire-fighting purposes, the time to reach a specified threshold in the reservoir may be calculated using equation 4. Note that for equations (2) to equation (5), it is assumed that there is no water loss from water leakage or any other means.

Where $t_{threshold\_w\_inf}$ represents the time to reach a specified limit/threshold in the reservoir while there are inflows from various sources that may include underground aquifers, water delivery from rivers, ocean, etc., through pipes. The expression $\sum_{j=1}^{k}(R_{\text{inf}\ \_1} + R_{\text{inf}\ \_2} + R_{\text{inf}\ \_3} + \ldots R_{\text{inf}\ \_k})$ is the summation of the rate of inflows from various sources.

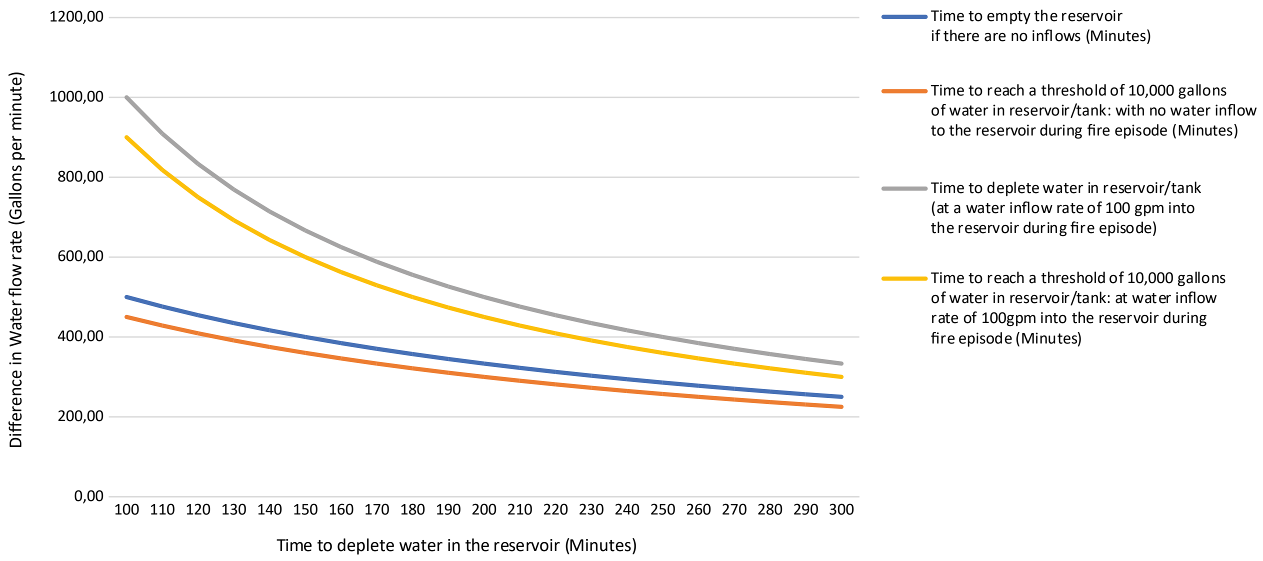


Figure 5. Managing water use during automatic fire suppression scenario: Comparison of the time to deplete water from the reservoir (and time to reach predefined threshold)

Source: Own elaboration.

Figures 5, 6, and 7 show analysis using Excel. Figure 5 shows a comparison of the time to empty the water reservoir and the time to reach a pre-determined threshold for 2 scenarios (i) when there is no inflow into the reservoir and (ii) when there is inflow at a rate of 100 gpm (0.0063 m^3/s). For the scenarios illustrated in Figure 5, the cumulative rate of outflow from the reservoir is greater than the rate of inflow. Hence, it is important to know how long the water can be sustained. The threshold was set at 10,000 gallons (37.85 m^3).

Note:
1 gallon (US) = 0.0037854118 m^3 (www.unitconverters.net)
1 gal/min = 0.000063090196403 43866 m^3/s (www.xconvert.com)
1 litre per minute = 1.6666667×10-5 m^3/s (www.xconvert.com)

Figure 6 compares the time to fill a 100,000-gallon (378.5 m^3) water reservoir with a varied rate of inflow between 200-400gpm (0.0126-0.0252 m^3/s) and varied rate of outflow.

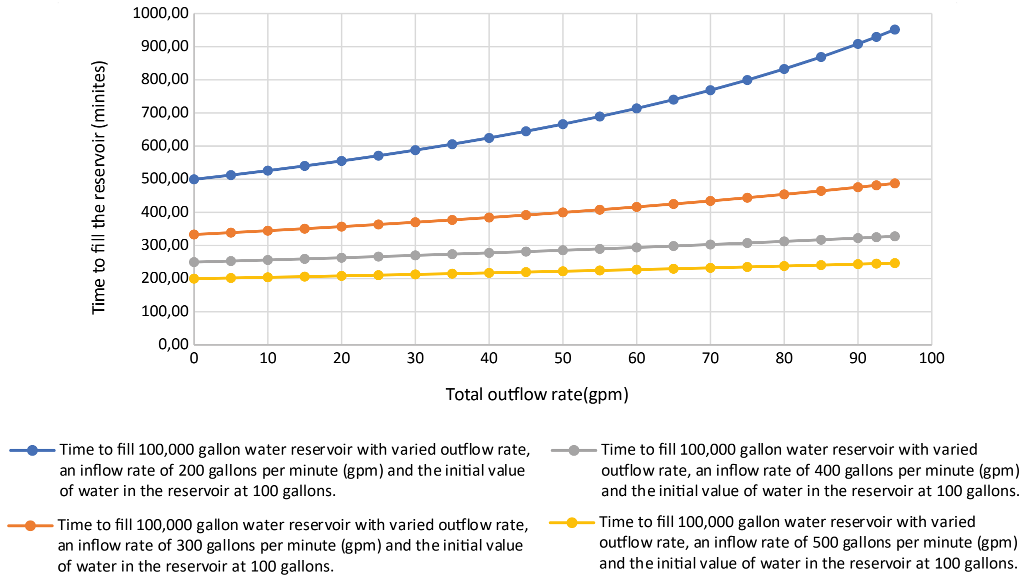


Figure 6. Comparison of time to fill a 100,000-gallon (378.5 m^3) water reservoir with varied rate of inflow: 200 to 500 gpm, (0.0126-0.0315 m^3/s) and varied rate of outflow

Source: Own elaboration.

$$t_{cap} = \frac{V_{cap}}{[(\sum_{j=1}^{k}(R_{\inf\_1} + R_{\inf\_2} + R_{\inf\_3} + ...R_{\inf\_k}) - (\sum_{i=1}^{n}(R_1 + R_2 + R_3 + ...R_n)]} \quad (5)$$

If the rate of water inflow into the reservoir is greater than the rate of water outflow from the sprinklers, the reservoir will be filled up at some point. While it will be good to know the amount of time that is required to fill a reservoir to a desired capacity, an automatic water shut-off system is recommended to prevent water wastage when the reservoir is full. In this case, the time to reach the desired capacity can be calculated as shown in Equation 5. While V_{cap} represents the desired capacity, t_{cap} represents the time that is required to fill the reservoir to the desired capacity given various inflows with inflow rates $R_{inf_1} + R_{inf_2} + R_{inf_3} + ... R_{inf_k}$, and outflows rates from the sprinklers are $R_1 + R_2 + R_3 + ... R_n$

Figure 7 indicates the time (minutes) to fill a 100,000-gallon (378.5 m^3) water reservoir with varied initial volume of water in the reservoir, varied water outflow rate and an inflow rate of 100 gpm (0.0063 m^3/s).

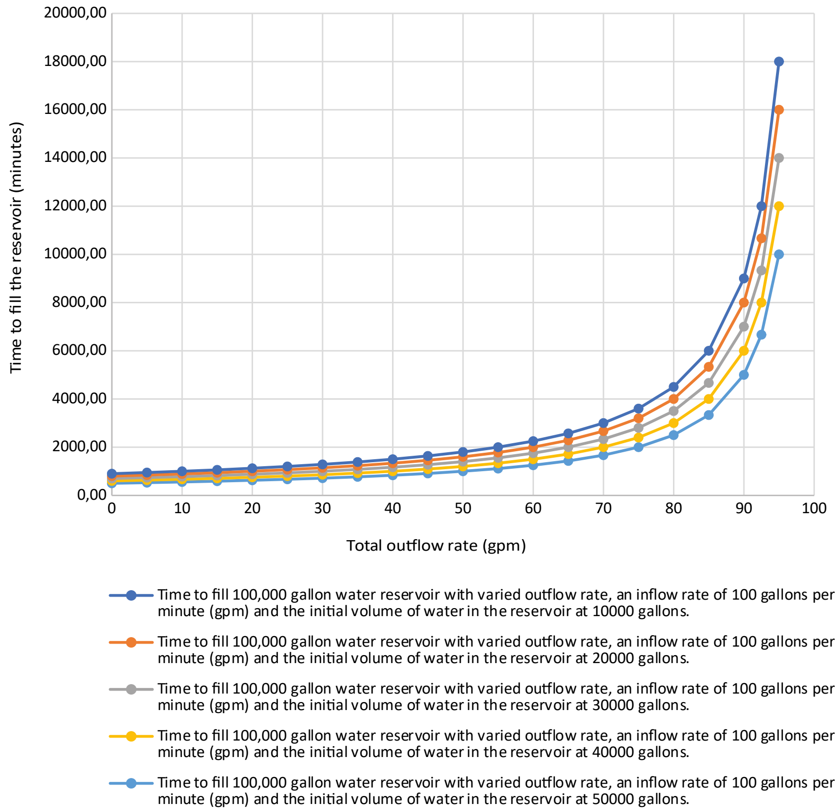


Figure 7. Managing water reserves for automatic fire suppression: Time to fill the reservoir with varied outflow rates, constant inflow rate and varied initial volume of water in the reservoir

Source: Own elaboration.

$$t_{f.in.v} = \frac{V_{tot} - V_{in.}}{[(\sum_{j=1}^{k}(R_{\inf\_1} + R_{\inf\_2} + R_{\inf\_3} + ...R_{\inf\_k}) - (\sum_{i=1}^{n}(R_{out\_1} + R_{out\_2} + R_{out\_3} + ...R_{out\_n})]} \quad (6)$$

For Figure 7, the time to fill the reservoir with an initial volume of water can be represented as a difference in the total capacity of the reservoir, and the initial volume of water in the reservoir divided by the difference in water inflow rate and the water outflow rate (6).

The illustrations above show that the time it will take automatic sprinklers to have enough water supply during the encroachment of seasonal forest fires on residential communities can be predicted. It is hoped that this will help reduce the burden on firefighters (during emergency periods) when forest fires encroach on residential communities. Further study is recommended on the quantity of water to be automatically discharged (by external water sprinklers) in response to various intensities of fire.

Potential area of further research for automatic fire fighting for exterior sections of buildings

Continuous research on the design of systems that can identify exterior fires from various parts of the building, while directing water sprinkling efforts in the direction of the fire is recommended. Mofolasayo [22] noted that more research to ensure that water sprinklers for neighbourhood firefighting can identify fires and can autonomously fight and eradicate fires (whilst considering the intensity of the fire) will be commendable.

In addition to the above:

– Continuous research on the systems that can automatically activate external sprinklers when the temperature gets to a certain threshold and automatically stop sprinkler operations when there is no threat of fire is recommended.
– Field testing to evaluate the effectiveness of external water sprinklers for mitigation of threats from seasonal forest fires is recommended.

Other strategies for the reduction of fire hazards in buildings

Reduction of forest fire hazards to residential communities includes efforts to reduce elements of the fire triangle that can lead to the unnecessary spread of fire. Removal of unnecessary combustible materials around various properties would be a commendable effort, creation of adequate buffers between residential communities and the forest, and removing dead but standing trees in the forest close to residential communities [23]. Various factors could lead to the death of a tree in the forest. These include wind storms resulting in windthrows (when some trees are blown down by the wind), insect infestation, disease infestation, etc. These dead trees are resources that can be used as biofuels. However, when left alone, they are also fire hazards for various communities. Hence, adequate clean-up of dead trees in the forest (especially the areas that are close to residential communities is recommended).

Figure 8. Reduce fire hazards by removing 'dead trees on the ground'
Source: Author's own archives.

Recommendation for dead trees in the forest:

– Remove dead trees from forest floors close to homes [23].
– Use dead trees as biofuels or other beneficial uses.
– Allow people to harvest dead trees if they find them lying around.

Figure 9. Reduce fire hazards by removing dead but standing trees, especially those close to the urban-wildland interface.
Source: Author's own archives.

Buffers between forest and residential communities

In the effort to develop efficient fire prevention strategies for properties (especially those close to the urban-wildland interface), a lot of research questions need to be addressed in the combustion of wood materials.

Figure 10. Reduce fire hazards by creating a reasonable buffer between residential buildings and the forest
Source: Author's own archives.

Designing buffers (spaces) between the wildland and residential communities

The creation of a buffer between the wildland and residential communities can come with various contentions as some people will build right next to the forest without much space between the wildland and the residences. Ordinarily, wood burns when enough heat is introduced to start active pyrolysis, and a pilot flame or other high-temperature source is applied to the combustible gases after they have escaped and mixed with air [24]. Given this knowledge, while evaluating how to reduce the negative impact of the encroachment of a wildfire on residential communities, it is important to study how to prevent high heat from wildfires from starting unwanted pyrolysis in the wooden buildings (or other combustible construction materials) in residential neighbourhoods. One of the ways this can be addressed is to provide adequate space between the wildland and the urban interface.

The amount of heat that is generated from a wildland fire is dependent on the amount of fuel that is available for the fire. Hence, it is important to reduce the amount of fuel in the forests that are close to residential communities to a level that will not generate excessive heat that will be difficult for firefighting efforts in the community to control. The goal here is to develop a system in which encroaching wildfires will no longer be a threat to residential communities. It is also known that forest fires can ignite communities when embers fall on combustible surfaces. Hence, it is important that the design of buildings that are close to the urban-wildland interface be upgraded to account for the potential impact of falling embers. To mitigate against this, all combustible surfaces that will be exposed to falling embers need to be reachable by adequate fire suppression systems. This may include a range of water sprinklers with varying discharge capacities to extinguish fires in their infancy before they spread and become difficult to manage. Reasonable spaces between buildings in the urban-wildland interface will also ensure that the risk of neighbouring buildings being ignited by fires from another building close by is reduced.

Knowing that enough heat is needed to start active pyrolysis when designing buffers between wildland and residential communities, it will be ideal to consider the amount of fuel in the forest at a reasonable distance from the residential communities, and the amount of heat that can be generated if that fuel is engulfed in fire, and the thermal conductivity of air at varied atmospheric conditions such as different temperatures and pressures (especially those that are typical with previous wildfires in the area). This information can be used to forecast the likelihood that the buildings will be engulfed in flames if there is a wildland fire. Information from analysis considering various associated factors that contribute to fire hazards for residential communities can be used to scientifically defend a minimum buffer. However, it should be known that sometimes unforeseen circumstances occur (which may be different from what has happened in various communities in the past). With that, it is reasonable to allow for some additional precautions in the design of buffers between residential communities and the wildland.

How can we reduce the toll on firefighters and also reduce the loss of life and property during episodes of fire encroachment on residential communities?

A strategy for the management of water reserves for autonomous firefighting systems during fire encroachment to residential communities has been described. However, it is important to design buildings in a way that all the exterior sections of the building can be reachable with autonomous fire suppression mechanisms such as high-pressured water sprinklers or water discharge nozzles. The use of video surveillance to detect the presence of fire on the building and the surroundings is also recommended to ensure that autonomous fire suppression can be deployed immediately. Although the use of automatic fire suppression systems is commendable in reducing the toll on firefighters while minimizing the associated losses, firefighters can still come round to ascertain that the threat of fire is adequately addressed.

Conclusion and recommendations

This study describes a conceptual framework on how buildings can be designed to better withstand the threats from seasonal forest fires. An adequate application of the water sprinkler technology for the exterior part of buildings is recommended. Simulation systems were used to evaluate how long water from various sources may be available for firefighting purposes. Rather than waiting for firefighters to come and help extinguish fires in residential communities, the design of our buildings can be such that will not only put a major focus on the automatic deployment of the water sprinkler effect for the interior sections of the buildings, but the improved designs for residential buildings (that are at risks of the encroachment of forest fires) should be such that automatic water sprinklers are available to cover all the exterior sections of buildings for a pre-determined length of time, to mitigate the effect of seasonal forest fires. Firefighters can come round to inspect the automatic fire suppression efforts to ascertain the efficiency and to provide additional support where needed. To avoid arguments and contentions on whether there is a need for a reasonable allowance between forests and residential communities, the study describes factors that can be considered to scientifically establish a minimum buffer that should be provided between the forests and residential communities. Field testing and validation of the proposed process are recommended to determine the optimum amount of water that will be needed to prevent buildings from being engulfed by fires during the encroachment of seasonal forest fires into residential neighbourhoods. Continuous research on autonomous fire suppression systems using adequate water sprinkler technology is recommended to reduce the negative impacts of fire encroachment on residential communities while reducing the toll on firefighters.

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