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Environmental Risk Assessment of Fire-Water Runoff from Vehicle Fire

Development of a predictive model intended for the fire-rescue service

Master’s thesis in Industrial Ecology

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Gothenburg, Sweden 2019

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In collaboration with Research Institutes of Sweden (RISE)

Technical report no ACEX30-19-87
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Cover: Fire-rescue service extinguishing a vehicle fire (The Telegraph, 2015).

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Abstract

The adverse effects that fires impose on the natural environment are numerous and occur through several different mechanisms. Extinguishing a fire requires use of suppression media such as water, firefighting foam or a combination of both. Runoff from suppression media may be inherently toxic and can contaminate soils, nearby surface waters, and groundwater which can pollute local drinking water sources. Vehicle fires, due to their sporadic occurrences and their varying locations, are of interest regarding fire-water runoff. The approach to vehicle fire extinguishment depends on the location of the fire and the characteristics of the surroundings.

This project is performed in collaboration with Research Institutes of Sweden (RISE). The aim is to develop a predictive model that assists the fire-rescue service with decision making. An environmental risk assessment (ERA) of fire-water runoff from vehicle fires is used as a basis for the development of the model. Three endpoints are considered in the ERA; the soil ecosystem, aquatic life in surface waters, and human drinking water quality. The model, called the Fire Impact tool, provides quantitative values regarding how firefighting tactics impact expected soil excavation, the volume of water required to dilute fire-water runoff to reach surface water guideline values, and the minimum distance between a vehicle fire and contaminated groundwater wells.

Users of the tool can make simple predictions regarding the environmental impacts and make informed decisions about vehicle fire extinguishment before a fire occurs. The results provided by the tool suggest that environmental impacts due to fire-water runoff are largely affected by the volume of extinguishant used. Results also show that the environmental impacts due to additives, such as firefighting foams, are significantly larger than the impacts due to contaminants stemming from the vehicle fire itself.

The ERA used to develop the Fire Impact tool is limited to environmental impacts due to fire-water runoff on three endpoints. It does not include all possible environmental impacts that can arise due to vehicle fires. Since the Fire Impact tool serves as a basis for decision-making, it is essential that users of the tool are familiar with the tool’s assumptions and limitations.

Keywords: vehicle fire, environmental risk assessment, fire-water runoff, ecotoxicity, firefighting tactics, monte carlo simulations

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Thank you,

Azra Vilic

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1. Introduction

1.1 Background

The adverse effects that fires impose on the natural environment are numerous and can occur through several different mechanisms. The fire plume contains dioxins, volatile organic compounds (VOCs) and polycyclic aromatic hydrocarbons (PAHs) which contaminate the air (Martin, Tomida, & Meacham, 2016). Furthermore, the soil beneath the fire can be polluted from fire debris particulates (Martin et al., 2016). The harmful elements in a fire may further depend on fuel type and burning conditions (Amon, Gehandler, & Stahl, 2016). Extinguishing a fire requires use of suppression media such as water, firefighting foam or a combination of both. The runoff water from the suppression media may be inherently toxic and can contaminate soils, nearby water sources, and groundwater which can pollute local drinking water sources (Kemikalieinspektionen, 2013). The runoff water can also transport already contaminated soil and pollute the natural environment further (Wallach & Shabtai, 1992). Due to the risks of the runoff water, there may potentially be a trade-off between quenching the fire or allowing it to burn out in order to prevent the release of harmful chemicals into the environment (Fowles, Person, & Noiton, 2001).

Firefighting foams contain fluorinated surfactants that lower surface tension by spreading out as a film over the fire (Dauchy, Boiteux, Bach, Rosin, & Munoz, 2017). Fluorinated surfactants are a subgroup of per-and polyfluorinated alkyl substances (PFASs), which is an umbrella term for a large number of chemical substances, many of which are present in firefighting foams on the Swedish market (KEMI, 2015). PFASs are synthetically manufactured and non-biodegradable which makes releases to the natural environment a long-term problem (Kemikalieinspektionen, 2013). Clinical animal testing shows a correlation between presence of PFAS and development of cancer as well as hormonal- and developmental effects, which makes PFAS presence in drinking water an alarming issue for human health (Rand & Mabury, 2017).

Because of the environmental risks associated with fire-water runoff, the fire-rescue service must be equipped with information regarding the ecosystem’s characteristics and how their firefighting tactics may affect the natural environment. Vehicle fires, due to their sporadic occurrences and their varying locations, are important to consider regarding fire-water runoff. The runoff from a vehicle fire may contain lead, copper, zinc and antimony which can impact drinking water quality (Lönnermark & Blomqvist, 2006). A mistaken use of suppression media on a vehicle fire may have severe adverse effects on the environment. In the summer of 2017, a tractor located on a water protection area caught fire in Karlstad, Sweden. The tractor’s fuel tank leaked, and diesel from the vehicle mixed with the 3000 litres of water that was used to quench the fire, along with harmful chemicals from the fire itself (Karlstadregionen, 2018). Consequently, the toxic runoff led to the excavation of 200 tonnes of contaminated soil, while estimates show that proper use of suppression media could have lowered this number to 15-25 tonnes instead (Karlstadregionen, 2018).

The environmental effects due to vehicle fires and the use of fire suppressants are of great importance to investigate to ensure a minimal amount of adverse effects on the local environment. An environmental risk assessment may be used as a basis for a third party, in this case the fire-rescue service, to make informed decisions to prevent adverse effects on the environment (Rosén, Svensson, Ekåsen, & Löfling, 1998.)

1.2 Aim

The aim of this project is to increase the understanding regarding environmental harm caused by vehicle fires, with a focus on fire-water runoff. The primary goal of this project is to develop a predictive model that assists the fire-rescue service with decision making. An environmental risk assessment (ERA) of fire-water runoff from vehicle fires is used as a basis for the development of the model. The model is a part of the Fire Impact tool developed by Research Institutes of Sweden (RISE), which is an Excel model that transforms fire-related input-data into scenarios of environmental effects, which aims to assist first responders in decision-making regarding vehicle fire extinguishing approach in Sweden. The ERA of vehicle fires in the Fire Impact tool aims to quantitively analyze three environmental impacts;

- *How much soil is estimated to be in need of excavation due to vehicle fire extinguishment?*
- *How does the choice of fire extinguishment approach affect the amount of water required to dilute fire-water runoff to reach surface water guideline values?*
- *Within which distance from a vehicle fire are groundwater wells expected to be contaminated?*

1.3 Delimitations

The ERA considers the soil ecosystem, aquatic life in surface waters, and human drinking water quality as endpoints, and subsequently, other endpoints are excluded from the study. While a vehicle fire poses an environmental risk both on a local and global scale, the global effects are not included in this project. This is on the basis that the fire-water runoff is the focal point of the study, which aims to assess the effects on the environment in close vicinity to the fire. In addition, local effects on the environment that are not due to fire-water runoff, such as air pollution, are excluded from the study. Furthermore, the environmental effects connected to replacement of damaged materials are not included in the study. Weather conditions that may affect the pathways of the fire-water runoff, such as wind and rainfall, are not considered in the study. This project aims to provide quantitative values of adverse effects on the environment due to fire-water runoff. It does not assess possible mitigation measures.

2.Theoretical background

2.1 Fire emissions

There are several emission pathways resulting from a fire. Using suppressants to extinguish a fire leads to toxic fire-water runoff, but the fire itself also releases toxicants. In Figure 1, an overview of the emission pathways from a vehicle fire is presented.

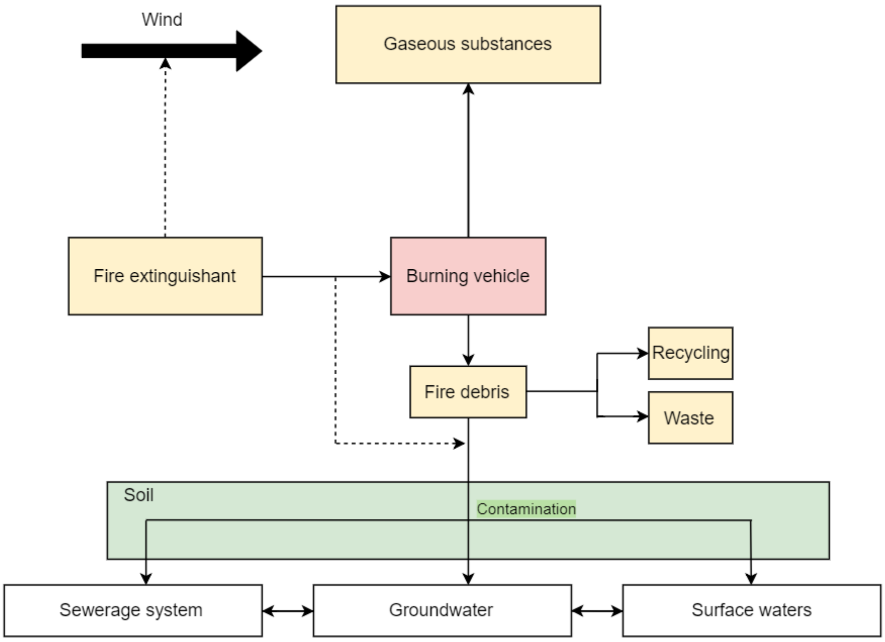


Figure 1. A conceptual model of the emission pathways from a fire. Adapted from (Holemann, 2008).

In Figure 1, extinguishing agents are applied to a burning object, in this case a vehicle. The fire releases gaseous substances into the air, as well as fire debris and residues to the soil beneath the vehicle. Air pollutants include carbon dioxide, carbon monoxide, soot, water and other volatile substances. They are distributed to the air, and their concentrations are reduced in the smoke due to dilution. However, some of the most toxic substances, such as PAHs, are bound to soot particles. (Holemann, 2008). Furthermore, impurities from the fire are present in the runoff water from the fire extinguishant, which contaminates the soil and may reach groundwater, surface waters and sewerage systems (Holemann, 2008).

Runoff water contaminated by a vehicle fire contains both organic compounds as well as metals such as lead, copper, zinc and antimony (Lönnermark & Blomqvist, 2006). As shown in Figure 1, fire-water runoff spreads via the soil and may contaminate surface waters, groundwater, and sewerage systems (Holemann, 2008). Surface waters are habitat to aquatic life whose ecosystem may be threatened by elevated levels of toxicants in fire-water runoff. Groundwater is an important drinking water source for humans, and contamination in the groundwater flow may have adverse effects on drinking water extracted from groundwater wells.

The portion of fire debris that is contaminated and inutile is disposed of as hazardous waste, while the portion that is still useful is recycled or reused (Holemann, 2008).

2.2 Vehicle fire extinguishment

In the last decades, vehicle fires have increasingly posed a problem in Sweden. In 2001, the rescue service assisted with a total number of 3916 vehicle fires, and between the years 1996 and 2001, the number of vehicle fires caused by arson increased with 150% (Lönnermark & Blomqvist, 2006).

When arriving at the scene of a vehicle fire, first responders must assess the situation and determine if there is a risk of the fire spreading, or if the vehicle might be carrying hazardous substances (Jakubowski, 2019). The most common fire extinguishant is water, however use of foam additives is common in vehicle fire extinguishment as well. In some cases, firefighting foam is added to vehicle accidents as a preventative measure against a possible fire (Räddningsverket, 2006). The extinguishing water that is not evaporated when added to the fire is what constitutes the fire-water runoff, which is emitted to the environment (Fowles et al., 2001). Preferably, the runoff water is collected and taken to analysis (Amon, Mcnamee, & Blomqvist, 2014).

The approach to vehicle fire extinguishment often depends on the location of the fire and the characteristics of the surroundings. Therefore, it is preferable that the fire-rescue service has access to a geographic information system (GIS), which maps out the existing environmental protection areas in a community (Räddningsverket, 2006). Fire surroundings and burning conditions largely influence the decision to extinguish a burning object or to let it burn out, which in some cases may favor the local environment (Räddningsverket, 2006).

2.3 Fire Impact tool

To minimize the harmful effects on the environment due to fires, it is preferable to act in a preventative manner (Räddningsverket, 2006). Depending on the surroundings of the fire, several different environmental consequences are possible. An area may be especially sensitive to chemical stressors both due to its natural condition, but also because of previous stress that the area has endured (Räddningsverket, 2006).

It is beneficial for numerous stakeholders to have access to a basis for informed decision-making concerning the extinguishment of fires (Amon et al., 2014). There are many ways that a fire may have a negative impact on the environment, with several different endpoints and stressors involved. To predict some of the substantial environmental impacts, the “Fire Impact tool” is developed.

Fire Impact is a tool developed by RISE that predicts the environmental impacts caused by fires in vehicles and school buildings, applicable to the area of Sweden. With the use of life cycle assessments as well as environmental risk assessments, it considers both local and global environmental impacts. The tool aims to provide a basis for decision-making for the fire-rescue service, to minimize the environmental impacts from extinguishing fires. It is preferably used as a preventative action so that large negative impacts on the environment can be avoided. The tool works by allowing the user to enter input data such as extinguishment approach, fire surroundings, and time of intervention. The tool is developed in Microsoft Excel and presents quantitative numbers on the local and global environmental impacts due to the selected scenario of input data, which provides the user of the tool an overview of the trends regarding environmental consequences due to their fire extinguishment approach.

2.4 Environmental risk assessment

An environmental risk assessment aims to provide scientific evidence concerning potential adverse effects imposed on the environment by analyzing available scientific data (Leeuwen & Vermeire, 2007). The assessment consists of four steps (Leeuwen & Vermeire, 2007), as shown in Figure 2.

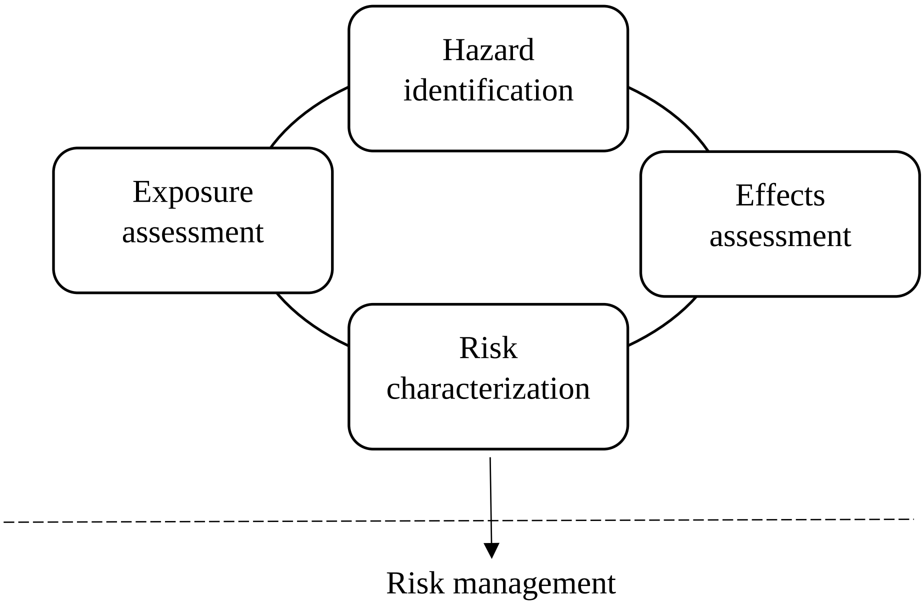


Figure 2. The four main steps of the environmental risk assessment framework. Adapted from (Leeuwen & Vermeire, 2007)

The hazard identification is the first step of the framework, which consists of acquiring knowledge about harmful substances that may cause adverse effects to the endpoints (Leeuwen & Vermeire, 2007). The exposure assessment describes the circumstances in terms of contact between stressor and endpoint, by analyzing pathways and concentrations of harmful substances (Leeuwen & Vermeire, 2007). Effects assessment is the step in the framework that is used to relate the dose of a substance to the severity of the adverse effect that can be observed in the endpoint (Leeuwen & Vermeire, 2007). Lastly, the risk characterization is composed of the preceding three steps, and it is used to evaluate the likelihood and severity of adverse effects on the endpoint (Leeuwen & Vermeire, 2007).

Environmental risk assessment has a considerable role in environmental management, both in policy and regulatory practices, as well as in industry (European Environment Agency, 2008). It is a common basis for decision-making and it enables efficient communication about risks between different actors (European Environment Agency, 2008).

3. Methodology

The aim of this project is to develop the Fire Impact tool which transforms fire-related input data into environmental effects from fire-water runoff resulting from a vehicle fire. The tool is developed with an environmental risk assessment of fire-water runoff which analyzes the adverse effects on the local environment surrounding a vehicle fire. The project is initiated with a literature study, to gather information required to perform the ERA and subsequently develop the Fire Impact tool. Lastly, to assess uncertainties and validate results, both a sensitivity analysis as well as an uncertainty analysis are conducted.

3.1 Literature study

The literature study is conducted to acquire knowledge about vehicle fires and their environmental effects, fire-water runoff, fire suppressants, and the methodology of environmental risk assessment. The literature study consists of searching for articles from scientific databases as well as reviewing literature in the form of books. Articles are searched with keywords such as “fire-water runoff”, “vehicle fires”, “fire suppression media” and “firefighting foam environmental effects”. In addition, data required for the study, such as soil data and guideline values, are obtained from scientific literature.

3.2 Environmental risk assessment

The environmental risk assessment focuses on the risks associated with fire-water runoff from a vehicle fire. It is used to assess acute adverse effects on the local environment in close proximity to a vehicle fire. As in the ERA framework described by Leeuwen & Vermeire in Figure 2, potential hazards with fire-water runoff are identified by assessing the possible toxicants that may be present in fire-water runoff. A previous study performed at RISE where fire-water runoff was collected during a vehicle fire experiment is analyzed to establish the number of chemicals present, as well as their concentrations in the runoff. Considering the harmful chemicals present in fire-water runoff, suitable ecological endpoints are selected.

Pathways from the vehicle fire to the endpoints are assessed, and their environmental risks are specified quantitively with mathematical formulas based on dispersion models. Furthermore, a conceptual model describing the pathways and endpoints considered in the ERA is constructed.

3.2.1 Hazard identification

The adverse effects that may be inflicted on the endpoints are due to exposure of stressors. An environmental stressor is a chemical, physical or biological agent that may potentially cause harmful effects on the environment (Linkov & Palma-Oliveira, 2000).

For fire-water runoff, the stressors may stem from either the vehicle fire itself, or from a potential additive used to extinguish a fire. The stressors in the runoff water that stem from the vehicle fire consist of a range of chemicals, many of them metals and PAHs (Lönnermark & Blomqvist, 2006). Benzo(a)pyrene is a PAH that is commonly used as an indicator species for PAHs (Avino, Notardonato, Perugini, & Russo, 2017), and therefore guidelines values for Benzo(a)pyrene represent the value for total PAH if no explicit total PAH guideline value is available.

Additives, such as firefighting foams, contain toxic and non-degradable substances. Additives contain a range of chemicals, although PFAS are of major concern due to their toxic and persistent qualities.

3.2.2 Selection of endpoints

In the context of environmental risk assessment, an endpoint is an ecological entity that is sought to be protected (Suter, 2010) Due to an infinite number of ecological entities, the selection of endpoints is affected by the attributes that an ecological entity holds and how valuable it is perceived to be (Suter, 2010).

Three endpoints are considered in this project; the soil ecosystem, aquatic life in nearby surface waters, and drinking water quality in groundwater wells. These endpoints are selected due to their large potential exposure to the fire-water runoff. The soil surrounding the vehicle, due to its direct contact with the chemicals of the runoff, may need to be excavated which can be a costly operation (Karlstadregionen, 2018). The soil quality may also change due to replacement of soil, which can be an expensive process (IADC, 2015). Aquatic life in surface waters is chosen as an endpoint because of the intrinsic value of the species that may be threatened. In addition, contaminated fish may negatively affect human health following ingestion (Naturvårdsverket, 2008). The quality of human drinking water is considered an important endpoint due to the potential harm that a vehicle fire may impose on local communities and their health.

3.2.3 Conceptual model

The emissions that are considered in the ERA consist of the fire-water runoff pathways adjacent to a vehicle fire site. To gather information regarding the potential transport of fire-water runoff to waste water treatment plants (WWTPs), communication with a WWTP operative in Borås, Sweden was established. Since contaminated fire-water runoff may contain toxicants that can damage the biological purification process in a WWTP, a general policy is that contaminated fire-water runoff is not sent to WWTPs (El-Charif, 2019). Therefore, the pathways included in the ERA do not consider fire-water runoff being sent to WWTPs. In Figure 3, a conceptual model visualizes the flows of runoff polluting the soil, surface water and groundwater wells. The model also depicts the inputs and outputs that are used in the Fire Impact tool, with units used in the tool in parentheses.

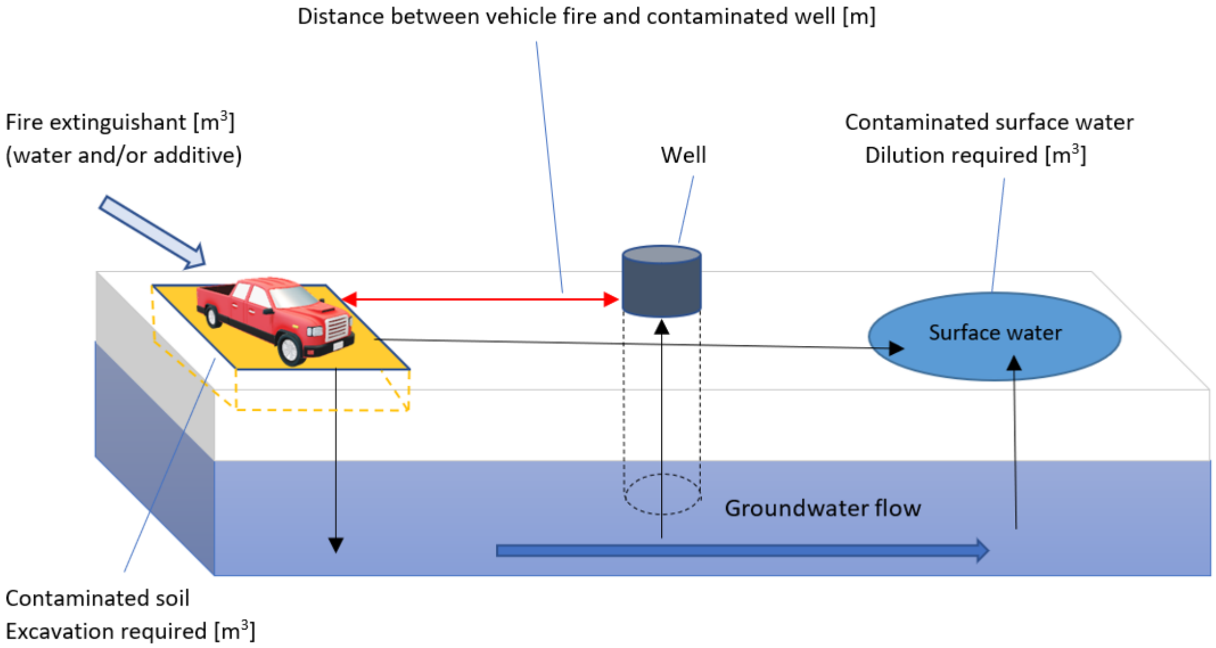


Figure 3. A conceptual model of the pathways of fire-water runoff considered in the ERA.

The black arrows represent flows of fire-water runoff, going from the vehicle fire through the soil and travelling to surface waters and the groundwater. The red arrow shows the distance between the vehicle fire and a contaminated well, which is an output in the Fire Impact tool. The blue arrow shows the groundwater flow and visualizes how the contaminants in the runoff water are transported with the groundwater and may end up in surface water or in groundwater wells. It is important to note that the assessment of the water required to dilute fire-water runoff to reach surface water guideline values is performed on the fire-water runoff itself, and not after it ends up in surface waters. The arrows that depict the pathway that fire-water runoff travels from a vehicle fire to a nearby body of surface water are merely a description of the contaminated runoff water exposing aquatic life in surface waters.

3.2.4 Exposure assessment

Fractions of the runoff water end up in each endpoint depending on factors such as firefighting tactics, soil characteristics and surface steepness (Cornell University, 2014). Soil data are needed to perform a quantitative analysis of both the soil ecosystem and the groundwater transport. Due to a variation of data depending on soil type, three soil types are considered in this study; moraine, sand and clay. Moraine soil is the most common soil type, covering around 75 % of the Swedish surface area (Sveriges Geologiska Undersökning, n.d.). Sand and clay are likewise chosen due to them being common soil types in Sweden (Statens Geotekniska Institut, 2019).

In the following subchapters, equations based on dispersion models for each endpoint are presented.

3.2.4.1 Soil ecosystem

The soil beneath the vehicle fire is subjected to infiltration of runoff water that contains harmful chemicals. It is assumed that the entire wetted volume of soil is contaminated and therefore required to be excavated. Also, it is assumed that the area of wetted soil is the same as a larger Swedish parking lot, which has an area of 5x5 meters (Tyréns AB, 2013). The depth of contaminated soil is related to its retention capacity (Rosén et al., 1998) and is derived from equation (1).

$$D = \frac{V_{Runoff}}{A \cdot R_C} \tag{1}$$

Where D is the depth of contamination [m], V_{Runoff} is the volume of runoff water [m^3], A is the area of contamination [m^2], and R_C is the retention capacity [m^3/m^3] of the soil. The fire-water runoff is approximated as water and therefore the soil's field capacity is used as a value for the retention capacity. Field capacity is a measurement of the water content in the soil after it has been completely wetted with water and free drainage has lowered to insignificant values (Wu et al., 2018). The volume of soil that is excavated is calculated with equation (2).

$$V_E = D \cdot A \tag{2}$$

Where V_E is the volume of excavated soil [m^3].

It is assumed that the distance from the soil surface to the groundwater is 3 meters, which is a value used in a model by the Swedish EPA. Therefore, the depth of contaminated soil has a maximum value of 3 meters. The time until contamination reaches groundwater depth is shown with equation (3) (Rosén et al., 1998).

$$t = \frac{D_{gw} \cdot n_e}{k_v} \tag{3}$$

Where t is the time until the runoff water reaches groundwater levels [m], D_{gw} is the distance from the soil surface to the groundwater surface [m], n_e is the effective porosity of the soil [m^3/m^3], and k_v is the hydraulic conductivity of the soil in vertical direction [m/s].

3.2.4.2 Surface water

To establish the number of stressors that exist in fire-water runoff, a previous study conducted at RISE was used where fire experiments were conducted on a vehicle and the runoff water was collected and analyzed. The study analyzed a volume of 105 litres of runoff water and presented the mass of each stressor in the runoff (Lönnermark & Blomqvist, 2006). The vehicle used in the experiment is described as a medium class model built in 1998. The study established that the fraction between BOD/COD (the biological oxygen depletion divided by the chemical oxygen depletion) was approximately 0,6. A BOD/COD higher than 0,43 means that the runoff is perceived as persistent (Lind et al., 2009).

The mass of contaminants in the runoff water is scaled depending on how developed the fire is before it is extinguished. It is assumed that the masses of stressors from the vehicle fire are limited and may reach maximum values. The concentrations of stressors in the runoff water are calculated by assuming that the stressors have reached maximum, constant mass values. The mass of each stressor is divided with the volume of runoff water to calculate concentrations.

However, for small volumes of runoff water, it is assumed that the stressors' masses have not yet reached maximum values. For these smaller volumes, it is assumed that the concentrations of stressors are constant. Constant concentration is applied on scenarios where the volume of runoff water is 105 litres or less, due to the Lönnermark & Blomqvist study where 105 litres of runoff water was produced.

Additives used in firefighting, and their compositions, are gathered from a global firefighting foam firm. The chemicals used in additives are listed and their compositions are used to calculate their corresponding concentrations in the fire-water runoff.

The concentrations of stressors are compared with guideline values for aquatic life in surface water. It is important to add that the concentrations of stressors are analyzed in the fire-water runoff itself, and not after it ends up in surface waters. The concentrations of contaminants in the runoff is directly dependent on the volume of extinguishant that is applied to the vehicle fire. The volume of water required to dilute the contaminated runoff water to reach guidelines values for aquatic life is expressed in litres and is calculated with equation (4).

$$Volume_{Dilution} = \frac{C_{Contaminant} \cdot V_{Runoff-sw}}{C_{Guideline-sw}} - V_{Runoff-sw} \tag{4}$$

Where $C_{Contaminant}$ [mg/L] is the concentration of contaminant in the fire-water runoff, $V_{Runoff\text{-}sw}$ [L] is the volume of runoff that goes to surface water, and $C_{Guideline}$ [mg/L] is the concentration that represents the guideline values of aquatic life in surface waters.

The volume required to dilute the stressors to reach guideline values is not a proposed mitigation measure. It is used to compare and communicate the extensiveness of how much the concentration of stressors in runoff water deviates from the proposed guideline values, while also providing a sense of how large a polluted body of surface water may be.

3.2.4.3 Groundwater wells

Fire-water runoff seeps through to groundwater through the soil and is transported to nearby groundwater wells. Groundwater wells within a certain distance from a vehicle fire may be contaminated by the runoff, which presumably occurs if the concentration of stressors in the water is above guideline values for human drinking water quality. Vehicle fire data are gathered from the study performed by Lönnermark & Blomqvist, 2006, and stressors found in additives and their respective compositions are taken from a global firefighting foam firm.

It is assumed that the change in concentration of contaminants in the groundwater flow is only affected by dilution taking place in the groundwater flow. The dilution factor ($DF_{gw\text{-}well}$) is dependent on the distance between the contaminant release and the well (Naturvårdsverket, 2016). This relation is described in a simplified model by the Swedish EPA, as seen in equation (5).

$$DF_{gw-well} = \frac{L \cdot I_r \cdot W}{k \cdot i \cdot d_{mix-well} \cdot (2 \cdot y_{mix-well} + W) + (W + y_{mix-well}) \cdot (L + x_{well}) \cdot I_r} \tag{5}$$

Where L is the length of the contaminated area in the direction of the groundwater flow [m], I_r is the groundwater recharge [m/year], W is the width of the contaminated area in perpendicular direction of the groundwater flow [m], k is the hydraulic conductivity of the soil [m/year], i is the hydraulic gradient [m/m], $d_{mix\text{-}well}$ is the thickness of the mixing zone in the aquifer [m], $y_{mix\text{-}well}$ is the spread of the mixing zone [m] and x_{well} is the distance to the well [m]. An overview of the groundwater transport model is shown in Figure 4.

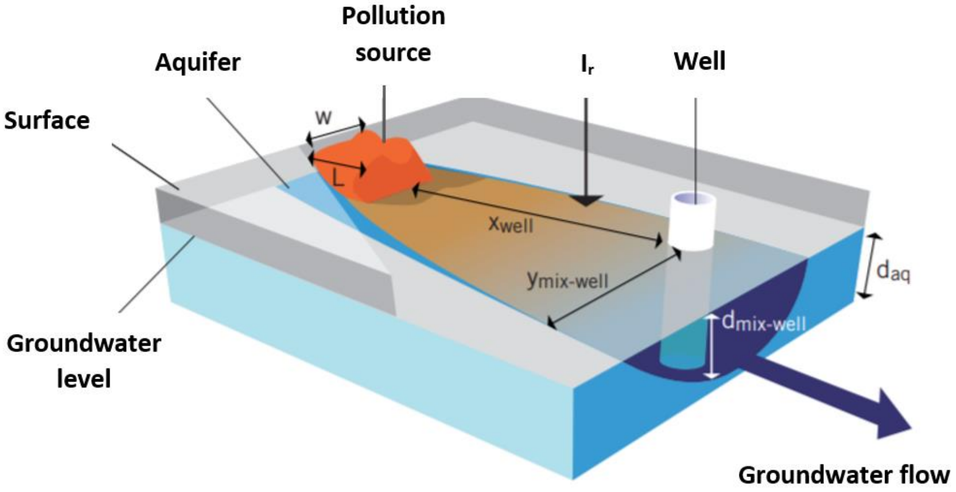


Figure 4. A conceptual model of the groundwater transport model. Adapted from (Naturvårdsverket, 2016).

$d_{mix\text{-}well}$ and $y_{mix\text{-}well}$ may be calculated with equation (6) and (7) respectively.

$$d_{mix-well} = \sqrt{0{,}0112 \cdot (L + x_{well})^2} + d_{aq} \cdot \left[1 - exp\left(-\frac{(L + x_{well}) \cdot I_r}{k \cdot i \cdot d_{aq}}\right)\right] \tag{6}$$

Where d_{aq} is the aquifer's thickness [m]. $d_{mix\text{-}well}$ may be approximated as d_{aq}, if $d_{mix\text{-}well} > d_{aq}$.

$$y_{mix-well} = \sqrt{0{,}0112 \cdot (L + x_{well})^2} \tag{7}$$

The dilution factor, $DF_{gw\text{-}well}$, is a dimensionless number that is the quotient of the concentration in the groundwater well and the concentration of the mobile contaminant in the ground, as seen in equation (8).

$$DF_{gw-well} = \frac{1}{\left(\frac{c_{well}}{c_{contaminant}}\right)} \tag{8}$$

Where in this case, C_{well} [mg/L] is the guideline concentration for drinking water quality and $C_{contaminant}$ is the concentration of contaminants in the runoff water. Soil data used in the groundwater transport model are representative of moraine and sand. Clay soil is not included due to its low permeability (Hasegawa, Osozawa, & Osozawa, 1994), and therefore it is assumed that the runoff water will not reach the groundwater when a vehicle fire is located on clay.

3.3 Fire Impact tool development

The ERA acts as a basis for the development of the Fire Impact tool by providing the quantitative values that are required to assess the environmental impacts resulting from fire-water runoff. The Fire Impact tool is created in Microsoft Excel, by connecting the acquired mathematical equations to input data that are relevant for the fire-rescue service. Development of the tool is a continuous process with several contributors working in collaboration with one another. Since the tool is intended for the fire-rescue service, communication with a reference group is established. The reference group contributes to the tool with their knowledge and expertise, as well as feedback on the tool and its design to make the interface user friendly.

The Fire Impact tool presents the results concerning environmental risks associated with fire-water runoff with graphs, to enable an easy comparison between different results. The values that are expressed as results in the tool’s graphs are represented by the stressor that provides the “worst case” result.

Calculations, soil data, and guideline values are placed in a separate, hidden sheet that requires authorization to access in order to prevent accidental changes to constants and equations, as well as to separate the results from the calculations.

3.4 Sensitivity analysis

The uncertainties surrounding the Fire Impact tool are assessed with a sensitivity analysis as well as an uncertainty analysis. A sensitivity analysis is performed on parameters used in the tool that may have varying values with large impacts on the results. An important parameter is the use of guideline values. Both surface water guideline values and drinking water guideline values are used in the Fire Impact tool to establish how much fire-water runoff must be diluted to reach acceptable levels. However, due to guideline values being uncertain, a sensitivity analysis is performed where guideline values are varied and subsequent impacts on results are recognized. The sensitivity analysis on guideline values is performed on the guideline values of stressors that contribute to the worst scenario results in the Fire Impact tool.

3.5 Uncertainty analysis

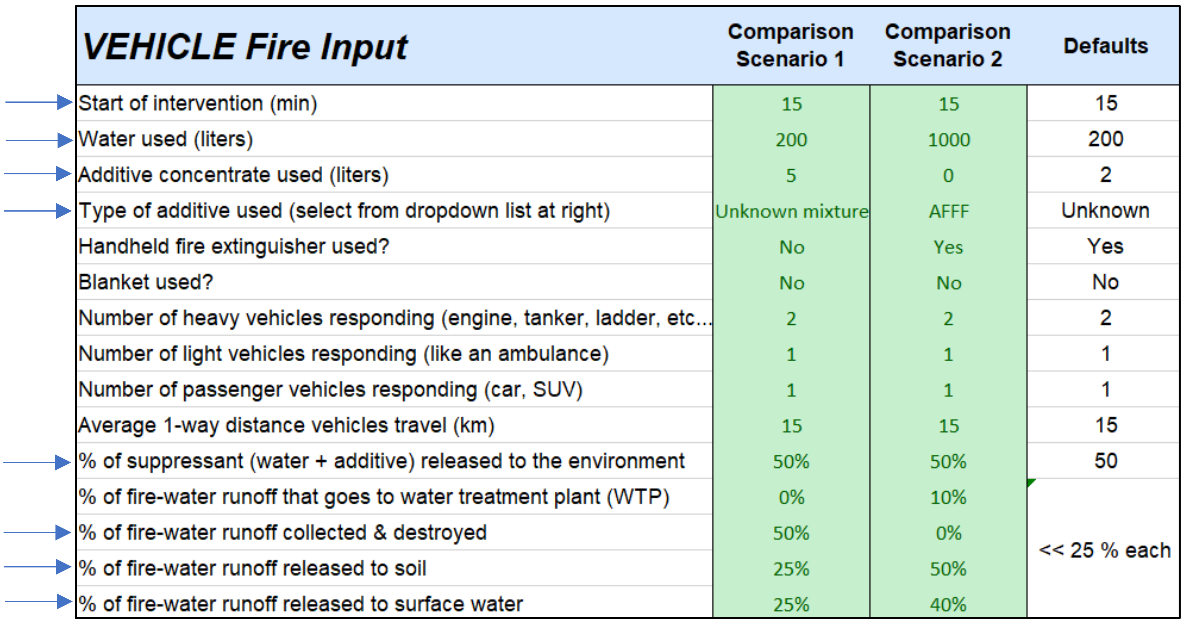
Equations used in the Fire Impact tool largely depend on soil data that are commonly presented with intervals due to uncertainties. In the Fire impact tool, specific data points are used which leads to results in the tool being presented with single point values. The specific data used in the Fire Impact tool are gathered by estimating the most likely value, sometimes explicitly expressed in data sources and in some cases median values are used. To understand how the different ranges of parameter values may impact the results, an uncertainty analysis is performed where a statistical simulation on data points is conducted using a Monte Carlo simulation.

A Monte Carlo simulation is performed in Microsoft Excel with the use of a software, @Risk, provided by Palisade Corporation. The simulation uses a range of data values and their probability distributions in order to repeatedly calculate results using a different set of values each time (Palisade, 2019). Results are presented with a range of possible outcomes with a statistical clarification of the most likely values.

4. Results

4.1 Fire Impact tool

The Fire Impact tool aims to translate extinguishment approach into environmental consequences. The tool allows the user to enter input data, as shown in Figure 5. The user may enter data in two columns called “comparison scenarios” to instantly see a side-by-side view of the outcomes resulting from the chosen inputs.

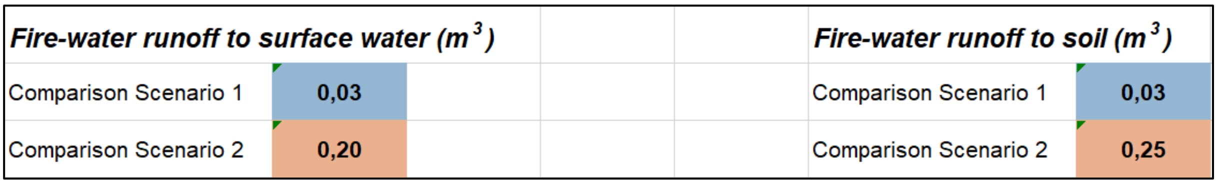


VEHICLE Fire Input	**Comparison Scenario 1**	**Comparison Scenario 2**	**Defaults**
Start of intervention (min)	15	15	15
Water used (liters)	200	1000	200
Additive concentrate used (liters)	5	0	2
Type of additive used (select from dropdown list at right)	Unknown mixture	AFFF	Unknown
Handheld fire extinguisher used?	No	Yes	Yes
Blanket used?	No	No	No
Number of heavy vehicles responding (engine, tanker, ladder, etc...	2	2	2
Number of light vehicles responding (like an ambulance)	1	1	1
Number of passenger vehicles responding (car, SUV)	1	1	1
Average 1-way distance vehicles travel (km)	15	15	15
% of suppressant (water + additive) released to the environment	50%	50%	50
% of fire-water runoff that goes to water treatment plant (WTP)	0%	10%	<< 25 % each
% of fire-water runoff collected & destroyed	50%	0%	
% of fire-water runoff released to soil	25%	50%	
% of fire-water runoff released to surface water	25%	40%	

Figure 5. Input data in the Fire Impact tool. Green boxes represent input data where a user may experiment with values and compare two scenarios. Inputs relevant for the ERA are pointed out with arrows.

The Fire Impact tool provides a quantitative analysis of a range of environmental impacts resulting from the extinguishment of a fire. For ERA results, relevant input data are; start of intervention, extinguishing water used, additive used (type and concentrate), % of suppressant released to the environment, % of runoff that is collected and destroyed, as well as the % of runoff released to soil and surface water respectively. An input of “unknown mixture” for type of additive leads to a combination of all available additives being used. The % of suppressant that goes to the environment is the fraction of suppressant that is not evaporated during the vehicle fire extinguishment and becomes fire-water runoff.

The volume of fire-water runoff released to surface water and soil corresponding to the input data in Figure 5 are shown in Figure 6. Users of the Fire Impact tool may experiment with different input data and gain an understanding of the environmental impacts caused by different fire extinguishment approaches. Default values are gathered from communication with the reference group.



Fire-water runoff to surface water (m^3)			***Fire-water runoff to soil (m^3)***	
Comparison Scenario 1	**0,03**		Comparison Scenario 1	**0,03**
Comparison Scenario 2	**0,20**		Comparison Scenario 2	**0,25**

Figure 6. Volume of fire-water runoff released to surface water and soil respectively.

4.1.1 Soil ecosystem

Given the input parameters in Figure 5, an estimation of the required soil excavation is shown in Figure 7. Calculations are presented in Appendix D, with soil data from Appendix A. In green, the graphs show the values resulting from comparison scenario 1, while in grey, values are represented by the input parameters in comparison scenario 2.

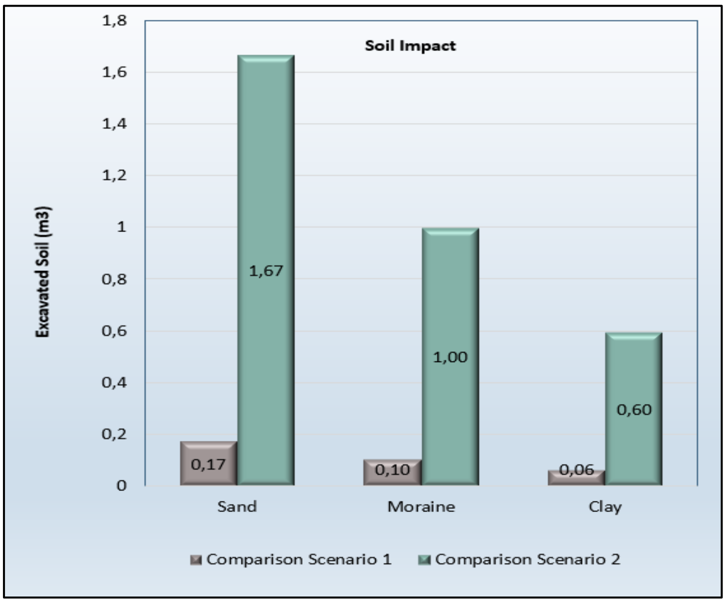


Figure 7. An estimation of required soil excavation for sand, moraine, and clay.

Because the soil calculations consider how much fire-water runoff that enters the soil, the only input parameter that changes the outcome of the soil graphs is the volume of runoff water that is released to soil. This parameter may change if there is more or less water (or additive) used to extinguish the fire, or if more or less runoff water is collected after the fire. In Figure 7, comparison scenario 2 shows a significantly higher volume of soil excavation compared to comparison scenario 1. Comparison scenario 2 includes a higher combined amount of water and additive used than comparison scenario 1. This example of results from the Fire Impact tool suggests that a larger volume of water or additive released to the environment has a more negative impact on the soil ecosystem.

Figure 7 also shows that the expected soil excavation differs significantly depending on soil type. An important soil parameter is field capacity, which is a measure of how much water a soil can retain. The highest value for excavation is represented by sand due to sand having a field capacity that is considerably lower than the field capacity for moraine and clay. This, in turn, entails deeper infiltration of runoff water into the soil, which leads to a higher excavation volume.

4.1.2 Surface water

A number of stressors found in fire-water runoff do not have established surface water guideline values. An extensive list of all stressors found in fire-water runoff from experiments conducted by Lönnermark & Blomqvist, 2006 is presented in Table 7 in Appendix B. The chemicals found in fire-water runoff that do have available surface water guideline values, and that contribute to the results in the Fire Impact tool are presented in Table 1. The guideline values are obtained by the USEPA's recommended aquatic life criteria (United States Environmental Protection Agency, n.d.), the Canadian council of Ministers of the Environment (CCME) (Canadian Council of Ministers of the Environment, 1999), as well as the Swedish Agency for Marine and Water Management (HVMFS, 2018)

Table 1. List of contaminants in fire-water runoff and their respective guideline values corresponding to aquatic life criteria.

Stressor	**USEPA Guideline value [mg/L]**	**CCME Guideline value [mg/L]**	**HVMFS Guideline value [mg/L]**
PAH (total)		0,000015	
Cadmium (Cd)	0,0018		
Lead (Pb)	0,065		
Arsenic (As)	0,34		
Chromium (Cr)	0,016		
Copper (Cu)	0,0048		
Zinc (Zn)	0,12		
Nickel (Ni)	0,47		
Mercury (Hg)	0,0014		
Glycols		192	
Mixture of fluorosurfactants (PFAS)			0,036

In Figure 8, the volume of water required to dilute fire-water runoff to reach surface water guideline values is shown, with the use of input data in the Fire Impact tool shown in Figure 5. The values represent the dilution required for the stressor in Table 1 that yielded the highest value, with calculations presented in Appendix D. The graphs in Figure 8 differentiate between required dilution for contaminants found in the vehicle fire, and contaminants found in additives. The vehicle fire contaminants and additive contaminants are represented by orange bars and blue bars respectively.

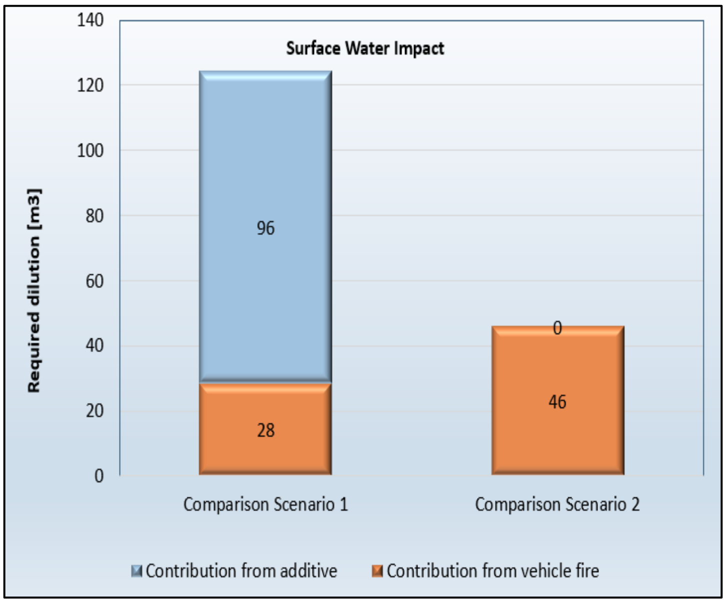


Figure 8. Volume of water required to dilute fire-water runoff to reach surface water guideline values.

Figure 8 shows that an increased use of extinguishing water, and a larger fraction of the runoff water going to surface water, represented by comparison scenario 2, entails a higher volume of water required to dilute fire-water contaminants. In comparison scenario 2, no additive is used and therefore the required dilution for additives is 0. In comparison scenario 1, both water and additives are used to extinguish the vehicle fire and the total dilution requirement is significantly higher for comparison scenario 1 than for comparison scenario 2. It can be seen that the required dilution is significantly higher for additive contaminants compared to vehicle fire contaminants. As seen in Table 1, chemicals found in the additives, PFAS especially, have stricter guideline values compared to some of the chemicals stemming from the vehicle fire. In addition, additives contain high concentrations of stressors, which leads to a large difference between the concentration of stressors in the runoff and the concentration proposed by guideline values.

4.1.3 Groundwater wells

In Table 2, stressors with available drinking water guideline values are presented. Guideline values are obtained by the National Food Agency of Sweden (Livsmedelsverket, 2015). An extensive list including all stressors found in fire-water runoff from the study by Lönnermark & Blomqvist, 2006 is presented in Table 8 in Appendix C.

Table 2. Stressors in fire-water runoff and their respective guideline values corresponding to drinking water quality.

Stressor	National Food Agency of Sweden Guideline value [mg/L]
PAH (total)	0,0001
Cadmium (Cd)	0,005
Lead (Pb)	0,01
Arsenic (As)	0,01
Antimony (Sb)	0,005
Chromium (Cr)	0,05
Copper (Cu)	2
Nickel (Ni)	0,02
Mercury (Hg)	0,001
Mixture of fluorosurfactants (PFAS)	0,00009

The concentrations of contaminants are diluted with the groundwater flow. The distance to a groundwater well is a measurement of how long the stressors need to travel with the groundwater flow until they are diluted to reach guideline values. Results provide a measurement of how far away from a vehicle fire that no groundwater wells may be located. Figure 11 represents the groundwater wells that are contaminated within a certain distance in meters, with input data in the Fire Impact tool from Figure 5. Soil data used in groundwater equations are presented in Appendix A.

Figure 11. Distance to the contaminated well that is furthest away from the vehicle fire, where vehicle fire contaminants and additive contaminants are represented by orange bars and blue bars respectively.

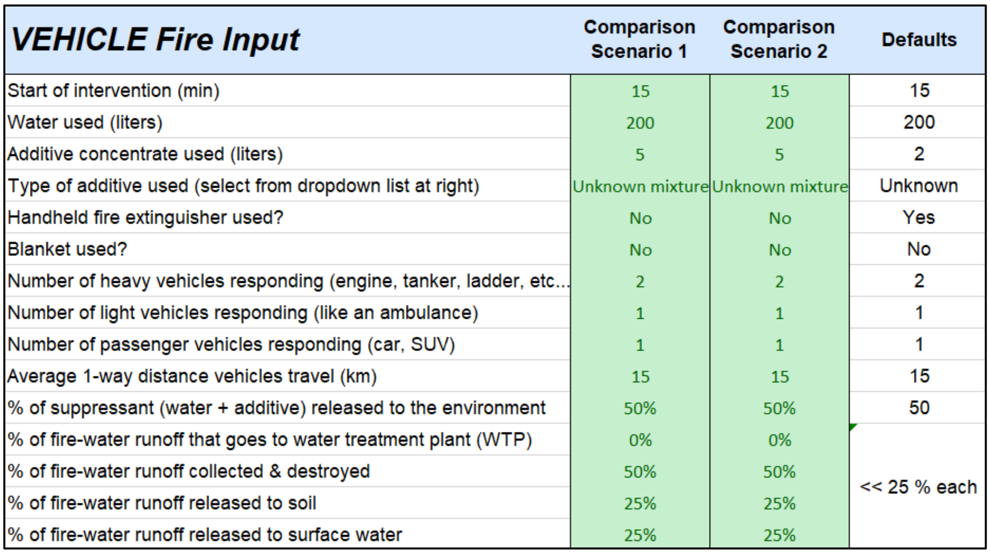
Figure 11 indicates that groundwater wells are contaminated within a much larger distance due to additives used in the fire extinguishment compared to the contaminants from the vehicle fire. Comparison scenario 2 uses a higher amount of extinguishing water which yields a shorter distance to the furthest contaminated groundwater well due to vehicle fire contaminants. This trend is a result of the dilution that takes place in the groundwater flow. A larger volume of extinguishing water subsequently reduces the concentration of the contaminants in the runoff, which entails a decreased need for dilution in the groundwater flow. This in turn, leads to a shorter distance to the furthest contaminated groundwater well.

The distance to the furthest contaminated groundwater well is slightly shorter when soil data representing sand is applied, compared to soil data representing moraine. Figure 11 also shows that the impact due to additives is significantly larger compared to the impact due to contaminants from the vehicle fire.

4.2 Sensitivity analysis

The results of this study are largely dependent on guideline values. In some cases, guideline values are still debated and uncertain. For instance, the proposed drinking water guideline value for PFAS is described as an "action threshold" rather than a guideline value (Livsmedelsverket, 2018). A sensitivity analysis is performed on guideline values for the most vital stressors to gain an understanding of how the results may vary due to variations in guideline values.

The most critical stressors that provide the results in the Fire Impact tool in Figure 8 for required dilution in surface waters are PAH and PFAS. The corresponding stressors for the distance to the furthest contaminated well from the vehicle fire, provided by the Fire Impact tool in Figure 9, are Antimony and PFAS. Guideline values established for chemicals in both surface waters and for drinking water quality are uncertain. To assess how the uncertainties of guideline values may have impacted the results of this study, the guideline values for PAH, PFAS (surface water), PFAS (drinking water) and antimony are individually varied. As seen in Figure 12, the input data in the Fire Impact tool is identical for both comparison scenarios, however comparison scenario 2 represents a variation in guideline values, while comparison scenario 1 represents the guideline values that are used in the study, presented in Table 1 and Table 2.



VEHICLE Fire Input	Comparison Scenario 1	Comparison Scenario 2	Defaults
Start of intervention (min)	15	15	15
Water used (liters)	200	200	200
Additive concentrate used (liters)	5	5	2
Type of additive used (select from dropdown list at right)	Unknown mixture	Unknown mixture	Unknown
Handheld fire extinguisher used?	No	No	Yes
Blanket used?	No	No	No
Number of heavy vehicles responding (engine, tanker, ladder, etc...	2	2	2
Number of light vehicles responding (like an ambulance)	1	1	1
Number of passenger vehicles responding (car, SUV)	1	1	1
Average 1-way distance vehicles travel (km)	15	15	15
% of suppressant (water + additive) released to the environment	50%	50%	50
% of fire-water runoff that goes to water treatment plant (WTP)	0%	0%	<< 25 % each
% of fire-water runoff collected & destroyed	50%	50%	
% of fire-water runoff released to soil	25%	25%	
% of fire-water runoff released to surface water	25%	25%	

Figure 12. Input data in the Fire Impact tool, where both comparison scenarios use the same firefighting tactics, but comparison scenario 2 uses a variation in guideline values.

4.2.1 Surface water guideline values

In Figure 13, comparison scenario 2 represents results after a lowering of guideline values for PAH and PFAS for aquatic life in surface by a factor 100, which means that the guidelines are stricter. Guideline values for PAHs and PFASs are chosen as parameters in the sensitivity analysis due to them providing the highest value for required dilution to reach surface water guideline values in section 4.1.2. In Figure 13, comparison scenario 1 represents the unchanged surface water guideline values. Due to a logarithmic scale used in Figure 13, total values are provided in bold above the graphs.

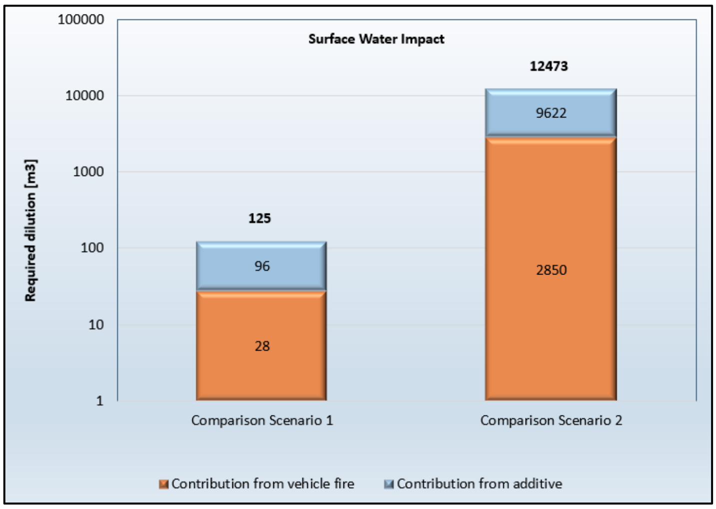


Figure 13. Volume of water required to dilute runoff water to guideline values after surface water guideline values for PAHs and PFAS are lowered with a factor 100.

Figure 13 conveys that stricter guideline values for aquatic life in surface water leads to a higher requirement for dilution to reach guideline values. A lowering of guideline values for PAHs and PFAS with a factor 100 leads to a hundredfold increase in required dilution. To further understand how trends regarding required dilution differs with variations in guideline values, the guideline values are increased by a factor 100 in Figure 14.

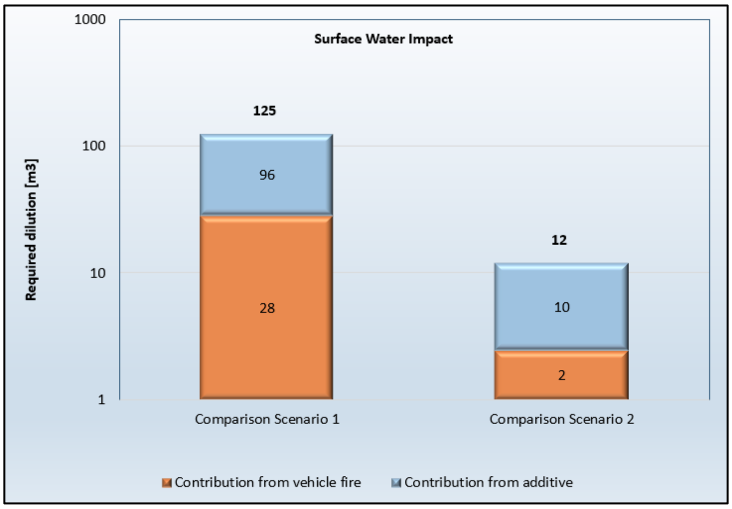


Figure 14. Volume of water required to dilute fire-water runoff to reach surface water guideline values after they have been increased by a factor 100.

Figure 14 shows that increasing the guideline values for PAH and PFAS with a factor 100 entails less strict guidelines, and therefore the required dilution volume lowers significantly. As seen in equation 4, guideline values are directly related to the amount of water required to dilute fire-water runoff to reach guideline values. Therefore, an increase in guideline values by a factor 100 leads to a lowering of the required dilution by a factor 100. Comparing Figure 13 and Figure 14 demonstrates that guideline values largely impact the results of this study. Uncertainties in surface water guideline values, and future changes to them, may alter the value for required volume of dilution greatly.

4.2.2 Drinking water guideline values

The sensitivity analysis on drinking water guidelines is applied with data representative of moraine soil. In Figure 15, comparison scenario 2 represents a lowering of guideline values for PFAS and Antimony for drinking water quality by a factor 100, which entails stricter guideline values.

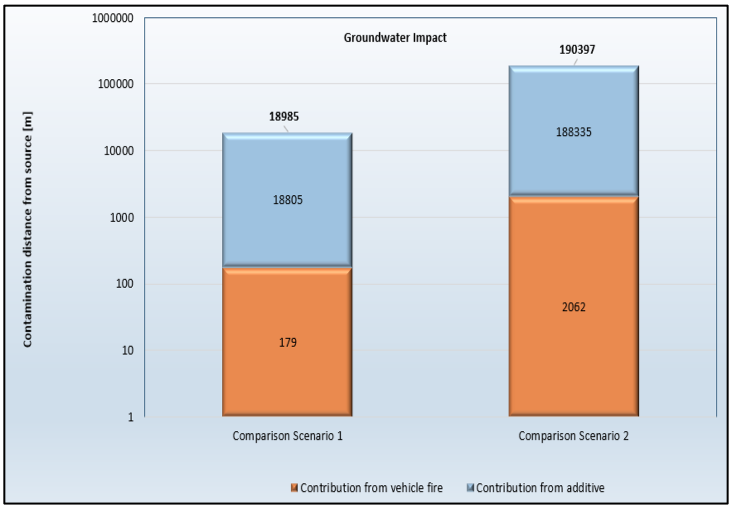


Figure 15. Distance between the vehicle fire and the furthest contaminated well for two comparison scenarios, with guideline values representing Antimony and PFAS lowered with a factor 100.

Figure 15 shows that the distance between a vehicle fire and the furthest contaminated groundwater well is larger for comparison scenario 2, which represents stricter guideline values, than for comparison scenario 1. Stricter guideline values mean that the runoff water must travel a longer distance until it is diluted enough by the groundwater flow to reach a concentration equal to guideline values. In Figure 16, the guideline values are increased by a factor 100.

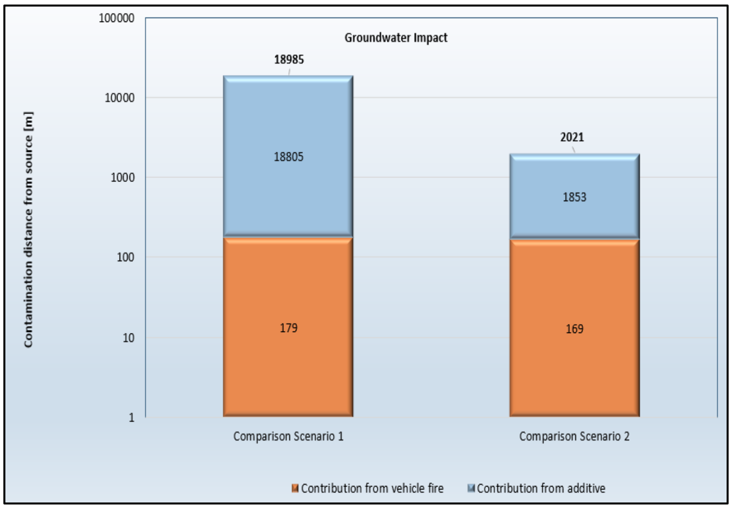


Figure 16. Distance to the furthest contaminated well, where comparison scenario 2 represents an increase in drinking water guidelines by a factor 100.

As seen in Figure 16, less strict guideline values lead to a shorter distance between a vehicle fire and the furthest contaminated groundwater well. Lowering the guideline value for Antimony led to PAHs providing results in the Fire Impact tool instead, which explains the non-linear change from comparison scenario 1 to comparison scenario 2 for the orange graphs. Results from Figure 15 and Figure 16 indicate that a variation in guideline values may largely change the required travel distance for fire-water runoff to reach dilution that matches guideline values.

4.3 Uncertainty analysis

The equations used in the Fire Impact tool that calculate expected soil excavation and distances to contaminated groundwater wells are largely dependent on soil data. Fire Impact presents results with point estimations by using specific data points for all variables used in equations. However, a range of possible soil data values are commonly presented with intervals with specified probability distributions. Furthermore, the concentrations of stressors found in fire-water runoff are gathered from a previous study’s experimental values where point values are presented.

An uncertainty analysis is performed on the Fire Impact tool, where uncertainties in parameter values are assessed by conducting a Monte Carlo simulation on expected soil excavation, the volume of water required to reach surface water guideline values, and the distance between a vehicle fire and the furthest contaminated groundwater well.

4.3.1 Monte Carlo simulation

A Monte Carlo simulation is performed with a software provided by Palisade Corporation. The software, @Risk, is an add-in feature installed in Microsoft Excel that repeatedly calculates results with 10 000 iterations using randomized sets of data points from an interval. The results are presented with probabilistic distribution sets where the likelihood of a certain outcome can be seen. A Monte Carlo simulation is conducted for data values representing moraine soil, to understand how the range of data values may impact the results in the Fire Impact tool, as well as the wetted surface area due to fire-water runoff. Furthermore, a Monte Carlo simulation is performed on the volume of water required to dilute fire-water runoff, where concentrations of stressors in the runoff water are varied within an interval of likely values.

4.3.1.1 Soil ecosystem

Soil data used in the Monte Carlo simulation for expected volume of soil requiring excavation is representative of moraine soil. The estimation of required soil excavation involves a value for the soil's field capacity. As seen in Appendix A, the value used in the Fire Impact tool is 0,25 m^3/m^3. However, as seen in Table 3, possible values range from 0,2-0,3 m^3/m^3, with a normal distribution. Soil data intervals and their corresponding probability distribution in Table 3 are gathered from (Stejmar Eklund, 2002). In the Monte Carlo simulation, it is assumed that the data interval represents a 95% confidence interval. Furthermore, the wetted soil area is assumed to be equal to a large parking lot, which is 25 m^2. In Table 3, an interval of possible values for the wetted area are assumed.

Table 3. Possible values for field capacity and wetted area, as well as their probability distributions.

Parameter	**Median**	**95% confidence interval**	**Probability distribution**
Field capacity [m^3/m$^{3]}$	0,25	0,2-0,3	Normal
Wetted area [m^2]	25	20-30	Normal

In Figure 17, a range of expected volumes of excavated soil are presented using the interval sets in Table 3, where Fire Impact parameters are identical to comparison scenario 2 in Figure 5.

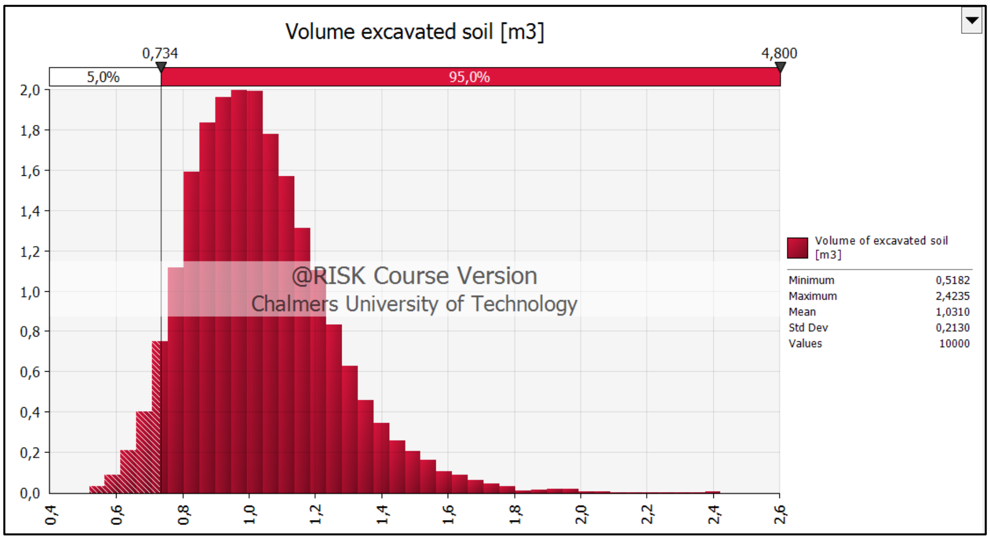


Figure 17. A probability distribution showing the range of possible volumes of expected soil excavation.

In Figure 17, the expected volume of soil requiring excavation ranges from 0,5182 m^3 to 2,4235 m^3, given repeated iterations of all data points for field capacity and wetted area. It can be seen that the values for excavated soil peak around 0,9-1,1 m^3. The corresponding value provided by the Fire Impact tool, which can be seen in Figure 7, is 1,0 m^3 which is within the range provided by the Monte Carlo simulation.

4.3.1.2 Surface water

The concentrations of stressors in fire-water runoff are given with point estimations from experimental measurements. However, it is likely that the concentrations vary within an interval. Due to a lack of interval sets for the concentrations of stressors in runoff water, an interval is assumed. The stressor that provided the worst-case result for required dilution due to vehicle fire contaminants in the Fire Impact tool was PAHs. Therefore, concentrations of PAH are used to perform the Monte Carlo simulation. In Table 4, parameter intervals for PAH corresponding to the input values in comparison scenario 2 in the Fire Impact tool in Figure 5 are shown. The median value is the concentration used in the Fire Impact tool, and the 95 % confidence interval is assumed on the basis that the concentration may vary slightly.

Table 4. Concentration interval and probability distribution representing PAH in fire-water runoff.

Parameter	**Median**	**95% confidence interval**	**Probability distribution**
PAH Concentration	0,00346	0,00192-0,00500	Normal

In Figure 18, a probability distribution of the volume of water required to dilute PAHs to reach surface water guideline values is shown.

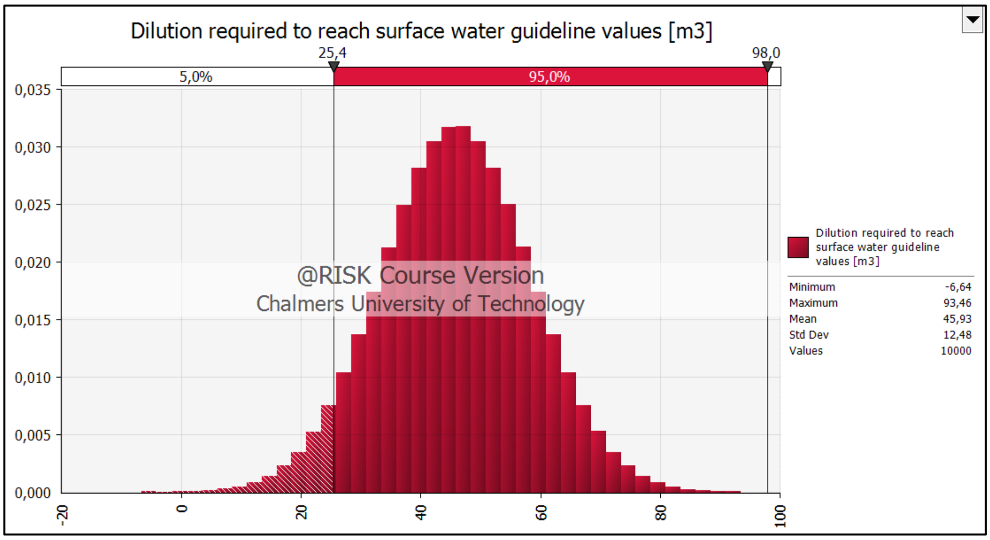


Figure 18. Probability distribution of likely values for the volume of water required to dilute fire-water runoff to surface water guideline values.

In Figure 18, it can be seen that the distribution of possible values for required dilution to reach surface water guideline values range from -6,64 to 93,46 m^3. A negative value means that the concentration of the stressor is not higher than its corresponding guideline value, which means that no dilution is required. However, Figure 18 shows a peak around 45-55 m^3. The value provided by the Fire Impact tool, which can be seen in Figure 8, is 46 m^3.

4.3.1.2 Groundwater wells

The distance between a vehicle fire and a contaminated groundwater well is calculated with equations using the following soil data; hydraulic conductivity, hydraulic gradient, groundwater recharge and aquifer thickness. Intervals and probability distributions for the soil data are presented in Table 5, with data for hydraulic conductivity and hydraulic gradient gathered from (Stejmar Eklund, 2002). Data intervals for groundwater recharge, aquifer thickness, and dilution factor are assumed. All data in Table 5 are representative of moraine soil. A Monte Carlo simulation is performed on the distance between a vehicle fire and contaminated well corresponding to Fire Impact input data for comparison scenario 1 in Figure 5. The input data in Figure 5 lead to antimony causing the furthest distance to a contaminated groundwater well, and therefore the Monte Carlo simulation uses the dilution factor for Antimony in the runoff.

Table 5. Data intervals and their corresponding probability distributions, representative of moraine soil.

Parameter	**Median**	**95% confidence interval**	**Max/min value**	**Probability distribution**
Hydraulic conductivity [m/s]	10^{-7}	10^{-8} - 10^{-6}		Lognormal
Hydraulic gradient [dimensionless]	0,01		0,05/0,001	Uniform
Groundwater recharge [m/year]	0,37	0,30-0,44		Normal
Aquifer thickness [m]	3	2-4		Normal
Dilution factor [dimensionless]	185,4	170,8-200,0		Normal

In Figure 19, a probability distribution is presented for the calculation of the distance between a vehicle fire and a contaminated groundwater well.

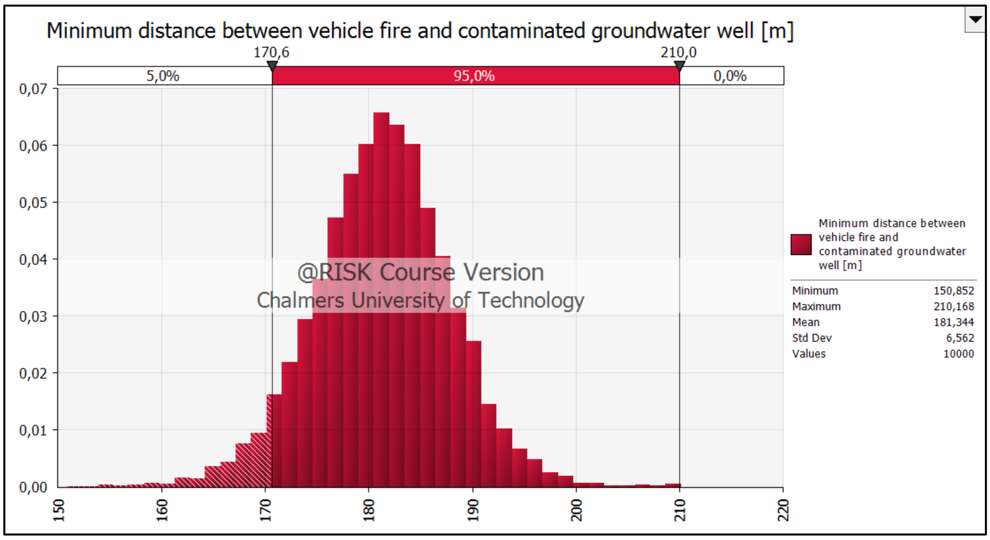


Figure 19. A probability distribution showing the possible values for groundwater transport required to dilute Antimony in polluted fire-water runoff to reach drinking water guideline values.

Figure 19 shows that the required groundwater transport to dilute antimony to drinking water guideline values is between 154,2 and 217,6 meters, where a peak can be seen around 178-184 meters. The distance provided by the Fire Impact tool, shown in Figure 11, is 179 meters.

5. Discussion

Fire-water runoff, its pathways through the environment, and its ecological impacts are complex. The runoff may negatively affect the environment in proximity to a vehicle fire in numerous ways, and therefore, the knowledge that arises from an analytical study is directed by the focus of the investigation. In this study, the focus is on three ecological entities; the soil ecosystem surrounding the vehicle fire, the aquatic life in nearby surface water, and drinking water quality from groundwater sources. The three endpoints are analyzed to gain a quantitative measurement of the ecological risks associated with fire-water runoff. The approach to determining the environmental risks with fire-water runoff stem from deriving measurable values that are readily interpreted and reviewed, so that fire extinguishment approach may be enhanced in an effective manner.

5.1 Fire Impact tool use and limitations

A highly important aspect of vehicle fire extinguishment is the characteristics of the area surrounding the vehicle. Ecological risks with fire-water runoff may change drastically if there is a water protection area in close vicinity to the vehicle, or if the soil beneath the vehicle is particularly sensitive. Moreover, there may be ditches connected to the soil directly next to a vehicle fire which could lead the runoff water away from the natural environment. Due to these unpredictable fire surroundings, the results of the Fire Impact tool should be analyzed with an understanding of the local region and how it may affect the quantitative values that the ERA provides.

The Fire Impact tool is meant to be utilized for simple predictions of environmental impacts. The equations used in the Fire impact tool are simplifications of how the stressors in fire-water runoff impact the endpoints. The results provided by the tool do not include all possible environmental impacts that can arise due to vehicle fires. Moreover, the Fire impact tool provides results using point estimations rather than a range of possible values, which may cause uncertainties in the results. Since the Fire impact tool serves as a basis for decision-making, it is essential that users of the tool are equipped with knowledge regarding the tool’s assumptions and limitations.

5.2 Interpretation of results

5.2.1 Fire Impact tool

The results of this study vary depending on how the Fire Impact tool is used, since the tool essentially offers users the opportunity to experiment with input data and analyze results themselves. Results presented in section 4.1 are obtained from experimenting with use of extinguishing water and additives. The volume of extinguishant used is an input in the Fire Impact tool that largely affects the results due to it being the source of the fire-water runoff.

Varying the input parameters in Fire Impact show that unsurprisingly, required soil excavation due to contaminated soil increases when more water is added to a vehicle fire. When the input of combined water and additive added to the fire is increased from 205 litres to 1000 litres, the value for excavated soil volume shows a tenfold increase. Naturally, an increased volume of water added to the vehicle fire entails a larger volume of water covering the soil which leads to a larger part of the soil being contaminated. The estimation of required soil excavation does not consider concentrations of stressors in the runoff water, but rather, the estimation is based on the total volume of contaminated water applied to the soil.

The required dilution to reach surface water guideline values shows different trends for use of water and additive as a suppressant. When added water is increased from 200 to 1000 litres, and the fraction of fire-water runoff reaching the surface water is increased, the required dilution to reach guideline values also increases. However, when use of additive is increased from 0 to 5 litres, the required dilution to reach surface water guidelines is greatly increased. The guideline values for the chemicals in additives, especially PFAS, are very strict compared to the vehicle fire contaminants’ guideline values, which means that even a slight increase in the volume of used additive leads to a large amount of water required to dilute the runoff.

The results comparing different scenarios for groundwater transport describe how far away from a vehicle fire that no groundwater wells may be located due to contamination. Results show that the distance to the furthest contaminated well is shorter when more water is added to a vehicle fire. This is due to the fact that stressors from the vehicle fire cannot increase infinitely, so at a certain point the mass values of the stressors are constant. When more extinguishing water is used, the stressors become more diluted by the runoff itself, which leads to a lower dilution required to reach drinking water guideline values in the groundwater flow. The distance to the furthest contaminated well due to stressors found in additives is much longer than the corresponding value for vehicle fire stressors. Again, additives contain stressors in very high concentrations and the guideline values for drinking water quality are strict for stressors found in additives.

5.2.2 Sensitivity analysis

The sensitivity analysis in section 4.2 shows that results are directly dependent on guideline values. With a variation of a factor 100 to both surface water guideline values as well as drinking water guideline values, the results also change with a factor 100. This correlation is explained by equation 4, where the concentration of a stressor is divided by its corresponding surface water guideline value.

In some cases, such as for PFAS in drinking water, the guideline values are uncertain and may change with further research in the future. Therefore, the sensitivity analysis in this study expresses how the results in the Fire Impact tool may change with future alterations to guideline values.

Furthermore, the sensitivity analysis performed on guideline values shows that a change in a guideline value may lead to another stressor becoming the critical stressor that provides results in the Fire Impact tool. As seen in section 4.2.2.2, lowering the drinking water guideline value for Antimony, which was the stressor that initially provided the result in the Fire Impact tool, led to PAH becoming the stressor providing the result in the Fire Impact tool instead.

5.2.3 Uncertainty analysis

The uncertainty analysis in this study is performed with a Monte Carlo simulation on parameter intervals. Since the Fire Impact tool uses point data for calculations, the results are shown with specific values. The Monte Carlo simulations in section 4.3 are conducted on the expected soil excavation, the water required to dilute fire-water runoff to reach surface water guideline values, and the minimum distance between a vehicle fire and contaminated groundwater wells. Soil data used in simulations are representative of moraine soil due to it being the most common soil type. Furthermore, the Monte Carlo simulation on required dilution to reach surface water guideline values is performed on PAHs due to PAHs providing the result to the corresponding analysis in the Fire Impact tool. Likewise, the stressor that provided the result in the Fire Impact tool's analysis of groundwater transport, Antimony, is used for the Monte Carlo simulation.

A Monte Carlo simulation uses all values within an interval and provides results with probability distributions. In all Monte Carlo simulations in this study, it can be seen that the most likely values, shown with peaks in the graphs, include the value provided by the Fire Impact tool.

5.3 Uncertainties

The environmental risks with fire-water runoff on aquatic life in surface waters, as well as drinking water quality in groundwater wells, are heavily dependent on guideline values. Results are based on the stressor that contributes to the highest value of required dilution, which is a relationship between the concentration of the stressor in the runoff, and the guideline value for that specific stressor. However, guideline values for all stressors are not available. Due to the lack of guideline values, there are stressors whose contributions to environmental risks that are not analyzed. In addition, some guidelines that exist have values that are still debated and are uncertain. As shown in the sensitivity analysis in this report, guideline values have a large impact on the results in the Fire Impact tool.

Furthermore, contributions to required dilution to reach surface water guidelines are measured from concentrations observed in fire-water runoff itself, and not from concentrations in surface waters. In reality, the concentration of varying chemicals will have changed during the runoff's path from the vehicle fire to nearby surface waters.

Considering groundwater transport, a simplification is made where the stressors are merely diluted with the groundwater flow. In reality, a complex process takes place where the chemicals may spread as the runoff water moves or reacts with other chemicals in the groundwater flow. These aspects are not considered in this project due to a large range of stressors that all may react differently and be subjected to different chemical reactions respectively. In addition, the assumption that the groundwater level is 3 meters below the soil surface is applied. In reality, the groundwater level differs across the country and may also change with the season. Furthermore, the minimum distance between a vehicle fire and a contaminated groundwater well may depend on the topography of the area and the direction of the groundwater flow.

Moreover, fire-water runoff is approximated as water when used in calculations, though it is a mixture of many different substances which affects the runoff's fluid characteristics. Furthermore, it is assumed that the entire volume of wetted soil due to fire extinguishment is contaminated and requires excavation. It is difficult to predict the exact volume requiring excavation due to different soils having different levels of sensitivity, as well as different availability of field capacity. Calculations in this study assume that the entire field capacity for a soil is available, which means that a maximum amount of water is retained in the soil. Also, it is assumed that fire-water runoff only infiltrates the soil vertically. It is uncertain how the expected volume of excavated soil may change due to horizontal movement of runoff water in the soil.

5.4 Validity of ERA dispersion models

The exposure of stressors to the endpoints considered in the ERA are analyzed with mathematical formulas connecting the emissions of contaminants in fire-water runoff to the environmental impacts surrounding a vehicle fire. The mathematical formulas are based on dispersion models that describe how fire-water runoff and its contents infiltrate the environment.

The dispersion models used in the ERA in this study are simplifications of the complex movements and reactions that take place in reality. To accurately validate the models and establish their precision, case scenario studies with experiments in known conditions are required. However, due to the lack of time and resources, experiments are not performed.

The dispersion models used for calculating an estimation of required soil excavation, as well as the distances between a vehicle fire and contaminated groundwater wells, are adapted from previous reports. The dispersion model used for the analysis of required soil excavation stems from a report published in 1998 by the Swedish Transport Administration and the Swedish Rescue Services Agency. Moreover, distances between a vehicle fire and contaminated groundwater wells are analyzed with a dispersion model provided by the Swedish Environmental Protection Agency. It is important to note that the dispersion models are gathered from previous studies but are adapted to fit the context of this report.

The equations used in the assessment of the volume of water required to dilute fire-water runoff to reach surface water guideline values are based on a previous study performed at RISE that established the mass of contaminants present in fire-water runoff, as well as assumptions regarding the concentrations of stressors in the runoff water. The calculations of required dilution are not based on dispersion models from other reports, as they are comparisons of concentrations of stressors in fire-water runoff and surface water guideline values.

5.5 Further studies

In this study, the stressors emitted from the vehicle fire were gathered from a previous study that analyzed fire-water runoff resulting from a vehicle fire using a petrol-powered car. An interesting addition to this study would be to include electric vehicles and investigate the environmental risks associated with fire-water runoff containing contaminants that are specific for electric vehicles, such as lithium and hydrogen fluoride from the vehicle battery.

Though not a part of the fire-water runoff, vehicle fires release contaminants in the air. Further studies may therefore include air pollution and ecological risks with air quality. Polluted air may have an adverse effect on human health, and since human health is an endpoint in this project, health effects due to inhalation of vehicle fire contaminants is an interesting field of study.

Moreover, it would be interesting to include a wider range of soil types in the study. This study analyses moraine, sand and clay. However, Sweden has a range of soil types, and data representing other soils would be an interesting potential addition to the study. Furthermore, there are many different types and variations of moraine, sand and clay, such as fine or coarse sand for example. Adding more variations of the soil types would ensure a more comprehensive study.

This project focuses on developing a tool that provides a descriptive answer to the extensiveness of environmental risks with fire-water runoff. An interesting addition to the tool would be the inclusion of potential mitigation measures, which could provide an understanding of the monetary consequences that arise from negative impacts on the environment. In addition, an interesting extension to the study would be to assess how large the probabilities are that a vehicle fire occurs on a specific location.

6. Conclusions

The environmental risks associated with fire-water runoff resulting from a vehicle fire are dependent on many factors such as firefighting tactics and fire surroundings. Fire-water runoff contains chemicals that are toxic to soils, aquatic life in surface water, and drinking water sources.

Development of a model, the Fire Impact tool, which aims to predict adverse environmental effects due to fire-water runoff, shows that decisions made by the fire-rescue service affects the severity of environmental effects on the local environment. The Fire Impact tool is used as a basis for decision making. It provides quantitative values regarding how firefighting tactics and fire surroundings impact expected soil excavation, the volume of water required to dilute fire-water runoff to reach surface water guideline values, and the minimum distance between a vehicle fire and contaminated groundwater wells.

Users of the Fire Impact tool may experiment with input data and analyze how the environmental impacts are affected by firefighting tactics to make informed decisions about vehicle fire extinguishment before a fire occurs. The results provided by the Fire Impact tool show that environmental impacts due to fire-water runoff are largely affected by the volume of extinguishant used and how developed a fire is before intervention begins. Results also show that the environmental impacts due to additives, such as firefighting foams, are significantly larger than the impacts due to contaminants stemming from the vehicle fire itself. In addition, results may vary significantly depending on which soil type that is subjected to fire-water runoff. The Fire Impact tool provides results with point estimations. An uncertainty analysis using Monte Carlo simulations shows that a range of likely values are possible depending on data taken from data intervals.

The ERA used to develop the Fire Impact tool is limited to environmental impacts due to fire-water runoff on three endpoints. It does not include all possible environmental impacts that can arise due to vehicle fires. The Fire Impact tool is most efficiently utilized with knowledge regarding its assumptions and limitations as well as how fire surroundings and other variables may influence the tool's results.

7. References

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Appendix A – Soil data

Soil data used in calculations are presented in Table 6.

Table 6. Soil data representative of moraine, sand and clay.

Soil type	**Field capacity (F_c) [m^3/m^3]**	**Hydraulic conductivity (k_v) [m/s]**	**Effective porosity (n_e) [dimensionless]**	**Hydraulic gradient (i) [dimensionless]**	**Groundwater recharge (I_r) [m/year]**	**Aquifer thickness (d_{aq}) [m]**
Moraine	0,25	10^{-6}	0,08	0,01	0,37	3
Sand	0,15	10^{-3}	0,2	0,005	0,42	15
Clay	0,42	10^{-9}	0,385			

For all three soil types, data for hydraulic conductivity as well as aquifer thickness were gathered from a report conducted by Geological Survey of Sweden (SGU) (Bovin, Vikberg, & Morén, 2015). The groundwater recharge values for both sand and moraine soil were also taken from a report by SGU (Rodhe, Lindström, Rosberg, & Pers, 2004).

Field capacity data for moraine and sand were gathered from the Swedish Geotechnical Institute (Back & Rosén, 2001), and for clay it was gathered from (Saxton & Rawls, 2006). The effective porosity for moraine and sand was taken from (Rosén et al., 1998). For clay it was taken from (Pitt, Talebi, Singer, Raghavan, & Blair, 2012). The hydraulic gradient for sand was gathered from (Rosén et al., 1998), while the hydraulic gradient for moraine was taken from (Stejmar Eklund, 2002).

Appendix B – Surface water guideline values

The extensive list of stressors found in fire-water runoff gathered from the study by Lönnermark & Blomqvist, 2006 as well as their surface water guideline values, are presented in Table 7.

Table 7. List of all stressors found in fire-water runoff and their corresponding guideline values.

Stressor	**USEPA Guideline value [mg/L]**	**CCME Guideline value [mg/L]**	**HVMFS Guideline value [mg/L]**
Particulates			
Phosphorus (P)			
Nitrogen (N)			
Total organic carbon (TOC)			
T(aliphatic)OC			
Non-polar aliphatics			
Adsorbable organic halides (AOX)			
Extractable organic halides (EOX)			
PAHs			
Fluoranthene			
Benzo(b+k)fluoranthene			
Benzo(a)pyrene		0,000015	
Indeno(1,2,3-cd)pyrene			
Benzo(g,h,i)perylene			
PAH (total)		0,000015	
Metals			
Cadmium (Cd)	0,0018		
Lead (Pb)	0,065		
Arsenic (As)	0,34		
Antimony (Sb)			
Chromium (Cr)	0,016		
Copper (Cu)	0,0048		
Zinc (Zn)	0,12		
Nickel (Ni)	0,47		
Mercury (Hg)	0,0014		
Cobalt (Co)			

Tin (Sn)			
Additives			
Glycols		192	
Magnesium salts			
Cocoamidopropilbetaine			
Alkyl sulphates			
Alkyl glucosides			
Mixture of fluorosurfactants (PFAS)			0,036
Anticorrosive additive			
Alkylamidopropilbetaine			
Xantham gum			
Biocide			
Alkylpropyl hydroxysultaine			
Glucides			

Appendix C – Drinking water guideline values

Table 8 shows the extensive list of stressors in fire-water runoff and their drinking water guideline values.

Table 8. List of stressors present in fire-water runoff and their corresponding drinking water guideline values.

Stressor	**National Food Agency of Sweden Guideline value [mg/L]**
Particulates	
Phosphorus (P)	
Nitrogen (N)	
Total organic carbon (TOC)	
T(aliphatic)OC	
Non-polar aliphatics	
Adsorbable organic halides (AOX)	
Extractable organic halides (EOX)	
PAHs	
Fluoranthene	
Benzo(b+k)fluoranthene	
Benzo(a)pyrene	
Indeno(1,2,3-cd)pyrene	
Benzo(g,h,i)perylene	
PAH (total)	0,0001
Metals	
Cadmium (Cd)	0,005
Lead (Pb)	0,01
Arsenic (As)	0,01
Antimony (Sb)	0,005
Chromium (Cr)	0,05
Copper (Cu)	2
Zinc (Zn)	
Nickel (Ni)	0,02
Mercury (Hg)	0,001
Cobalt (Co)	
Tin (Sn)	

Additives	
Glycols	
Magnesium salts	
Cocoamidopropilbetaine	
Alkyl sulphates	
Alkyl glucosides	
Mixture of fluorosurfactants (PFAS)	0,00009
Anticorrosive additive	
Alkylamidopropilbetaine	
Xantham gum	
Biocide	
Alkylpropyl hydroxysultaine	
Glucides	

Appendix D - Calculations

Due to values in calculations used in this project varying depending on inputs in the Fire Impact tool, the calculations shown in Appendix B are representative of values corresponding to comparison scenario 1 in the Fire Impact tool inputs in Figure 5. Moreover, the calculations involving concentrations of stressors correspond to concentration of PAHs, and soil data are representative of moraine soil.

Soil ecosystem

Volume of runoff water released to the environment= 102,5 L

Wetted area = 25 m^2

Retention capacity = [field capacity] = 0,25 m^3/m^3

Assuming that the entire field capacity is available, the depth that the runoff water infiltrates into the soil is calculated with equation (i).

$$D = \frac{0{,}1025}{25 \cdot 0{,}25} = 0{,}0164\, m \qquad \text{(i)}$$

The depth, *D*, is used to calculate the volume of soil wetted by fire-water runoff which is assumed to require excavation, with equation (ii).

$$V = 25 \cdot 0{,}0164 = 0{,}41\, m^3 \qquad \text{(ii)}$$

Surface water

The volume of fire-water runoff that is released to the environment= 102,5 L.

From the study conducted by (Lönnermark & Blomqvist, 2006), the mass of PAHs found in fire-water runoff is 1,7 $\cdot 10^{-3}$ g. The concentration of PAHs in the runoff water is calculated with equation (iii).

$$C_{PAH} = \frac{1{,}7 \cdot 10^{-3}}{102{,}5} = \frac{1{,}659^{-5}\, g}{L} = 0{,}01659\, mg/L \qquad \text{(iii)}$$

The surface water guideline value for PAHs is 0,000015 mg/L. The volume of water required to dilute the concentration of PAHs in the runoff water to reach surface water guideline values is calculated with equation (iv).

$$Volume_{Dilution} = \frac{0{,}01659 \cdot 102{,}5}{0{,}000015} - 102{,}5 = 113230\, L \qquad \text{(iv)}$$

Groundwater wells

The volume of fire-water runoff that is released to the environment = 102,5 L.

From the study by (Lönnermark & Blomqvist, 2006), the mass of PAHs found in fire-water runoff is $1{,}7 \cdot 10^{-3}$ g. The concentration of PAHs in the runoff water, calculated with equation (iii), has a value of 0,01659 mg/L. The drinking water guideline value for PAHs is 0,0001 mg/L. In equation (v), the dilution factor for PAHs is calculated.

$$DF_{gw-well} = \frac{1}{\left(\frac{0{,}0001}{0{,}01659}\right)} = 166 \qquad \text{(v)}$$

The relationship between the dilution factor, $DF_{gw\text{-}well}$ to the distance to a contaminated groundwater well, x_{well} is shown in equation (vi).

$$DF_{gw-well} = \frac{L \cdot I_r \cdot W}{k \cdot i \cdot d_{mix-well} \cdot (2 \cdot y_{mix-well} + W) + (W + y_{mix-well}) \cdot (L + x_{well}) \cdot I_r} \qquad \text{(vi)}$$

Where $d_{mix\text{-}well} \approx d_{aq}$ and $y_{mix\text{-}well}$ is expressed in equation (vii).

$$y_{mix-well} = \sqrt{0{,}0112 \cdot (L + x_{well})^2} \qquad \text{(vii)}$$

From equation (vi) and (vii), x_{well} may be calculated with equation (viii),

$$x_{well} = \frac{\sqrt{111999889 \cdot {d_{aq}}^2 \cdot i^2 \cdot k^2 + 1058300\,000 \cdot {I_r}^2 \cdot L \cdot DF_{gw-well} \cdot W + 2500\,000\,000 \cdot {I_r}^2 \cdot W^2} - 10583 \cdot d_{aq} \cdot i \cdot k - 10583 \cdot I_r \cdot L - 50\,000 \cdot I_r \cdot W}{10583 \cdot I_r} \qquad \text{(viii)}$$

Where d_{aq} = 3 m, i=0,01, k=31,536 m/year, m/s, I_r=0,37 m/year, L=5 m as shown in Table 6 in Appendix A. Due to the assumption that the wetted area is equal to 25 m^2, the width and depth of the contaminated area, *d* and *w*, are both 5 m.

The distance between vehicle fire and a contaminated groundwater well is calculated with equation (ix).

$$x_{well} = \frac{\sqrt{111999889 \cdot 3^2 \cdot 0{,}01^2 \cdot 31{,}536^2 + 1058300\,000 \cdot 0{,}37^2 \cdot 5 \cdot 166 \cdot 5 + 2500\,000\,000 \cdot 0{,}37^2 \cdot 5^2} - 10583 \cdot 3 \cdot 0{,}01 \cdot 31{,}536 - 10583 \cdot 0{,}37 \cdot 5 - 50\,000 \cdot 0{,}37 \cdot 5}{10583 \cdot 0{,}37} = 168{,}3\ m. \qquad \text{(ix)}$$