New Zealand Fire Service
Research Report

SCOPING PRINCIPLE FACTORS AND PARAMETERS TO INCLUDE IN AN ENVIRONMENTAL STEWARDSHIP MODEL FOR FIREFIGHTING IN NEW ZEALAND

INSTITUTE OF ENVIRONMENTAL SCIENCE AND RESEARCH

June 2017

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New Zealand Fire Service Commission Research Report Number 154

ISBN Number 978-1-92-728720-0
ISSN Number 1178-3648

Scoping Principle Factors and Parameters to Include in an Environmental Stewardship Model for Firefighting in New Zealand.

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PREPARED FOR: **New Zealand Fire Service Commission**
CLIENT REPORT No: **CSC17001**
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INSTITUTE OF ENVIRONMENTAL SCIENCE AND RESEARCH LIMITED

ACKNOWLEDGEMENTS

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1. EXECUTIVE SUMMARY

The environmental stewardship model is intended to be a tool, or part of a tool, that can be used to inform incident commanders of risks to the environment from fire-fighting operations. It will enable them to assess these risks within context of each specific incident and inform decisions regarding deployment of specific operational tactics for resolving the incident. This will be achieved through the combination of specific validated environmental modelling processes, with local geographical and environmental information.

The model will recognise that fire and fire-fighting activities interact with the surrounding environment and may cause harm through a number of routes. These routes of contamination may be broadly categorised as fire-ground run-off; gaseous and particulate emissions to air; atmospheric transport and deposition of these emissions to receiving environments. These routes lead to either primary[1] or secondary[2] contamination of soil, surface water, groundwater and built environments. The International Standard Organisation (ISO) guidelines for assessing adverse impact of fire effluents provides a framework for assessment of impacts. The standard provides broad headings identifying the environmental compartments at risk and how they may be affected. The compartments identified in the ISO 26367-1 standard will be used as a basis for assessing the parameters and factors that should contribute to an environmental fire-fighting model. The scope of this project adds the built environment to the compartments in the ISO standard.

The model parameters and factors that this project has identified contribute to the core functionality of the model. They will be used to define the interactions and mobility of contaminants arising from fire-fighting activities within environmental compartments; between environmental compartments; and relating these interactions to potential environmental impacts. The model parameters will be provided within a development framework including the local geographical and environmental data.

Each environmental compartment that would be affected by emissions from a fire, rural or urban, has been considered individually and key parameters and factors are reported. A consolidated list of each parameter or factor and the respective environmental compartment to which it is related is provided in the following table.

Factor/parameter	**Environmental compartment**
Combustion source	
Emission rate (plume)	Atmos.
Site description	Atmos., Terr., S. water
Fuel mixture	Atmos.
Fuel loading	Atmos., Terr
Combustion temperature	Atmos.

[1] Contamination arising at the source of the fire.
[2] Contaminant arising of primary effluent with the environment.

Run-off rate (contam emission rate)	Terr., S. water, G. water
Application rate firefighting water	Terr., S. water
Fire-fighting additive products	Terr., S. water, G. water
Composition of fugitive effluent	Terr., S. water, G. water
Meteorological	
Precipitation rate	Atmos., Terr., S. water, G. water
Precipitation duration	Atmos., Terr., S. water, G. water
Wind speed	Atmos.
Wind direction	Atmos.
Upper mixing limit	Atmos.
Lower mixing limit	Atmos
Environmental	
Contaminant identity	Atmos., Terr., S. water, G. water
Topography	Atmos., Terr., S. water, G. water
Proximity to critical infrastructure	Atmos., S. water, G. water.
Proximity to sensitive receiving environment	Atmos., Terr., S. water, G. water
Ecological sensitivity of receiving environment	Atmos., Terr., S. water, G. water
Soil or surface porosity/permeability	Terr., S. water, G. Water
Soil media chemistry/type (e.g. clay, loam, sand etc.)	G. Water
Background contaminant level	Atmos., Terr., S. water, G. water
Proximity to reticulated drainage (storm drains)	Terr., S. water
Size of receiving water (vol., flow rate)	S. water
Soil scouring/erosion	Terr., S. water
Minimal seasonal depth to water table	G. water

Where: Atmos. = Atmosphere; Terr = terrestrial environment, S.water = surface water; G. water = Groundwater

The factors and parameters identified in this report are considered to be significant elements of an operational environmental stewardship model. However, each environmental compartment could also be treated in isolation, used to assess the impact of activities in the immediate vicinity of an incident.

2. INTRODUCTION

2.1 SCOPE OF ENVIRONMENTAL STEWARDSHIP MODEL

The use of the term ‘environmental stewardship’ is intentional and specific. The definition of environmental stewardship as adapted from the US Department of Defense[3] is:

“The integration and application of environmental values into the mission in order to improve quality of life, strengthen civil relations, and preserve valuable natural resources.”

Similar to the place given to environmental stewardship by the US Department of Defense it is anticipated that it might be a philosophy that informs, rather than dictates, the approach of the organisation to their operations.

2.2 DEFINING THE MODEL

The environmental stewardship model is intended to be a tool, or part of a tool, that can be used to inform incident commanders of risks to the environment from fire-fighting operations. It will enable them to assess these risks within context of each specific incident and may inform decisions regarding deployment of specific operational tactics for resolving the incident. It is anticipated that this will be achieved through the combination of specific validated environmental modelling processes with geographical and environmental information and a range of pre-programmed fire-fighting options.

The model will recognise that fire and fire-fighting activities interact with the surrounding environment and may cause harm through a number of routes. These routes of contamination may be broadly categorised as fire-ground run-off, gaseous and particulate emissions to air; atmospheric transport and deposition of these emissions to receiving environments. These routes lead to either primary[4] or secondary[5] contamination of soil, surface water, groundwater and built environments. The International Standard Organisation (ISO) guidelines provides a framework for assessment of impacts of fire effluents. The standard provides broad headings identifying the environmental compartments at risk and how they may be affected. The areas identified in the ISO 26367-1 standard will be used as a basis for assessing the parameters and factors that should contribute to an environmental fire-fighting model.

The objective of this report is to identify the key environmental and physical parameters and factors that would be fundamental in the development of an operational decision-support tool. The model parameters and factors that this project identifies will contribute to the core functionality of the model. They will be used to define the interactions and mobility of contaminants arising from fire-fighting activities within environmental compartments; between environmental compartments and relating this to potential environmental impacts. The model parameters are provided within a development framework that establishes a series of assumptions regarding the peripheral data available for data interpretation.

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[3] Definition of the term environmental stewardship - US Dept of Defense – accessed 03/10/16
[4] Contamination arising at the source of the fire.
[5] Contaminant arising of primary effluent with the environment.

A number of valuable data sets are already compiled and maintained by the fire-fighting agencies within New Zealand. These datasets appear to be split to represent the rural or urban operational environments. The content of these datasets may, in many cases, be of relevance to delivery of an environmental stewardship model. The range of data available in these resources is discussed in the following sections.

2.2.1 Rural fire

In New Zealand, rural fire can be broadly categorised as fire in forest, grass or scrub, whether these be natural or managed environments such as reserves or farms. These incidents may be attended by the National Rural Fire Authority (NRFA), Department of Conservation, or New Zealand Defence Force, with NRFA having the largest number of staff. The NRFA has a wide range of environmental information resources available on the NRFA website[6]. The resources (NRFA 2016) cover:

- Composite Fire Danger class (FDC) - Indication of the ease of suppression (or the difficulty of control) of fire burning in the predominant local fuel type.
- Forest fire danger class - Indication of the ease of suppression (or the difficulty of control) of fire burning in the forest fuel type.
- Grass fire danger class - Indication of the ease of suppression (or the difficulty of control) of fire burning in the grass fuel type.
- Scrub fire danger class - Indication of the ease of suppression (or the difficulty of control) of fire burning in the scrub fuel type.
- Fine fuel moisture content (FFMC) - An indicator of the relevant ease of ignition and flammability of fine fuels.
- Duff moisture content (DMC) - A rating of the average moisture content of loosely compacted organic layers of moderate depth.
- Drought code (DC) - A rating of the average moisture content of deep, compact, organic layers. This code is a useful indicator of seasonal drought effects on forest fuels and amount of smouldering in deep duff layers and large logs.
- Initial spread index (ISI) - Combines the effect of wind speed and the Fine Fuel Moisture Code, providing a numerical rating of fire spread rate.
- Build-up index (BUI) - Combines the Duff Moisture Code and Drought Code and represents the total amount of fuel available for combustion.
- Fire weather index (FWI) - Combines the Initial Spread Index and Build-up Index to indicate the intensity of a spreading fire (on level terrain).

Each resource contains regularly updated, geographically displayed information providing user-friendly visual representations of the risk levels for each category. Base data is presented in fire weather data tables that are updated hourly. These data are used in the calculation of fire risk that is communicated to the public through television, radio and

[6] NRFA - Fire Weather System page accessed 19/12/16

billboard media. It is also used to assist NRFA staff in decision making when attending incidents.

Further resources have been developed in New Zealand and overseas. The Scion Rural Fire Research group[7] has developed a number of New Zealand specific resources that are used in support of decision making on the fire-ground. These resources can be found on the website and include:

- New Zealand Fire Behaviour Prediction Manual
- Fire Behaviour Toolkit
- Scion Fire Behaviour App
- Prometheus – A Canadian wildland fire growth model, adapted for New Zealand by Scion.

All of the resources have been developed with the aim of prevention of fire and improving fire-fighting outcomes; they contain an array of valuable data collections. There is little or no content within these tools with regard to environmental stewardship, other than the value of extinguishing a fire as quickly as possible. However the presentation of the Fire weather tables as geospatial data in the NRFA resources provides a valuable platform for expansion into mapping of sensitive environments.

2.2.2 Urban fire

Through the urban centres of New Zealand, fires are attended by the New Zealand Fire Service (NZFS). It should be noted that NZFS also attend a very wide range of other incidents and situations. The NZFS maintains the SMART Map database. SMART Map holds geospatial data that, amongst other content, includes data for:

- Water infrastructure (mains and hydrants)
- Incident type
- Administrative boundaries
- Lifeline utilities (gas)
- Major Hazard facilities
- Fire season status (by jurisdiction)

Locations can be searched for, and visualised on screen using place name, street address, road name, CAD number (computer aided despatch No.), or 'other' (which includes *x,y* coordinates, or map grid reference).

The NZFS 'Foundation for Mobility' project is developing the capability to deliver the functionality in SMART Map, into a tool that can be used in incident response. The project will "provide frontline fire fighters with crucial data that will assist them in responding to incidents: incident information, building plans, maps, water supply locations, and site reports at their fingertips on one device"[8]. The facility provided by this decision support tool to

[7] Scion : Rural Fire Research accessed 19/12/16
[8] NZFS: Foundations for Mobility Project - Tech Solutions by Fire Fighters for Fire Fighters accessed 20/12/16

integrate multiple layers of data and provide frontline firefighters with timely information would also be valuable in the context of environmental stewardship decision making.

3. FIRE EFFLUENT

3.1 EFFLUENT GENERATION

During each stage of fire development; ignition, growth, fully developed and decaying or extinguishing, a range of different compounds are produced. The make-up of this range of compounds will be determined by a number of factors including fuel type, fire temperature, and oxygen availability. Additionally the choice of fire-fighting technique will produce further effluents, through modification of the fire-behaviour and washing out of both burned and unburned products from the fire ground.

These interactions may cause effluent to be released to a receiving environment through:

- Direct gaseous and particulate emission to atmosphere
- Spread of atmospheric emissions
- Deposition of atmospheric emissions
- Soil contamination, and
- Groundwater and surface water contamination

Each effluent product will have specific distribution characteristics, determined by the physical form and the mode of mobilisation

Primary effluents are products arising from the fire source. Secondary effluent are produced from interactions of primary effluents with the environment (ISO 2011).

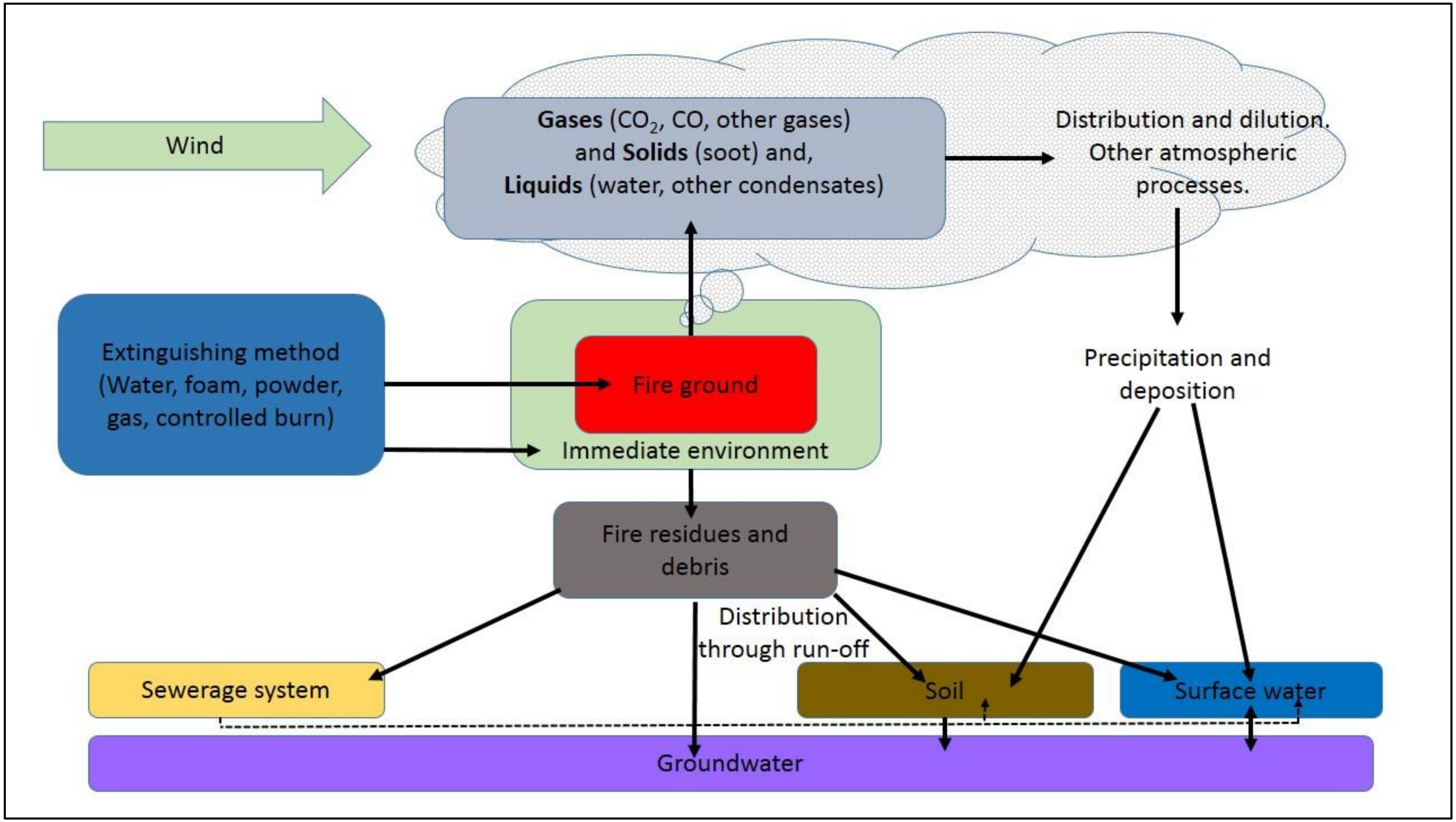

Figure 1 - Emission pathways for fire effluents (adapted from ISO (2011))

4. EFFECT OF INTERVENTION AND THE ENVIRONMENTAL CYCLE OF POLLUTANTS

4.1 EMISSIONS TO AIR

Emissions to air take the form of smoke plumes and gas releases. Smoke plumes are a mixture of combustion gases, steam and particulate matter. The temperature of the fire will determine the relative composition of each of these elements within the plume. The dispersion of the plume as it enters the atmosphere introduces elevated concentrations of airborne pollutants that decrease as the plume travels and is mixed over distance. The plume also increases the risk from exposure to these pollutants and may reduce visibility for fire-fighters or members of the public.

The composition of a smoke plume will vary depending on the fuel type and fuel loading. Examples of toxic pollutants determined in plumes are described in ISO/DIS26367-2 they are summarised in Table 1 below.

Table 1 - Pollutant emission data from various types of fire

Fire type	Major pollutants	Reference
Domestic dwelling (fully furnished rooms)	**Inorganic gases -** Carbon dioxide (approx. 900 g/kg); Hydrogen Chloride (approx. 1 g/kg) **Volatile Organic Compounds (VOC)** – Benzene (approx. 1 g/kg); toluene, phenol, styrene and benzonitrile (approx. 0.1 g/kg each); **Poly-aromatic hydrocarbons (PAHs)** (approx. 1 g/kg [9]) **PCDD/PCDF** [10] (0.0022 – 0.033 µg/kg TCDD-TEQ[11])	(Simonson, Blomqvist et al. 2000, Andersson, Simonson et al. 2003)
Vehicle fire (laboratory test burn of a car)	**Inorganic gases** - Carbon dioxide (265 Kg, 2400 g/kg); Hydrogen Chloride (1.4 kg, 13 g/kg); Sulphur dioxide (0.5kg, 5 g/kg)	(Lönnermark and Blomqvist 2006)

[9] Approximately equivalent to 0.02 g/kg Benz-alpha pyrene (BaP) toxic equivalent quotient
[10] Polychlorodibenzodioxin and polychlorodibenzofuran
[11] Trichlorodibnzodioxin Toxic equivalent quotient

	VOC – Benzene (322 g, 3.0 g/kg); toluene, phenol, styrene and benzonitrile 0.2 -0.7 g/kg **PAHs** (119 g, 1.1 g/kg) **PCDD/PCDF** (71 – 87 µg TCDD-ITEQ) **Metals** – zinc (3200 mg/kg); lead (820 mg/kg); copper (27 mg/kg); antimony (15 mg/kg) and manganese (5.7 mg/kg) as mass loss yields.	
Deep-set domestic waste fires (landfill simulation)	**PAHs** (approx. 0.1 – 0.6 g/kg) **PCDD/PCDF** (0.02 – 0.04 µg/kg) **PCB** (14 – 140 µg/kg PCB7, 0.001 – 0.06 µg/kg WHO-TEQ) **Metals** – Zinc dominating (in mass loss yields)	(Lönnermark, Blomqvist et al. 2008)
Wildfire. (USA, monitored approx. 30km from burn site)	**CO** 1 – 5 mg/kg **Formaldehyde** 0.002 – 0.01 mg/kg **Acetaldehyde** 0.001 – 0.01 mg/kg **$PM_{2.5}$** 70 – 120 µg/m^3	(Na and Cocker 2008)
Peat fire	**VOC –** Dichlorodifluoromethane (0.001 mg/kg); chloromethane (0.02 – 0.03 mg/kg); bromomethane (0.001 – 0.002 mg/kg); Benzene (0.02 – 0.03 mg/kg); Toluene (0.007 – 0.01 mg/kg);	(Blake, Hinwood et al. 2009)

4.1.1 Fire plume zone

The fire plume zone is the area over which a plume disperses. The size of this area is determined by the amount of primary effluent generated, temperature of the fire, topography of the land beneath and surrounding the plume; and meteorological conditions. Fire-fighting strategy and availability of resources can also impact the plume dispersion. A fast, high volume water attack may extinguish a fire quickly, reducing the atmospheric pollution. However in other instances a controlled burn may be appropriate if a fire is too large to be quickly extinguished, as this may minimise the number of pollutants in the fire plume. Whereas a fire attack with insufficient or sporadically available water may lead to the generation of products of incomplete combustion in the plume.

Short-term environmental impacts are most significant in this zone. Local geographical features, natural and manmade can limit the dispersion of the plume and facilitate rapid deposition of contaminant products.

4.1.2 Plume deposition

The plume deposition zone is the area beneath the fire plume zone. Deposition of combustion products occurs through:

- Physical sedimentation; where soot particles drop out of suspension due to their own size and weight. These can be single particles or aggregations of particles that will drop out due to their mass when conditions allow. Conditions affecting the rate of sedimentation will be plume temperature, ambient temperature, wind speed, topographical features of the local environment and meteorological effects, such as inversion layers and different plume types.
- Wash-out of soot particles and gaseous and liquid combustion products. The action of rain will accelerate the deposition of combustion products. This is through both physical 'collection' of products during precipitation; and through adsorption of hydrophilic species into rain drops during formation or during passage through a plume.

4.1.3 Model types

A number of different models are available for estimating the distribution and behaviour of atmospheric contaminants. A representation of the modelling process is given in Figure 2, stage 1 – data input, is the key area relevant to this project. However a brief description of some of the types of model available is also provided in this section.

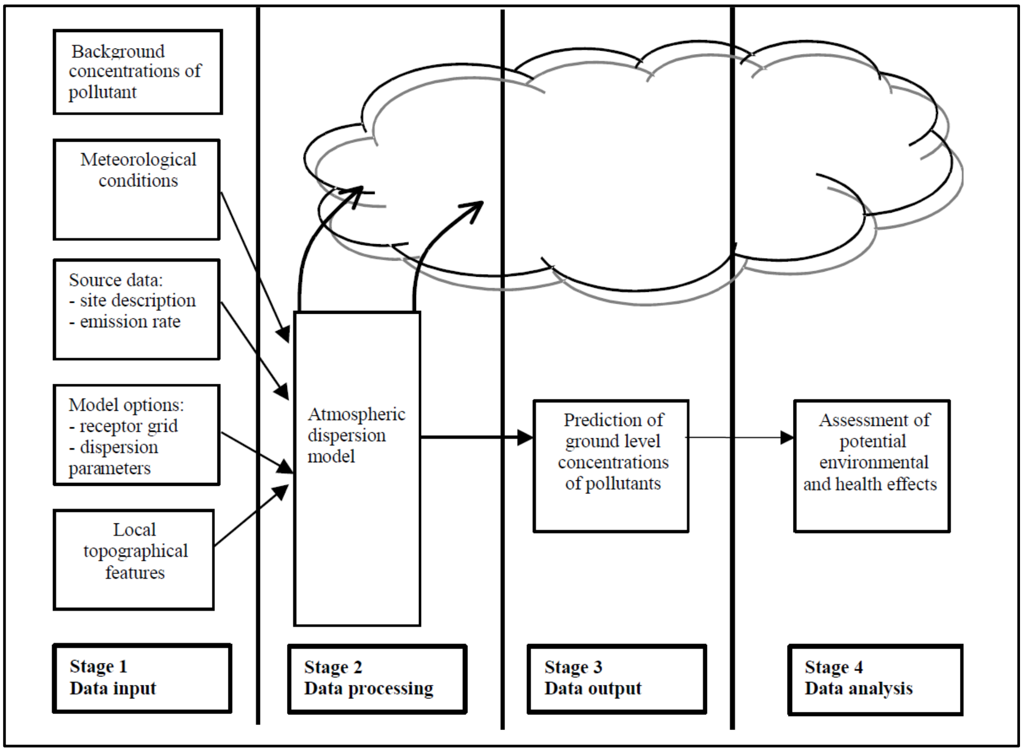

Figure 2 - Overview of air pollution modelling procedure

The following descriptions of models are drawn from Goodrick *et al* (2013)

Box Model

This approach uses a single box to represent the spatial distribution of an airshed. The upper limit being the highest point that the plume reaches; and the horizontal dimensions being the length and width of the plume. Box models assume that there is instantaneous mixing and homogenisation of contaminant distribution throughout the volume of the box. This assumption is a gross simplification of the complex spatial and temporal processes that constitute large-scale mixing of solid, liquid and gas phase products.

Gaussian plume model

Gaussian plume models use a point source or area to define the origin of a smoke plume. The transport of smoke in the atmosphere is modelled assuming uni-directional travel driven by wind that is constant over time. Dispersion from crosswind is modelled using a Gaussian distribution. Gaussian plume models do not accommodate variances or violation of these steady state conditions. Hence, the impact of weather systems or topographical features cannot be included in the determination of the plume spread.

Puff models

Puff models use a series of time-resolved, independent ‘puffs’ released from a source to create the model. Each puff is of a specified initial volume and hence contains a specific loading of contaminant. Over time, puffs are transported by wind that can vary in direction and strength. Additionally, the volume of puffs increases with time due to diffusion of the original specified volume through entrainment of ‘clean’ air.

Puff models are valuable in tracking the potential transport of contaminants as they allow the additional complexities introduced from meteorological and topographical factors to be included in the calculations, thus leading to a more detailed representation of the practical outcomes. Puff models can also include time-varying emissions sources, this allows resolution of contaminant emissions through the stages of fire development.

Particle models

“In particle (or random walk) models there is no numerical diffusion of the pollutants. Each particle represents and infinitesimal air parcel containing a fixed mass of pollutant. Individual particles respond to the mean and turbulent components of the wind field making diffusion a direct result of the movement of particles rather than a parameterised process. Pollutant concentrations are then determined by examining the number of particles within a given volume.”

Particle modelling theoretically provides direct simulation of particle/contaminant dispersion. This dramatically increases the computing requirements for processing and producing data. The increased computational requirements also increase the time required for models and predictions to be prepared and the financial cost of doing so.

4.1.4 Key factors and parameters for development of atmospheric model of contaminant transport

The availability of a number of atmospheric contaminant transport model types provides for greater or lesser degrees of complexity to be represented. However, the fundamental data that are required to populate the model remains reasonably consistent; these are presented in brief in Table 2.

Table 2 - Atmospheric contaminant transport modelling parameters

Parameter	Description
Combustion source	
Emission rate	Rate of release of combustion product to atmosphere (m^3/hr)
Site description	Locale and type of fire, for example wildfire, forest fire, urban structural (vented or unvented), vehicle fire
Fuel mixture	The range of combustible products involved in an incident
Fuel loading	The amount of each specific combustible product involved in an incident
Combustion temperature	The temperature of the fire at a specific point in time. This will increase and decrease through the life of the fire.
Meteorological	
Wind speed	Speed of wind – this will vary with time and altitude
Wind direction	Direction of wind – this will vary with time and altitude
Upper limit mixing layer	The upper height limit of combustion product plume
Lower limit mixing layer	The lower height limit of combustion product plume
Precipitation rate	Rate of rainfall (mm/hr)
Precipitation duration	Length of time of rain event (hr)
Environmental	
Topography	The artificial and natural geographical features of an area
Background contaminant level	The existing level of contaminants prior to introduction of combustion products from an incident.
Critical infrastructure	Proximity of roads, particularly with regard to reduction of visibility from smoke plumes.

4.2 EMISSIONS TO TERRESTRIAL ENVIRONMENT

"Contamination of the terrestrial environment occurs both from direct emissions from the fire and emissions prompted either by fire-fighting or post-fire clean-up activities, or through interaction with weather (e.g. wind and rain). Atmospheric releases also effect the terrestrial environment through deposition of pollutants, which can be exacerbated through the effect of weather" (ISO 2011).

The main impacts from fires for the terrestrial environment will arise from the mobilisation of contaminants from the site of the fire. Excepting the atmospheric dispersal route, dispersal of contaminants from the fire-ground will be relatively limited. These limitations will be greatly expanded when fire-fighting activities are undertaken. The use of water as a fire fighting resource will increase the distribution of contaminants greatly through fire-ground run-off. Additionally, the optional inclusion of a range of additive products to fire-fighting water will introduce further chemicals to the fire-ground run-off. These chemicals will amend the composition and potentially the physical and physicochemical characteristics of the effluent. Fire-fighting additive products contain a range of chemical compounds, each of which is intended to fulfil a specific role within a product. Key amongst these compounds are surfactant products, these aid penetration of water into otherwise water-resistant materials by reducing the surface tension of water droplets thereby allowing water to be absorbed by resistant materials. This property is of significance when released to the environment in fire-ground run-off as the enhanced properties may allow deeper penetration of contaminants into sub-surface zones (Britton 1998), or alternatively may retard progress of the contaminant through the zone of saturation (Allred and Brown 2001). It may also enable contaminants to cross hydrophobic boundaries such as leaf surfaces (Hess and Foy 2000) or insect exoskeletons (Ebeling 2012) potentially allowing direct introduction of contaminant chemicals into the ecological food chain. Flame retardants used in rural fire-fighting commonly contain high levels of nitrogen and phosphorous compounds. These also act as fertilisers when applied to land, leading to increased growth of plants (Larson and Duncan 1982, Couto-Vasquez, Garcia-Marco et al. 2011). In greater concentrations it has been shown that growth of indigenous species may be inhibited (Couto-Vasquez and Gonzalez-Prieto 2006) and invasive species promoted (Martin, Waller et al. 2016).

The topography of an area will exercise influence in determining the direction of travel of fire-ground run-off; the run-off will almost entirely go downhill, with perhaps a small amount heading a short way uphill through immediate sub-surface capillary action. The surface integrity of an area will also have a significant impact on the distance of surface travel and the contaminant concentration levels that will result. The more permeable a soil or surface, the quicker fire-ground run-off will penetrate the surface and have progress slowed. This process leads to greater or lesser degrees of localised contamination, and potential for transfer to groundwater.

Opposing conditions are seen in urban environments where large areas are covered in relatively impermeable products, designed to facilitate run-off of rainwater to storm drains, streams or rivers and ponds. The construction of the urban environment offers routes for transport of significant quantities of fire-ground run off away from the seat of the fire and into sensitive infrastructure or ecological areas (Meharg 1994, Martin, Tomida et al. 2016). However, these same factors may also offer opportunity for more effective mitigation to be put in place to prevent these sensitive resources being impacted.

The ecological sensitivity of a receiving environment will obviously vary with location. With respect to terrestrial contamination some of the more significant exposures may occur in the rural environment. New Zealand’s rural areas host a wide array of environments and unique ecologies. These require careful management of human impacts to prevent disturbing their ecological balance; to maintain their biodiversity or sustain the biological heritage. Anecdotal examples of the impact of fire-fighting practices on sensitive environments, such as New Zealand high country environments are plentiful. Anecdotal descriptions of ‘lush green’ growth across the high-country slopes that coincide with the areas where nitrate-rich flame-retardant products have been applied are plentiful, but underreported in literature. However, the implications of these descriptions is that the application of flame-retardants provides support to the growth of species that would not typically be viable in the environment, thereby adapting the ecology of a delicately balanced system.

The range of parameters that would be relevant to establishing the potential impact of fire-fighting activities on the terrestrial environment are presented in Table 3. The parameters represent both operational activity data and base environmental data regarding the local environment.

Many of the environmental data required to populate the model databases are curated by Landcare Research within the 'Soil and Landscapes' portfolio of work. Of particular relevance is the work of the Strategic Land-use and Pedology group[12]. This group performs research to populate the following databases of interest:

- S-map; which provides, amongst other data, definition of NZ soil families and soil landscape models; and
- Soil and the movement of water; providing spatial prediction of entry, storage and release of water, and the fate of nutrients or contaminants in the environment.

Such data would potentially provide geographically specific information regarding the soil type and contaminant attenuation factors. These data would be valuable for supporting decisions regarding the type of mitigation to be undertaken.

[12] Strategic land–use & pedology | Soils & landscapes | Landcare Research

Table 3 - Terrestrial contaminant transport modelling parameters

Parameter	Description
Combustion source	
Application rate	Rate and duration of application of fire-fighting water (L/s)
Additive products	Type of product, induction rate (%), duration of application (s)
Run-off rate	Volume of fire-ground run-off produced from application rate (L/m)
Site description	Locale and type of fire, e.g. wildfire, forest fire, structural (vented or unvented), vehicle fire
Fuel mixture	The range of combustible products involved in an incident
Fuel loading	The amount of each specific combustible product involved in an incident
Fugitive effluent	Unburnt fuels products or products contained at fire site released in fire-ground run-off – e.g. diesel, bleach, cooking oil, milk
Meteorological	
Precipitation rate	Rate of rainfall (mm/hr)
Precipitation duration	Length of time of rain event (hr)
Environmental	
Topography	The artificial and natural geographical features of an area
Soil (or surface) porosity	Rate of permeation of fire-ground run-off through surface to sub-surface layers
Proximity to sensitive receiving environment	Actual path distance to sensitive area (determined by topography)
Sensitivity of receiving environment	The ecological or heritage value of the receiving environment
Proximity to reticulated drainage	Actual path distance to storm drain-head
Background contaminant level	The existing level of contaminants prior to introduction of combustion products from an incident.

4.3 EMISSIONS TO SURFACE WATER

In general the release of secondary effluent to surface water will be a localised event; the exception to this being situations where aquifer systems contribute to recharge of surface waters. The release of primary effluent from fire plumes to surface water is most likely to be over a larger area, this will produce relatively diffuse and low-level contamination. The release of fire-ground run-off to surface water, if not prevented, is likely to have serious consequences. The consequences range from high level short-term contamination impacting on the biota, to contamination of drinking-water supplies.

4.3.1 Surface Water

In most cases the route of contaminants to surface waters will be over the terrestrial environment. In rural operations this will be solely over soils and natural materials. Many of the factors that have been identified for emissions to the terrestrial environment will also be key factors in the transport of contaminants to surface water. Additional factors will include the collection and transport of scoured or eroded soils to the receiving water. These soils may have pre-existing levels of contamination that will add to the chemical contaminant loading in the run-off. The factors considered most relevant are identified in Table 4

In urban operations the transport will frequently be over sealed, impermeable surfaces leading either directly to a receiving water, or to storm drains that discharge to a receiving water environment.

Table 4 Surface water contaminant transport modelling parameters

Parameter	Description
Combustion source	
Application rate	Rate and duration of application of fire-fighting water (L/s)
Additive products	Type of product, induction rate (%), duration of application (s)
Run-off rate	Volume of fire-ground run-off produced from application rate (L/m); this may be mitigated through losses in transport over intervening ground
Site description	Locale and type of fire, e.g. wildfire, forest fire, structural (vented or unvented), vehicle fire
Fugitive effluent	Unburnt fuels products or products contained at fire site released in fire-ground run-off – e.g. diesel, bleach, cooking oil, milk. This will include scoured/eroded soil and its' entrained pre-existing contaminants carried to receiving water
Meteorological	
Precipitation rate	Rate of rainfall (mm/hr)
Precipitation duration	Length of time of rain event (hr)
Environmental	

Topography	The artificial and natural geographical features of an area
Soil or surface porosity	Rate of permeation of fire-ground run-off through surface to sub-surface layers
Proximity to receiving water	Actual path distance to receiving water (determined by topography)
Size of receiving water	Volume, flow rate
Sensitivity of receiving environment	The ecological or heritage value of the receiving environment
Proximity to reticulated drainage	Actual path distance to storm drain-head
Background contaminant level	The existing level of contaminants prior to introduction of combustion products from an incident.
Soil scouring/erosion	Potential for soil to be physically displaced and carried to receiving water.

4.4 EMISSIONS TO GROUNDWATER

Vulnerability of groundwater to contaminants is site specific. Infiltration of fire-ground run-off through the unsaturated zone is the most probable route (but not exclusive route) via which contaminants can impact upon groundwater. Upon entering the groundwater system contaminants can become distributed via a number of different artificial or natural transport mechanisms. Depending upon site specific conditions, impacts on the subsurface environment can be long-term, potentially lasting decades, due to the high storage potential and slow rates of flow and contaminant transport that commonly apply to groundwater systems. Contaminants carried in fire-ground run-off may undergo chemical transformation through chemical or biological processes whilst in transit to, and resident in groundwater. The presence in aquifer systems of compounds used in class B fire-fighting foam has been well documented, in particular the presence of per- and polyfluorinated compounds (Moody, Hebert et al. 2003, Houtz, Higgins et al. 2013, Zareitalabad, Siemens et al. 2013, Lee and Mabury 2014, Barzen-Hanson and Field 2015, Anderson, Long et al. 2016, Willach, Brauch et al. 2016).

4.4.1 Conventional approaches for assessing groundwater vulnerability

There are three classes of methods for assessing groundwater vulnerability from land-based pollution sources, which can provide input to an assessment of risk, these are (NRC 1993):

- Overlay and index methods that involve combining various mapped physical attributes. Such methods are useful for making large-scale assessments, although they do not attempt to fully describe processes that lead to contamination.
- Process-based simulation models that attempt to predict contaminant transport in both space and time. They are really only suited for making assessments at a localised scale.

- Statistical methods, which rely on information about where groundwater has been contaminated and, like process-based methods, are scale-specific.

For the purposes of developing a model for a practical or operational application that would assess risk at the national scale, overlay and index methods are definitely the most appropriate and pragmatic approach to use. They are executed within a Geographical Information System (GIS) framework.

The general principle is to identify physiographical factors of interest that are available as a map layer. Each factor (map layer) is assigned a weight, proportional to its perceived importance in terms of affecting potential vulnerability. Normally, the most significant factor is assigned the highest weighting. Discrete zonal properties within a layer (whether they be numerical ranges or specific classes) are categorised and assigned a numeric rating. Again, the numeric value for the rating reflects the relative influence on aquifer vulnerability or pollution potential. The overall relative pollution potential/vulnerability of the system at a discrete geospatial point is then evaluated from the summed product of the various weighted ratings. The basic principle is demonstrated in Figure 4.

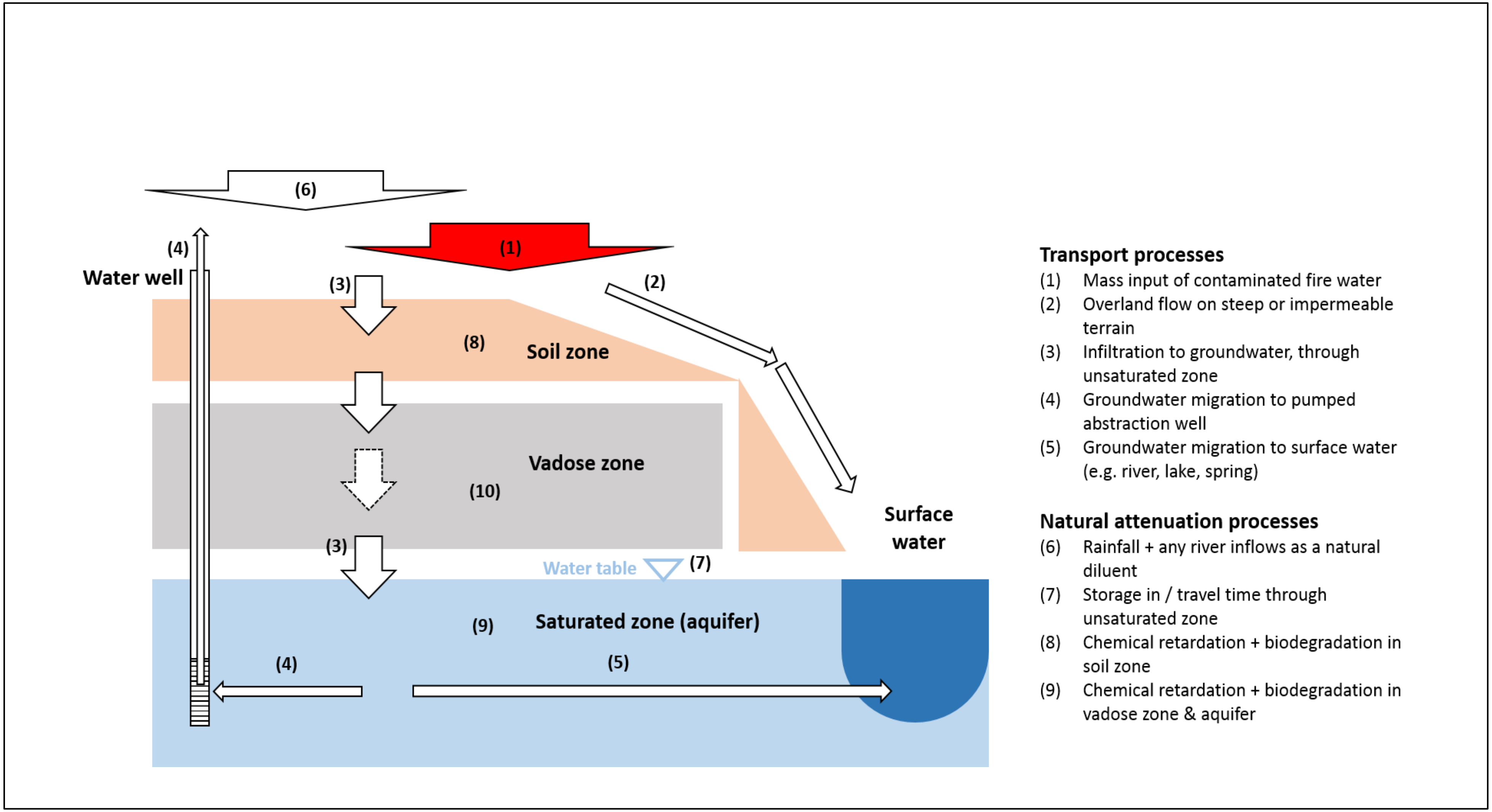

Figure 3: Simplified systems model for contaminant transport from land-based fire-fighting activities, as related to groundwater.

4.4.2 Notes on existing overlay and index methods used in NZ

The DRASTIC system is a popular means for evaluating groundwater pollution potential at large scales that was originally developed for the USA (Aller, Bennet et al. 1987). It provides a good starting point. DRASTIC is a mnemonic for a set of seven mapped indices used for assessing groundwater vulnerability, these being:

D - Depth to water [table]

R - (Net) Recharge

A - Aquifer media

S - Soil media

T - Topography (slope)

I - Impact of the vadose zone

C – [Hydraulic] Conductivity of the aquifer

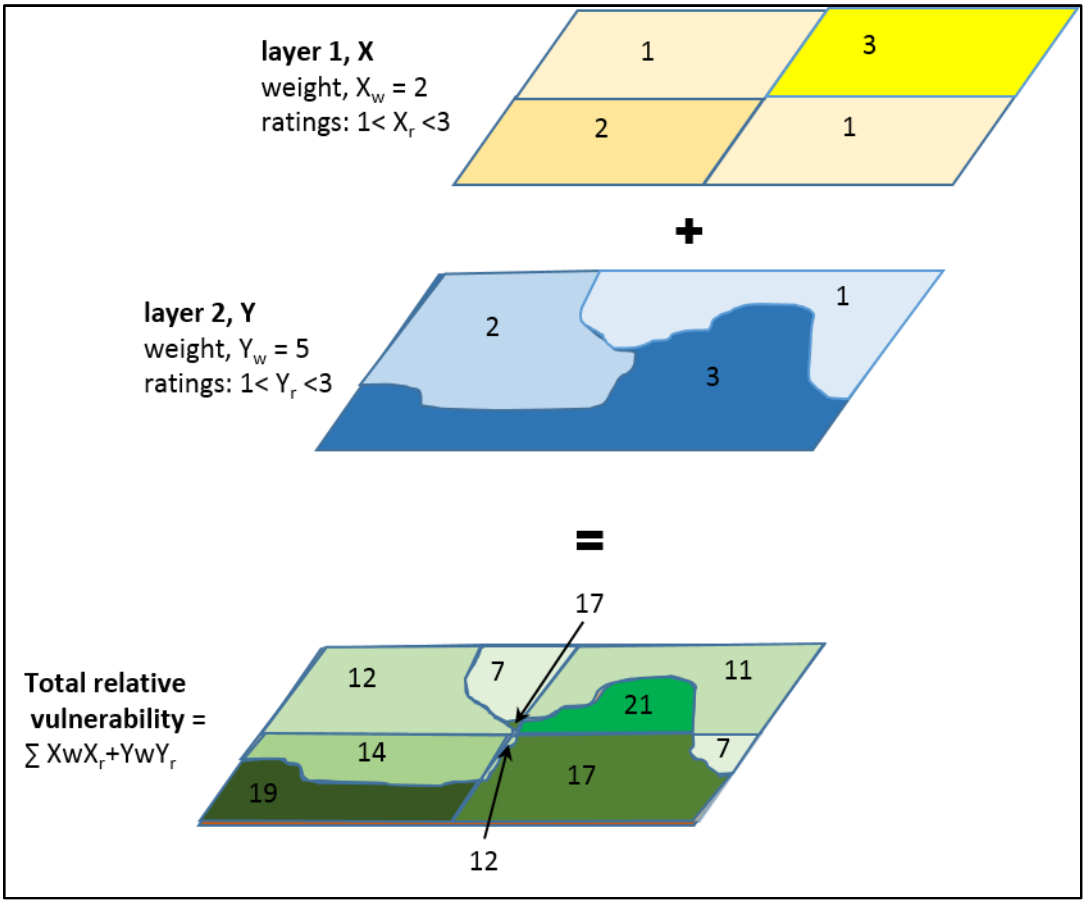

Figure 4: Generalised form of overlay-index methods applied to map vulnerability. A layer (factor) represents a mapped physiographical unit (e.g. geology, depth to water etc.) that is given a relative weight. Discrete features within a layer are indexed and applied an individual rating. In the example shown, the total vulnerability is evaluated from the weighted sum of two layers.

A few examples can be found of DRASTIC having been applied at regional scales within NZ for assessing pollution potential from pesticides (Close 1993, Webb and Lilburne 1999) and most recently nitrate (Pearson 2015).

A document by Sheppard, Brown et al. (that can be found on-line and appears to be a Landcare Research archive, reports on an alternative index and overlay method they developed for contaminated land-water systems, tailored to NZ conditions. Sheppard et al.'s objective was to provide a means for assessing environmental risk to surface waters from sites contaminated by hydrocarbon and/or metals and accidental spills, at the national level. Groundwater vulnerability was an implicit factor in the assessment. The methods they explain used DRASTIC as a starting point, but modified and extended the original factors, weightings and methods of combinations in DRASTIC to suit the specific vulnerability problems they addressed. Details on ratings and weights they assumed for the various factors are explained in the report. Unlike the approach used in DRASTIC that computes vulnerability by adding weighted factors together (as shown in Figure 4), Sheppard et al.'s approach multiplied weighted factors. The thirteen-plus factors they considered were split into three categories and are given in Table 5.

It has not been possible to ascertain what became of the vulnerability assessment method described by Sheppard et al. (2007), whether it proved effective or was ever adopted as a routine practical method used in NZ. It is conceivable however that the work conducted by Sheppard et al. informed the Risk Screening System that is published by the Ministry for the Environment (MfE) as part of the NZ Contaminated Land Management Guidelines No. 3[13]. The MfE Risk Screening system is available as a spreadsheet application and assessments are conducted manually on a site specific basis.

Table 5: List of factors for overlay-index environmental vulnerability assessment method described by Sheppard et al.

General factors	Site specific factors	Other factors
(1) Rainfall (2) Direct discharge [to surface water] (3) Special site specific factors [that could conceivably enhance contaminant mobility] (4) Quantity [of the contaminant release/spill] (5) Area [of the spill] (6) Substance of concern	(7) Minimum seasonal depth to water table (8) Soil media integrity: (8.1) Permeability; (8.2) Preferential flow (9) Aquifer media: (9.1) Heterogeneity; (9.2) Preferential flow (10) Vadose zone properties (11) Aquifer properties	(12) Distance [between spill site and surface water environmental receptor] (13) Sensitivity [of the surface water environmental receptor]

13 http://www.mfe.govt.nz/publications/hazards-land/contaminated-land-management-guidelines-no-3-risk-screening-system

In terms of assessing risk to groundwater pathway receptors, the MfE Risk Screening system simplifies the problem to consideration of only two factors. These being:

(1) Thickness of any low-permeability layer (silt, clay or paved);

(2) Distance to receptor from the contaminant release point.

4.4.3 Factors relevant to a contaminated groundwater vulnerability assessment

The tables provided in this section list a comprehensive suite of physiochemical factors considered pertinent to contaminated groundwater risk assessment for the conceptualised systems model provided in Figure 3. Implicit to the list are the factors considered in the published vulnerability assessment methods reviewed above.

Factors are broken down into those affecting transport to (Table 6); within (Table 7), and from (Table 8) groundwater. Environmental receptors we perceive as being at risk from exposure to groundwater are also listed. Known sources from which data might be obtainable are provided.

Table 6: Main factors affecting transport to groundwater

Transport route	Relevance across NZ	Controlling factors	Governing parameters	Data source
1. Infiltration of contaminated fire water through overlying soils/vadose zone	High	Soil type, both in terms of: • Hydraulic properties that govern permeability / potential rate at which dissolved contaminants can infiltrate to groundwater. Including potential for preferential flow via soil macro-pores.	• Soil drainage class. • Pavement coverage (artificial surfaces present a protective cap to groundwater resources; presumably in urban settings most water is deviated to surface water) • Thickness of unsaturated zone (i.e. depth to groundwater table).	• NZ soil map (SMap). • General maps. • Note: Few data available on vadose zone properties. • Local knowledge held by Regional Councils, e.g. piezometric contour maps (note data will be sparse)
		• Geochemical properties that govern potential for attenuation of contaminants	• Organic matter, primarily as a sorbent for organic contaminants; secondly in terms of facilitating microbial activity and stimulating biodegradation. • Ion exchange capacity; nature of clay in soils.	• NZ soil map (S-Map)
		Topography – steep slopes increase likelihood for surface run-off (i.e. reduces chance for infiltration to subsurface).	• Topographic slope	• Digital terrain model; topo' map

2. Indirect transport via impacted surface water	Low	Alluvial aquifer inherently related to a river where flow losses to ground are known to occur (sometimes referred to as riparian aquifer system).	• Geology (alluvial sediments of Holocene age more likely to be connected to river than older sediments). • Driving head differential between river and groundwater.	• NZ geology map (GNS QMap) • Local knowledge held by Regional Councils

Table 7: Main factors affecting fate and transport of contaminants within groundwater

Mechanism	Controlling factors	Governing parameters	Data source
1. Movement and dilution via physical advection and dispersion	Hydrogeological characteristics of aquifer system, such as: • Size of aquifer system; • Magnitude of aquifer through-flow (recharge from rainfall and rivers); • Direction of flow as determined by hydraulic gradients; • Heterogeneity of aquifer materials that determine dispersion of contaminant plume.	• Aquifer thickness. • Recharge – both effective rainfall and river inputs. • Piezometric gradients. • Hydraulic conductivity incl. potential for preferential flow via fractures in bedrock systems or openwork gravels (for alluvial gravel aquifers), as determined by geology.	• Aquifer thicknesses and piezometric gradients are often unknown, but details on specific aquifer systems will be available from Regional Councils. • Climate data available from NIWA (e.g. cli-flo database). • Few hydraulic conductivity measures of NZ aquifer sediments, but can crudely assume from mapped geology.
2. Mass loss processes	Chemical reactions due to hydrochemical state and geochemistry of aquifer.	• Chemical redox state (e.g. dissolved oxygen; Eh). • Ion exchange capacity of aquifer material and organic matter content (as per soils).	• Few data available. • Groundwater redox maps available for some regions (see Close et al., 2016). • Geochemistry inferable from geology maps.
	Biological degradation	• Potential for biodegradation largely determined by chemical redox state.	• As per above

Table 8: Main factors affecting direct or indirect exposure to contaminated groundwater

Mechanisms by which exposure to groundwater can occur[14]	Examples/determining factors	At risk receptor	Data source
1. Natural groundwater discharge to surface water environments.	• Springs. • Groundwater-fed lakes – impact depends on size of lake. • Groundwater-fed rivers – impact depends on size of receiving river. • Groundwater discharge to sea.	• Aquatic ecology. • Humans through recreational contact.	• Local knowledge, largely held by Regional Councils. • River data available from LINZ (topo maps).
2. Anthropogenic groundwater discharge.	• Pumped abstraction. Note: in addition to horizontal separation distance, vertical distance (i.e. well depth) also a determining factor in terms of potential for exposure, as does whether or not the water supply is treated.	• Humans - domestic or public water supply • Stock if groundwater used for stockwater supply. • Crops if groundwater used for irrigation.	• Location of community supply wells known by Ministry of Health, also Regional and District Councils • Info on private bores is region specific. If available, held by Regional Councils.
3. Direct exposure of subsurface ecology to contaminated groundwater.	• Stygofauna in karstic or alluvial gravel aquifer systems.	• Groundwater fauna.	• No data available in NZ.

[14] Note in case of 1 and 2, vulnerability determined by physical separation distance between contaminant source and environmental receptor.

4.4.4 Recommended short-list of factors to consider

The comprehensive list of factors tabulated in the preceding section is beyond that which one could consider pragmatic for developing a risk based screening tool at the national scale, using an overlay-index approach. Table 9 contains a list of the key factors believed to be an appropriate starting point. Some clarification for choice of factors, when considered against the three pre-existing methods referenced in section 4.4.2, is provided, below.

It is recommended, initially at least, to assume identical factor weights and index ratings to those described by Sheppard et al., at least for factors that are common to both models. To start with, use of a multiplicative model rather than additive model, would seem appropriate, based on the reported findings of Sheppard et al. Common practice in development of overlay-index methods is to conduct a sensitivity analysis of the model, the findings from which will ultimately guide refinement of factor weights and ratings assumed in the final working model.

General factors	Subsurface factors	Health exposure factors
(1) Chemical of concern (2) Recharge (rainfall + river) (3) Topography	(4) Thickness of any low-permeability layer (silt, clay or paved); (5) Minimum seasonal depth to water table (6) Soil media: (6.1) Chemical composition, e.g. organic content; (6.2) Permeability; (6.3) Presence of preferential flow (7) Aquifer media: (7.1) Permeability; (7.2) Preferential flow	(8) Distance between fire site and known water supply wells (9) Sensitivity [of the supply well] (10) Distance between fire site and groundwater-fed surface waters (e.g. springs)

Table 9: Proposed shortlist of factors to be incorporated (initially at least) in an overlay-index method applied to assess groundwater vulnerability from fire-fighting, at a national-scale.

The MfE Risk Screening system appears simplistic and ignores prior knowledge available pertaining to hydrogeological conditions and groundwater vulnerability in NZ. Whilst Sheppard et al. provide a critique of DRASTIC, there is no evidence in the published literature to demonstrate their modified approach was any more practicable or effective. As Sheppard et al. rightfully note, because alluvial aquifer systems are common in NZ, river recharge can be a significant component of many groundwater systems and can be an effective diluent of land surface impacts to groundwater. DRASTIC overlooks this phenomenon, although it can easily be incorporated into a generic recharge factor.

Sheppard et al. omitted topography as an explicit factor in their vulnerability assessment method, mainly because they conceived contaminated sites to be located on developed or productive low-lying land. Such an argument does not hold in the case of rural fire fighting, where forest fires presumably could occur in hilly country. For this reason it is suggested that topography be included as a factor in assessing groundwater vulnerability, as per the original DRASTIC method.

Perceivably the list of major contaminants of concern could be quite limited for the fire-fighting case study (see Table 1). The choice of ratings applied to soil and aquifer property factors (that in practice translate to contaminant attenuation factors), will invariably be influenced by the chemical characteristics of the fire-fighting agents, notably their potential to sorb to clay minerals and organic carbon, also their ability to biodegrade. Although the physiochemical properties are reasonably well defined for NZ soil classes, the geochemical properties of aquifer sediments are less well known. On this account, out of pragmatism, we recommend a simplified model that overlooks the geochemical properties of aquifers would be appropriate. The obvious implication of this is that the potential for any chemical retardation/biodegradation is assumed to be solely governed by the soil zone.

Although groundwater systems in themselves represent ecosystems and host fauna, at this present time little is known about the nature of these ecosystems and they are off the radar in terms of any legislative environmental protection. For this reason, at this stage of development, we recommend they are omitted as a potential environmental receptor. In this case, the factors that determine exposure to groundwater impacts are limited to pumped abstraction and natural discharge features.

5. DISCUSSION

The development of a list of key factors and parameters for an environmental stewardship model for operational fire-fighting activities has been undertaken. Each environmental compartment that would be affected by emissions from a fire, rural or urban, has been considered individually and key parameters and factors reported. A consolidated list of each parameter or factor and the respective environmental compartment to which it is related is presented in Table 10. Further to these data provided, an assessment of the nature of the data has been provided, detailing whether the parameter/factor is a fixed value or a variable value and where the supporting data for these could be found.

The classification of these parameters shows that there are a number of fixed parameter values; these predominantly represent geographical or location–based data, such as geological characteristics or proximity to receiving waters. Such factors and parameters could be readily stored as GIS base maps similar to those already used by NZFS in the SMART Map database. This would greatly reduce the number of parameters needing to be considered and entered into a decision support tool by incident commanders.

Amongst the variable value factors and parameters, there are two distinct groupings; those that vary with time and those that are incident specific. Time-variable factors and parameters include data such as meteorological information; seasonal depth to groundwater; flow rate/volume of receiving water and rural fire conditions (duff and fine-fuel moisture content, grass-curing etc.). These time-variable factors and parameters could also be uploaded with a real-time logging GIS system. This would constitute a part of the standard set-up of the environmental stewardship model and the decision support tool. Suggested sources for each of these data sets, where available, are provided in Table 10. These suggested sources are not exhaustive; there may be alternative data sets that better meet the requirements of this model.

Incident specific factors and parameters are those which, on the whole, represent the output from situational analysis (sizing-up) and operational decisions made during response to an incident. With regard to the development of the environmental stewardship model and the decision support tool these data would be collected and uploaded during an incident. The inclusion of these data in the decision making process would create incident-specific options relating to potential environmental impacts of specific operational tactics (e.g. addition of class A fire-fighting foam instead of 'plain' water). The interpretation of the impact of each of the decisions would be processed by the model and result in notification of likely adverse environmental outcomes. The notifications would be intended to prompt either change in operational tactics where feasible, or the application of contamination reduction strategies to prevent contaminants reaching the wider environment.

To prevent excessive burden of additional data collation and interpretation being placed upon incident commanders it may be considered prudent to only consider the key receiving environment at specific incidents. This function could be undertaken in the model, resulting in a reduced suite of notifications for incident commanders to consider in their response. Furthermore, the onus of populating the decision making tool data fields could be passed away from incident commander and become a function of regional communications centres. Communication centre operators could upload data to a tool during each periodic situation report that is passed from an incident; and pass notifications to the incident commander when appropriate, or despatch additional resources (operational support staff or regional authority pollution prevention/clean-up teams) in support.

Table 10 - Consolidated table of model parameters and factors for all environmental compartments addressed.

Factor/parameter	Environmental compartment	Variable/fixed value (V or F)	Data source(s)
Combustion source			
Emission rate (plume)	Atmos.	V	Incident specific
Site description	Atmos., Terr., S. water	V	Incident specific
Fuel mixture	Atmos.	V	Incident specific
Fuel loading	Atmos., Terr	V	Incident specific
Combustion temperature	Atmos.	V	Incident specific
Run-off rate (contam emission rate)	Terr., S. water, G. water	V	Incident specific
Application rate firefighting water	Terr., S. water	V	Incident specific
Fire-fighting additive products	Terr., S. water, G. water	V	Incident specific
Composition of fugitive effluent	Terr., S. water, G. water	V	Incident specific
Meteorological			
Precipitation rate	Atmos., Terr., S. water, G. water	V	Meteorological service
Precipitation duration	Atmos., Terr., S. water, G. water	V	Meteorological service
Wind speed	Atmos.	V	Meteorological service
Wind direction	Atmos.	V	Meteorological service
Upper mixing limit	Atmos.	V	Meteorological service /Incident specific
Lower mixing limit	Atmos	V	Meteorological service /Incident specific

Factor/parameter	Environmental compartment	Variable/fixed value (V or F)	Data source(s)
Environmental			
Contaminant identity	Atmos., Terr., S. water, G. water	V	Incident specific, site fire safety plans
Topography	Atmos., Terr., S. water, G. water	F	Land Information New Zealand Topo maps[15]
Proximity to critical infrastructure	Atmos., S. water, G. water.	F	Local Authority (LA) infrastructure databases, SMART Map (NZFS)
Proximity to sensitive receiving environment	Atmos., Terr., S. water, G. water	F	LA, Department of Conservation, Landcare
Sensitivity of receiving environment	Atmos., Terr., S. water, G. water	F	LA, Department of Conservation, Landcare
Soil or surface porosity/permeability	Terr., S. water, G. Water	F	Landcare, GNS
Soil media chemistry	G. Water	F	Landcare, GNS
Background contaminant level	Atmos., Terr., S. water, G. water	F	LA, HAIL register (Ministry for Environment or Regional Authority)
Proximity to reticulated drainage (storm drains)	Terr., S. water	F	LA infrastructure databases
Size of receiving water (vol., flow rate)	S. water	F	NIWA river and stream flow assessment[16], Regional Authorities
Soil scouring/erosion	Terr., S. water	V	LA, HAIL register (Ministry for Environment or Regional Authority)
Minimal seasonal depth to water table	G. water	V (but known)	GNS[17], Regional Authority databases[18]
Aquifer porosity/permeability	G. water	F	

Where: Atmos. = Atmosphere; Terr = terrestrial environment, S.water = surface water; G. water = Groundwater

[15] Topographic maps | Land Information New Zealand (LINZ) accessed 19/01/17
[16] Flow assessment and management | NIWA accessed 19/01/17
[17] GNS Science Geothermal and Groundwater Database (GGW) accessed 19/01/17
[18] E.g. Otago Regional council: Groundwater Information accessed 19/01/17

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