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PAPER

Environmental impacts on soil and groundwater at airports: origin, contaminants of concern and environmental risks†

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Environmental impacts of airports are similar to those of many industries, though their operations expand over a very large area. Most international impact assessment studies and environmental management programmes have been giving less focus on the impacts to soil and groundwater than desirable. This may be the result of the large attention given to air and noise pollution, relegating other environmental descriptors to a second role, even when the first are comparatively less relevant. One reason that contributes to such "biased" evaluation is the lack of systematic information about impacts to soil and groundwater from airport activities, something the present study intends to help correct. Results presented here include the review of over seven hundred documents and online databases, with the objective of obtaining the following information to support environmental studies: (i) which operations are responsible for chemical releases?; (ii) where are these releases located?; (iii) which contaminants of concern are released?; (iv) what are the associated environmental risks? Results showed that the main impacts occur as a result of fuel storage, stormwater runoff and drainage systems, fuel hydrant systems, fuel transport and refuelling, atmospheric deposition, rescue and fire fighting training areas, winter operations, electrical substations, storage of chemical products by airport owners or tenants, and maintenance of green areas. A new method for ranking environmental risks of organic substances, based on chemical properties, is proposed and applied. Results show that the contaminants with the highest risks are the perfluorochemicals, benzene, trichloroethylene and CCl_4. The obtained information provides a basis for establishing the planning and checking phases of environmental management systems, and may also help in the best design of pollution prevention measures in order to avoid or reduce significant environmental impacts from airports.

1. Introduction

The objective of this article is to present and discuss the relevant information regarding sources of contamination of soil and groundwater at airports, the associated contaminants of concern and their environmental risks. The paper is intended as a support tool for environmental management and impact assessment of airport facilities. The synthesis is based on the review of over seven hundred documents, both scientific articles and technical reports. The majority of the available information is from

Environmental impact

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reports, as the publication of results of severe soil and groundwater contamination in international journals is much less frequent. Fifty-two studies explicitly reported causality relationships between the origin of emissions and detected contaminant concentrations. Results from these studies are used here to establish rankings of importance of contaminants and the location where their emission occurs.

All the information presented in this paper is of public domain and therefore does not include the many studies on the subject conducted at airports where confidentiality issues limit the publication of environmental data. Notwithstanding, results from other unpublished studies known to the authors confirm the results presented here. No distinction is made between civil and military airports, but contaminants specific to the latter are not included, as for instance TNT and radionuclides. The article focuses on potential impacts during airport operation, as they are more significant and representative for economic activity. Case-specific indirect impacts caused by urban, industrial or services development outside the airport's property are not considered.

Though much effort has been made to assess and mitigate impacts of new airports, or the expansion of existing ones, namely through regulation by national and international agencies (*e.g.*, International Civil Aviation Organisation, ICAO), this effort has been channelled more toward socio-economy, air quality, noise and surface water quality, as is reflected both in the number of technical documents and specific regulations supporting environmental management programmes and in the programmes themselves. Some authors, however, claim that the overall impact on water quality (surface and groundwater) is more likely to be a problem than the impact on air quality,[1] which has been the focus of much attention lately, due in particular to global climate impacts. Environmental management practices at airports have played an important role in the reduction of impacts and externalities, essentially due to more efficient aircraft ground handling, cargo handling, de-icing and anti-icing operations and environmental control. However, with the estimated doubling of air traffic until the second decade of the present century,[2,3] even with the introduction of more efficient environmental control measures, impacts will necessarily increase. Existing airports will have to expand their facilities and new airports will have to be built, potentially overlying important groundwater resources. Over the next 20 years, world passenger volume is expected to annually rise by 4.2 percent,[3] so that the current number of civil airports, approximately 9300, will necessarily grow to follow that demand (Fig. 1). China and India alone, two of the countries with the highest growth rate of the number of passengers, will need to build 53 and 46 new airports, respectively, by 2020.[4,5] Europe alone has 30% of all facilities, followed by Africa (18.8%), Central and South America (16.4%), Asia (15%), North America (8.4%), Middle East (5.6%), and Oceania (4.9%).

Despite the wealth of technical information on the overall need to assess the impacts of airport activities on soil and groundwater, as well as on specific aspects of the required assessment, the reported environmental management programmes of many airports are not following these recommendations. The reasons are that: (i) the technical documentation lacks sufficient detail, or does not include a ranking of importance of each contaminant source, which would allow setting priorities of investment in monitoring and assessment programs; (ii) recommendations included in national or regional technical documents are considered as regulating the activity for particular countries or regions; (iii) subsurface contamination assessment has been introduced in environmental management programmes of airports only recently, in many airports as recently as in the beginning of the XXI century; (iv) the true potential impact of the activity has not yet been fully acknowledged, as indicated by the secondary role given by international agencies, such as ICAO. Table 1 summarizes technical orientations given at a strategic level by such agencies.[6] These orientations are intended to regulate the activity at a global scale. Countries or groups of countries transpose these orientations into internal strategic/operational level regulations and technical documentation. Examples are the regulations produced by the USA Federal Aviation Administration.[7] Both the global and national orientations are then transposed into the airports' operational environmental procedures. Upon transposition, the level of detail increases, and many of the supporting documents lack the

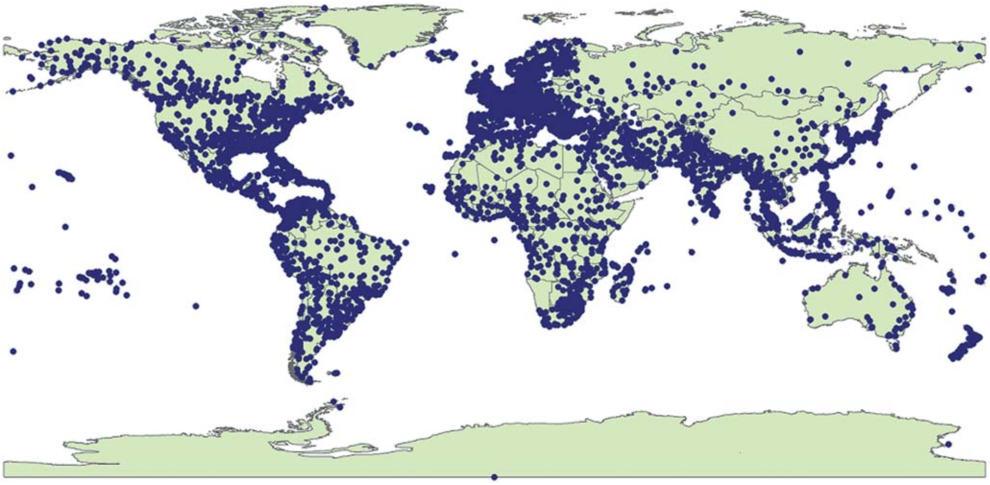

Fig. 1 World civil airports—figure made with data from Partow[143] (Common Public License).

Table 1 Assessment of environmental impacts of airports to soil and groundwater, from global strategic to national operational levels[a]

Global strategic level (international agencies)	National strategic/operational level (national agencies)	Operational (airports' environmental management practices)
Groundwater for supply	General soil and groundwater quality protection sometimes indicated separately	Most airports in developed countries have monitoring programmes, though the set of measured parameters may vary, and the number of points may be too low to quantify all potential sources
No significant distinction between groundwater and surface water quality—protection indicated generally for both	Indication of potential sources (non-exhaustive, and/or not specific for soil and groundwater)	
Necessity to protect soil from contamination—general	In some cases guidelines are not in agreement with evidence from practice	Environmental reports indicate some, but not all, potential sources and contaminants of concern

[a] See text.

necessary detail to support operational evaluation: for instance, the clear indication of what variables to assess and where. Consequently, the assessment of soil and groundwater contamination often does not fully comply with national strategic/operational recommendations, or reflect the international experience on contamination at airports. This discrepancy between scientific evidence and operational procedures can be reduced if operators become more aware of the real impacts of their activity, namely through comparative assessment between airports. Sharing experience is even more relevant for developing countries, where facilities have traditionally less maintenance, environmental programmes are less developed, when existent, and the national strategic/operational level is incipient.

Different operations and activities are distributed inside the airport limits, both on the airside and landside. The following definitions regarding the evaluation of emissions are used: (i) *operation* refers to any activity or facility specific to the activity; (ii) *location* refers to the physical place where the emission is made; and (iii) *origin* refers to the process driving the emitted contaminant from the source to soil and groundwater (Table 2). Emissions from single *operations* may take place at different *locations*. An example is aircraft handling operations, responsible for emissions at the aprons during servicing, but also for diffuse emission of atmospheric contaminants. The *origins* may also have overlapping *locations*, as for instance surface runoff from aprons and leaks from fuel hydrants. The analysis in this paper is made per *origin*, where the relevant emission sources (*operations* and *locations*) are identified.

Following the analysis of the origins of soil and groundwater contamination at airports, potential environmental risks are evaluated by combining a new index that quantifies the probability of exposure of receptors to the contaminants of concern with available information on related health hazards. Contaminants are then ranked according to their environmental risk. Environmental risk assessment (ERA) builds upon environmental impact assessment (EIA) in that risks are impacts when the likelihood of occurrence and magnitude of consequences are uncertain.[8]

Table 2 Origins, locations and operations

Origin	Location	Operations
Surface runoff	Runways, taxiways, aprons, roadways, maintenance areas, vehicle parking areas, hangars, workshops, and other paved areas	Refuelling, handling, de-icing and anti-icing, parking of vehicles, maintenance of aircraft, vehicles and other equipment, drained by rainwater, melted snow water and pavement cleaning
Leaks from fuel storage and distribution	Aprons, fuel farms, petrol stations, storage areas, hangars, and workshops	Refuelling (hydrant systems, fuel farms, and petrol stations) and storage of other chemical substances (pesticides, fuels, lubricants, solvents, *etc.*)
Atmospheric deposition	Unpaved areas	Aircraft operations (engine starting, run-ups, testing, ground manoeuvring, take-off, and landing), handling vehicles and equipment, heating systems, and winter operations
Direct release	Unpaved areas, fire-fighting training areas, and storage facilities	Weed control, fire-fighting training, storage/deposition of substances in unpaved/pervious areas
Accidental contamination (other origins)	Electrical substations, green areas, hangars, workshops, cargo terminal, and storage facilities	Leaks during operation or servicing of electrical substations, spills of pesticides, spills of chemical substances used in cleaning and maintenance of aircraft, handling vehicles and other equipment, spills from cargo

2. Origins of soil and groundwater contamination at airports

2.1. Surface runoff

To guarantee the safety of aircraft operations and durability of pavements, runoff is drained from the pavement as soon as possible and collected in an adequate drainage system. Airport drainage planning and design follows dimensioning methods similar to other urbanized areas, though more stringent to avoid ponding.[9] In, or near, paved areas most of the drainage structures (pipes) will be buried underground, accessible through manholes. These pipes are usually in concrete, though plastic pipes are preferable where industrial wastes, spilled petroleum products, or other substances harmful to bituminous paving and coating in corrugated metal pipe are apt to be present.[9] Aprons have a pavement and drainage system similar to that of runways and taxiways, though some particular conditions are required concerning the safety of personnel and fire hazard to the terminal. More specifically, runoff should converge away from terminals and fixed structures in the apron, in order to reduce the risks associated with spills of fuel and flammable lubricants.

Runoff from aprons depends on the number of refuelling and other ground handling operations, the frequency of anti-icing and de-icing operations, the characteristics of the pavement and runoff collecting system, and the compliance with standards and safety procedures. Operations taking place at the aprons are important sources of contaminants, as identified in a questionnaire made to the tenants at the John F. Kennedy International Airport, New York[10] where the following substances were mentioned as being present in stormwater drainage in the majority of more than one hundred of the facilities operated by air companies: oils, greases, halogenated solvents, non-halogenated solvents, oil and grease solvents, non-petroleum based greases, petroleum hydrocarbons, fuel vapours, glycols, vehicle fluids, cleaning solutions, pesticides/herbicides/fertilizers, battery acid, lavatory chemicals, lavatory waste, lavatory truck wash water, sediments, sodium acetate, and potassium acetate.

Surface fuel spills, which most frequently occur at aprons and usually originate from topping off or overfilling of aircraft and vehicles, constitute an important contaminant source. Though large spills are usually cleaned, minor spills can be transported into the stormwater drainage system,[10,11] part of which may be pervious, therefore allowing contaminated water to leak into the soil.

Data from the Copenhagen and Perth airports (Tables 3 and 4), for which more detailed published data are available, bring some more insight as to the volumes of fuels, lubricant and hydraulic oils usually reported as being spilled over paved areas.[12–18] The data are presented in Tables 3 and 4, discriminated by the dimension of the spill, number of occurrences and type of fluid spilled, along with relevant operation information. Four emission factors (EFs) for fuel and oil spills are calculated according to eqn (1)–(4) and presented in Table 5. These EFs, though specific for these airports, are a valuable reference for other airports where this information is not available, or for comparison purposes. Given the proactive environmental policy used by these two airports, the calculated EFs are probably among the lowest worldwide.

$$f = \frac{\text{total fuel and oil spilled(L)}}{\text{fuel used(m}^3\text{)}} \quad (1)$$

$$g = \frac{\text{total fuel and oil spilled(L)}}{\text{number of refuelling operations}} \quad (2)$$

$$h = \frac{\text{total fuel and oil spilled(L)}}{\text{number of passengers}} \quad (3)$$

$$k = \frac{\text{total fuel and oil spilled(L)}}{\text{number of aircraft operations}} \quad (4)$$

Considering the estimate made by the International Aviation Organization for the number of passengers in the year 2010 of 5360.5 million passengers worldwide[3] and the lowest of the calculated EFs, $h = 0.110$ L/1000 passengers, the global volume of spilled fuel and oil during ground handling operations is estimated to be at least 0.59 million litres. Part of this volume may eventually find its way into soil and groundwater. A report of soil and groundwater contamination for the Castle Airforce Base, USA indicates the occurrence of BTEX (benzene, toluene, ethylbenzene and xylene), other fuel hydrocarbons, solvents and several heavy metals around paved areas.[19] At the Kai Tak airport, Hong Kong, soils around the aprons showed high concentrations of BTEX and other fuel hydrocarbons, but heavy metals were not detected.[20] Vasarevicius *et al.*[21] reported high concentrations of fuel oils along the runway and aprons of the Gaiziunai Military Airport, Lithuania, up to a distance of one hundred metres and a depth of at least one metre.

Aircraft fuselage cleaning is made with aqueous based biodegradable aircraft fuselage shampoo, for most exterior cleaning requirements, with heavy duty water dilutable foaming for heavily contaminated undercarriage or smoke trail areas, wheel

Table 3 Operational data for Copenhagen airport[12–17] and Perth airport[18]

	Year						
Operational data	2001	2002	2003	2004	2005	2006	2007
Copenhagen international airport							
Number of passengers	18 136 274	18 272 174	17 714 007	19 034 585	19 981 872	20 877 496	21 409 526
Fuel used/m^3	915 000	857 000	845 000	935 000	970 000	985 000	960 000
Aircraft operations	288 739	266 894	259 002	272 518	268 655	258 356	257 591
Refuelling operations	130 000	120 000	120 000	127 000	126 000	121 000	119 539
Perth international airport							
Number of passengers	4 811 154	5 332 745	6 038 804	6 656 139	7 134 880	8 089 423	9 179 154
Aircraft operations	74 440	75 936	78 776	86 664	92 078	99 466	107 489

Table 4 Fuel and oil spills at Copenhagen airport[12–17] and Perth airport[18]

	Year							
Range	2001	2002	2003	2004	2005	2006	2007	Total
Copenhagen international airport								
0–9/L	152	172	184	131	143	128	99	1009
10–49/L	103	71	95	66	115	81	88	619
50–249/L	15	12	10	17	6	12	21	93
>250/L	1	1	0	3	0	5	1	11
Total number of spills	271	256	289	217	264	226	209	1732
(a) Volume of spilled fuel/L	8448	1899	1422	1577	1352	5349	10 226	30 273
(b) Volume of spilled lubricant and hydraulic oils/L	1753	1438	1586	1202	1649	1956	1667	11 251
Total volume: (a) + (b)/L	10 201	3337	3008	2779	3001	7305	11 893	41 524
Perth international airport								
Total number of spills	113	91	89	83	118	657	111	1262
(a) Volume of spilled fuel/L	2455	2183	601	340	1937	811	1896	10 223
(b) Volume of spilled lubricant and hydraulic oils/L	1446	587	327	393	457	657	990	4857
Total volume: (a) + (b)/L	3901	2770	928	733	2394	1468	2886	15 080

Table 5 Calculated emission factors for Copenhagen and Perth airports

Emission factor	2001	2002	2003	2004	2005	2006	2007	Median
Copenhagen international airport								
f (L m^{-3}) × 10^3	11.149	3.894	3.560	2.972	3.094	7.416	12.389	3.894
g (L per refuelling op.) × 10^3	78.469	27.808	25.067	21.882	23.817	60.372	99.491	27.808
h (L per passenger) × 10^3	0.562	0.183	0.170	0.146	0.150	0.350	0.556	0.183
k (L per aircraft op.) × 10^3	35.329	12.503	11.614	10.197	11.170	28.275	46.170	12.503
Perth international airport								
h (L per passenger) × 10^3	0.811	0.519	0.154	0.110	0.336	0.181	0.314	0.314
k (L per aircraft op.) × 10^3	52.405	36.478	11.780	8.458	26.000	14.759	26.849	26.000

wells, landing gear and engine area, and with liquid polish for polishing. Repair of composite pieces will generate wastes with *Kevlar*, fibreglass, and organic solvents, including toluene and acetone. Repair of electrical circuits generates wastes with cleaning fluids to remove solder flux, wax, oil and grease from electronic parts, metals and other materials. Engine maintenance and repair of wheels, tyres and brakes generate wastes with halogenated and non-halogenated solvents, fuels, hydraulic, brake and lubricating jet oils, greases and special purpose oils (*e.g.*, dielectric heat transfer fluids). Repair, testing and substitution of security equipment and seating will produce toluene-based fabric stripper and ketone-based adhesives. Cabin cleaning uses low foaming wipe-on/wipe-off biodegradable products and biocidal products for use in galley and other areas that need disinfection. All these substances can contribute to soil and groundwater contamination. Soil samples collected at Castle Air Force Base (AFB)[19] showed high levels of petroleum hydrocarbons, trichloroethylene (TCE), tetrachloroethylene (PCE), 1,1-dichloroethene, *cis*-1,2-DCE, benzene, carbon tetrachloride and total volatile petroleum hydrocarbons, at levels requiring remediation. These substances were presumably originated at the aircraft and vehicle maintenance facilities, including a wash rack. Similar results were mentioned for contamination from repair shops at Middletown airfield,[22] Tri-County Public airport,[23] George and El Toro AFBs,[24,25] and Yuma MCAS.[26] More examples are included in the exhaustive dataset provided as ESI (Tables S1 and S2 in the ESI†). Fig. 2 combines the reported occurrence of the contaminants of concern at airports with each origin. For surface runoff, contamination with solvents is referred to in 15.4% of the studies, fuel and oil hydrocarbons in 11.5%, and lead in 9.6%, indicative of a very high potential environmental risk (see Section 3). The magnitude and extent of contamination involving light and more soluble hydrocarbons, such as engine fuels, are difficult to estimate. The adsorbed phase can slowly leach into water for many years; some of it may evaporate into soil air and into the atmosphere; part will undergo chemical and biological degradation. The lighter monoaromatic hydrocarbons (BTEX) have a relatively high pollution potential due to their high concentration in fuels, higher solubility and lower adsorption coefficient.

Surface runoff can further contain products applied during winter operations, necessary due to the accumulation of snow and ice on the pavement and aircrafts, including: (i) removal of snow and ice from movement area surfaces and (ii) removal of ice and snow from aircrafts and application of anti-icing agents. Ice from the pavement can be removed mechanically, using plows, blowers/throwers and brushes, or and chemically, by applying pavement deicer chemicals such as those indicated in Table 6. To remove snow and ice from aircrafts these are sprayed with aircraft de-icing and/or anti-icing fluids (ADAFs). The volumes of chemicals necessary to treat each aircraft depend on many factors, such as size of the aircraft, air temperature, type of substance, time of application, turnaround time and method of application. Volumes range from 230 L (sometimes as low as 10 L)[11] to 4000 L.[27]

ADAFs appear in soils and groundwater at airports mainly due to leaks from the runoff collection system and atmospheric deposition. In the latter case the spreading occurs during takeoff

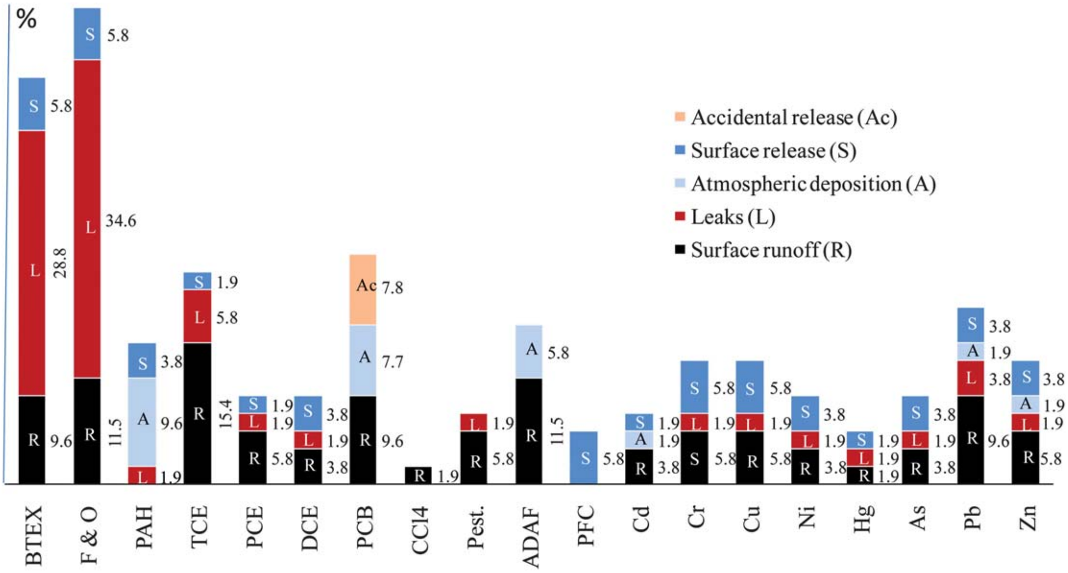

Fig. 2 Reported occurrence of contaminants of concern associated with each origin. F&O: Fuels and Oils; ADAF: anti-icing and de-icing fluids; PFC: perfluorochemicals.

Table 6 Chemical agents frequently used as de-icers and anti-icers at airports

Chemical agent name	Objective	Presentation
Sodium acetate	Pavement skid prevention	Granular
Sodium formate	Pavement skid prevention	Granular
Potassium acetate	Pavement skid prevention	Liquid
Potassium formate	Pavement skid prevention	Liquid
Urea	Pavement skid prevention	Granular
Calcium magnesium acetate	Pavement skid prevention	Granular
Propylene glycol, ethylene glycol, and diethylene glycol (+additives)	Aircraft ice prevention and/or removal	Liquid

and may extend for several hundred metres away from the runways. The presence of ADAF triazole additives in groundwater has been recorded since the late nineties, sometimes in concentrations approximately 25 times higher than the reported acute EC50 values in *Microtox* assays.[28,29] Triazoles in soils have been detected at airports of all sizes.[28,30,31] The number of studies already referring contamination by de-icing and anti-icing fluids is 11.5% for surface runoff and 5.8% due to atmospheric deposition, but the number of detections is expected to increase as more dedicated monitoring is performed.

2.2. Leaks from fuel storage and distribution

Refuelling at the aprons is made either with tankers (*e.g.*, 80 000 L capacity) or through fuel hydrants. The first method is used essentially in older and smaller airports, with lower traffic density. Tanker refuelling is unpractical for large aircrafts with fuel tank capacities of over 300 000 L and/or when the traffic density demands low apron turnaround times. Fuel hydrants have several advantages over tankers:[11] (i) a higher fire safety, as the only fuel on the apron is that supplied by the hydrant, more easily shut down if necessary; (ii) lower probabilities of fuel spill, and (iii) a smaller area required during technical servicing of the aircraft. Though hydrants reduce the probability of spillage, they are not leak-proof, as has been demonstrated at many airports (see Tables S1 and S2 in the ESI†).

Fuels and oils are produced to satisfy the specificities of each engine and mechanical part. Aviation fuels belong to two groups: aviation gasolines for reciprocating piston engines (aviation gasoline) and aviation turbine fuels (Jet Fuel, such as A and A1) for use in turbo-propeller and turbo-jet engines.[32] Fuels also receive many additives. In fact, additives are what make military (JP-8) and civil (Jet A-1) fuels different, as these two are otherwise similar.[33] Ground support equipment and vehicles use automobile gasoline, diesel and liquefied petroleum. The differences in the chemical composition of these fuels can help identify the source of contamination by chemical fingerprinting, as indicated in Table 7.[34,35]

Fuel storage and distribution at airports has been reported as one of the main causes of soil and groundwater contamination due to leakage from piping, from large above ground storage tanks (AGST) for aircraft supply, as well as from small underground storage tanks (UST) for gasoline and diesel for ground support vehicles, public supply and car rental services (Tables S1 and S2†). In a study conducted at Seattle–Tacoma International Airport high concentrations of petroleum hydrocarbons were found in groundwater due to leaking gasoline UST and piping at petrol stations.[36] In the same study, high concentrations of petroleum hydrocarbons (Jet A) and BTEX were detected in soil and groundwater adjacent to underground jet fuel hydrant pipelines, as well as in six of the fuel farms. A similar contamination profile was detected at twelve other airports. In some cases, the detected contamination cannot be attributed to a single source, as the chemical signature indicates the presence of distinct origins. For instance, at Twin Cities Reserve Smallarms Range Air Force Base (AFB) and at George, Yuma Marine

Table 7 Weight distribution of some hydrocarbons and heavy metals in fuels and oils[a]

Chemical	Gasoline	Diesel	Jet A1 (JP-8)	Jet B (JP-4)	Oils
Metals/ppm					
As	—	—	—	—	5
Ba	—	—	<0.3	—	48
Cd	—	—	—	—	3
Cr	0.0027	—	—	—	5
Pb	0.13–1.1	0.17	<3	—	240
Mg	—	—	9.6	—	—
Mb	—	—	1.9	—	—
Ni	—	0.27	<1	—	—
Ti	—	—	2.7	—	—
V	—	—	<0.6	—	—
Zn	—	—	2.4	—	480
Aromatics (%)					
Benzene	2.34	<0.013	0.0082	0.50	0.002
Ethylbenzene	1.90	0.031	0.06	0.37	—
Toluene	8.21	0.036	0.08	1.33	0.038
m-Xylene	3.50				
o-Xylene	2.71	1.95	3.56	2.32	0.055
p-Xylene	3.50				
PAH total	5.6–10.7	5.2–10.9	2.66	1.81	
Naphthalene	0.09–0.49	0.035–0.16	0–0.5	0.50	0.033
Halogenated hydrocarbons/ppm					
TCE	—	—	—	—	100
PCE	—	—	—	—	106
PCBs	—	—	—	—	5

[a] —: not available; from ref. 132–142.

Corps[24,26,37] contaminations from aircraft fuel, lubricant oils and solvents from UST and AGST were detected. Released volumes can be very high. Kampbell *et al.*[38] referred to the presence of 466 000 litres of jet fuel in the subsoil at Myrtle Beach AFB, of 380 000 litres at McChord AFB, and 314 000 litres at a Defence fuel supply point, which, according to the authors, resulted in thicknesses of free-phase fuel of 1.16 m, 0.04 m and 0.55 m, respectively. At Sangster International Airport, in Jamaica,[39] a total of 3000 litres of free-phase fuel and 1500 m^3 of contaminated soil had to be removed from beneath the leaking fuel hydrant system. Peter *et al.*[40] determined a mean spatial and temporal apparent kerosene thickness of 0.3 m, frequently with free phase, as a result of leaks from tanks in the fuel farm at a former airfield near Berlin. Similar contamination profiles were reported for other airports as indicated in Tables S1 and S2†. Of all reviewed studies, 38.5% reported leaks from fuel distribution systems as the cause of the detected contamination, predominantly at the fuel farm (in 17 cases). BTEX and fuel and oil hydrocarbons were the dominant groups of contaminants with 34.6% and 28.8% of the reported cases, respectively (Fig. 2). Leaks dominate as the origin of contamination with fuel and oil hydrocarbons and BTEX, followed by surface runoff.

2.3. Atmospheric deposition

During servicing of an aircraft a series of specialized operations are performed, many of which by specialized motorized vehicles. These are important sources of emissions of substances, both to the atmosphere and to the pavement. The emissions are difficult to separate from those of aircrafts, though. The more vehicles are necessary to give ground assistance to aircrafts, the higher the risk of accidents and spills and the higher the total emissions on the airside. For this reason international commercial airports have been introducing measures to reduce vehicle traffic and/or traffic emissions, namely by substituting gasoline and diesel vehicles by substitute fuels, or electric ones, and providing as many fixed ground handling services as possible (*e.g.*, electricity and water supply, refuelling by hydrant and discharge of sanitary wastewater).[41]

Atmospheric deposition has also been reported to contribute to contamination with hydrocarbons, heavy metals, polychlorinated biphenyls (PCBs) and PAHs around aprons, taxiways and runways (see Tables S1 and S2 in the ESI†). Heavier particles will settle near the origin (up to 100 m from the source), while lighter ones will be transported to larger distances. Fuel burning is one of the sources for atmospheric PAHs, aromatic hydrocarbons with three or more rings, which will eventually deposit on the soil. PAHs with a higher number of rings are associated with incomplete combustion or direct spills and those with a lower number to combustion sources, such as aircrafts.[42] In a study of the upper soil (first 20 cm) at the Deblin military airfield, Poland, Baran *et al.*[43] showed how different activities inside an airport affect the distribution and type of PAH found. Near locations where fuel spills are more probable, five-ring hydrocarbons, characteristic for oils and fuels predominated (>30%), whereas in soils along the taxiways and runway PAHs (mostly three-ring) (38–62%) coming from the scattered-source combustion processes in the airfield engines predominated. These results are in agreement with those of Ray *et al.*[44] for the Delhi International Airport, where they found that the majority of the samples collected around the runway had the highest concentrations of heavier PAHs, in particular on the landing side due to incomplete combustion of fuel (low engine power settings). Concentrations, however, may vary substantially from airport to airport,[43–47] due to different emission sources and climatic conditions, as well as the presence of external sources of PAHs, affecting atmospheric dispersion and deposition. Atmospheric deposition was considered the most important origin for soil contamination by PAHs, in 9.6% of the studies, and by ADAF in 5.8% of the studies (following surface runoff).

2.4. Surface release

One airport operation that is responsible for direct surface release of contaminants to the soil is that of airport rescue and fire fighting (ARFF) training. The dimension of ARFF areas varies with the dimension and the number of movements of the aircrafts using the airport. ICAO[48] defined ten categories based on these criteria. Contamination in ARFF training areas stems from the (past) use of oils, fuels, solvents, and any other combustible products used for setting up the fire in training exercises, the subsequent burning of metal parts, and finally the use of fire extinguishing agents. The primary extinguishing agent is aqueous film forming foam (AFFF), to which a necessary amount of complementary agents has been added.[48] Foams consist of perfluorinated surfactants with a foam stabilizer and viscosity control agents. Stabilizing additives and inhibitors are added to all foams to protect against freezing, to prevent corrosion of equipment and containers, to resist bacterial decomposition, to control viscosity and to assure readiness.

The perfluorinated surfactants that constitute most of the AFFFs belong to the family of perfluorochemicals (PFCs), which are highly stable in the environment[49] and are bioaccumulative in humans and animals. The physicochemical properties of PFCs indicate that they partition primarily into water, due to their high solubility (>0.5 g L^{-1} for perfluorooctanoate (PFOA) and perfluorooctane sulfonate (PFOS)[50]), whereas their simultaneous hydrophobic/lipophobic nature results in low sorption to organic matter and consequently high mobility.[51,52] Values for log K_{OC} have been determined in the range of 1.23–2.7 (ref. 51 and 53–55) for PFOS and between 1.90 and 3.65 (ref. 51) for many of the other PFCs, which are much lower than for persistent organic pollutants of similar molecular weight such as PCB congeners (log K_{OC} range of 4 to 6), indicating a greater tendency to stay in the aqueous phase.

Perfluorocarboxylate surfactants were used as a component in AFFF between the mid-sixties and mid-seventies.[56,57] As these substances are stable to acids, bases, oxidants and reductants and are generally not believed to undergo metabolic or other degradation in the environment, historical losses through degradation are assumed to be negligible.[58] Empirical evidence has demonstrated that some perfluorinated carboxylic acids (PFCAs) are bioaccumulative and persistent hence subject to long-range transport, resulting in trends of increasing concentrations of long-chain PFCAs in wildlife over the last 30 years.[59] These substances were found in groundwater in high concentrations at fire-fighting training areas in Fallon Naval Air Station, Tyndall AFB and Wurtsmith AFB by Moody and colleagues.[60–62] Potential interactions between AFFF components and co-contaminants can alter co-contaminant transport and biodegradation. Some hydrocarbon surfactants are known to enhance the apparent solubility and/or the mobility of dense non-aqueous phase liquids in contaminated groundwater.[63] Reduction in water-dense hydrocarbons interfacial tension may promote the displacement of residual hydrocarbons and in consequence increase migration velocity in the subsurface.[61] Supplementary agents are also employed in ARFF, either alone or in combination with aqueous film forming foams, to accomplish particular aircraft fire fighting operations such as three-dimensional running fuel fires.[64]

The number of studies concerning the effect of application of AFFF at airports is very limited, though more attention has been given to the subject in recent years, as indicated in Tables S1 and S2 in the ESI†.[61,62,65–68]

In recent years, PFCs have been associated with soil and groundwater contamination at fire fighting training areas, namely at Tyndall AFB and Wurtsmith AFB, both in the USA[61,62] and at an unspecified airport, as indicated by Paterson *et al.*[66] The presence of PFCs in groundwater at Wurtsmith AFB, Michigan, was detected five or more years after their last known use, indicating a long residence time in this environment. Remediation of groundwater with these contaminants is difficult due to their resistance to degradation, as demonstrated in practical circumstances.[69] In fact, the hydrolysis half-life for PFOA, in the pH 5.0–9.0 range, may be higher than 97 years in surface water.[54,55] As half-lives in groundwater for most organic contaminants are higher than in surface water, PFOA is potentially non-hydrolysable in groundwater. PFCs are recalcitrant towards conventional organic degradation technologies such as biological remediation[70,71] and ozone/hydroxyl radical oxidation,[49,72] as used in most wastewater treatment plants and in the final step of water treatment plants. This justifies the presence of these compounds in many treated wastewaters,[73,74] the environment and in drinking water supplies.[75–78] PFCs have been detected in groundwater,[74,79] sometimes at concentrations comparable to those in wastewater and road runoff. In the near future other emerging PFC substances will certainly appear as more research is made on this subject. One example is the primary and secondary substituted perfluoroalkyl sulfonamides.[80]

At Castle Airport the following contaminants were detected in the soil at the fire training area, attributed to the burning of surplus fuels and solvents in open pits and trenches: benzene, CCl_4, chloroform, *cis*-1,2-DCE, 1,2-dichloroethane, TCE, total volatile petroleum hydrocarbons, total extractable petroleum hydrocarbons, toluene, Freon 11, 1,2,4-trimethylbenzene, zinc, cadmium and nickel.[19] Groundwater at the facility also showed high concentrations of TCE, *cis*-1,2-DCE, tetrachloroethene, and 1,2-dichloropropane. Similar contamination was also detected at Middletown airport[22] and New Hanover County Airport.[81] Contamination with heavy metals is only occasionally mentioned, though they may appear to be associated with waste oils, solvents and metal debris (Cd, Cr, Cu, Pb, Ni, V, Zn and Hg).[18,19,82] Even modern fire training facilities are exposed to failure and to eventual losses to the soil. For instance, leakage of jet fuel from an oil skimmer has resulted in soil contamination at the fire training site of the Oslo International Airport,[83] resulting in contamination of groundwater with hydrocarbons, namely BTEX and naphthalene.

The chemical signature of the contamination in fire-fighting training areas is closely related to the type of substances used to ignite and extinguish the fire, as well as metal parts (Fig. 2). Fuel and oils, BTEX, PFCs and heavy metals are mentioned in 5.8% of the studies, followed by solvents and PAH (3.8%). The number of reported contaminations with PFCs should increase in the near future as more studies concentrate on these contaminants at airports.

2.5. Accidental contamination

Two main causes for accidental soil and groundwater contamination are referred to in the reviewed studies: (i) spills from electrical substations and (ii) spills from containers of chemical substances. The main concern with contamination from electrical substations comes from the use of PCBs as dielectric fluid in capacitors, in high concentrations and quantities (litres), and in oils used in transformers, in much lower concentrations (hundreds of ppm). Only equipment produced between the 1940s and the end of the XX century use PCB, after which its use was phased out. Capacitor leakage was identified as one of the main sources of PCB to the environment in the UK in 1999, accounting for 75.89%, transformers accounted for 1.54%.[84] Vasilic *et al.*[85] studied the concentration of PCBs, namely Aroclors, in soils of four Croatian airports, where almost half of the soil samples showed PCB contamination (expressed as Aroclor 1242/Aroclor 1260 mixture) above 1.5 μg kg^{-1} dw. The three highest PCB mass fractions (5314–41 327 μg kg^{-1} dw) were determined in samples collected along the airport aprons where the aircrafts were serviced and refuelled. The maximum and median PCB mass fraction values in samples collected along the airport runways were one order of magnitude lower than those in soils taken close to the aprons. Higher values were obtained at an unspecified airport in "East" Berlin (single sample with 60 000 μg kg^{-1} dw).[86] These values are in the range of those reported for urban and industrial areas.[87–93]

The maintenance of buildings and green areas may result in the accidental emission of pesticides, oils and greases and petroleum hydrocarbons; however, information on these emissions is not available in the reviewed literature. Complementary services such as rail and public transport access, hotels and in some cases industrial uses are usually found at, or in the close vicinity of, airports. These services may cause accidental emissions to the soil, but are not reviewed here due to the large variety of possible services. Airport management practices should include tools to control and force tenants to comply with environmentally safe practices, namely in what regards the proper storage of hazard substances. For instance, in Crystal City Airport, a severe top soil contamination was found with organochlorine pesticides and herbicides, arsenic and minor amounts of other semi-volatiles. The only indicated cause for the contamination was the incorrect deposition of drums of various aerial pesticides and herbicides and other unspecified products directly on the soil by a tenant.[94,95]

3. Evaluation of the risk

3.1. Methods

The risk posed by a contaminant towards humans and ecosystems is a function of the probability that the contaminant reaches the receptors and of its hazard. Many particular factors are affecting the migration between sources and receptors. They can be divided into two types: those that depend on the properties of the local hydrogeology, climate and land use and those dependent on the properties of the contaminants. Under the same hydrogeological and climatic conditions, the properties of the contaminants are the control factors affecting their mobility in the subsoil. Of these properties, relative density (ρ), water solubility (S), partition coefficient between water and soil organic matter (K_{OC}) and degradation rates as measured by the half-life ($t_{1/2}$) can help build an exposure risk index, useful for comparing exposure probabilities dependent on chemical properties. The index is made relative to naphthalene as this contaminant is a good indicator of contamination with petroleum hydrocarbons and its mobility in the subsurface is intermediate between mobile species, such as methyl *tert*-butyl ether (MtBE, a gasoline additive) and very immobile ones, such as high molecular weight PAHs (*e.g.*, chrysene). Naphthalene has a groundwater ubiquity score (GUS) of 1.8,[96] therefore located exactly at the lower limit for mobile chemicals. The naphthalene exposure risk index (NERI) is obtained by the following equations for the horizontal and vertical directions.

$$\mathrm{NERI_H} = \frac{\log\left(S_\mathrm{i}\right)}{\log\left(S_\mathrm{Naph}\right)} + \frac{\log\left(t_{1/2\mathrm{i}}\right)}{\log\left(t_{1/2\mathrm{Naph}}\right)} - \frac{\rho_\mathrm{i}}{\rho_\mathrm{Naph}} - \frac{\log\left(K_\mathrm{OCi}\right)}{\log\left(K_\mathrm{OC\,Naph}\right)} \tag{5}$$

$$\mathrm{NERI_V} = \frac{\log\left(S_\mathrm{i}\right)}{\log\left(S_\mathrm{Naph}\right)} + \frac{\log\left(t_{1/2\mathrm{i}}\right)}{\log\left(t_{1/2\mathrm{Naph}}\right)} + \frac{\rho_\mathrm{i}}{\rho_\mathrm{Naph}} - \frac{\log\left(K_\mathrm{OCi}\right)}{\log\left(K_\mathrm{OCNaph}\right)} - 2 \tag{6}$$

The NERI is an empirical index which considers that higher solubility and half-life times contribute to increasing the probability of a contaminant to migrate between the source and the receptor; contaminants denser than water will migrate more vertically, therefore increasing their vertical mobility, but decreasing the horizontal; higher adsorption will always cause retardation, thereby decreasing the probability of the contaminant reaching the receptor by providing more time for degradation. Density is not logarithmized, because unlike the other parameters it does not follow a lognormal distribution (as tested by the Chi-square test, $p < 0.05$, made for the chemical dataset of 365 substances presented here). The constant in the last term of eqn (6) serves for zeroing the index for naphthalene.

Similar indexes were proposed for the unsaturated zone by Gustafson[96] and Laskowski *et al.*[97] The NERI allows the ranking of the probability of finding an organic contaminant in groundwater downstream from a source. Values of NERI lower than 0.0 indicate that this probability is very low due to its very limited mobility, or very low residence time. The index is not suited for heavy metals as their mobility in the subsurface is largely determined by physicochemical conditions which are frequently more relevant than sorption onto organic matter. Values for the parameters necessary to calculate the NERI were obtained from EPI Suite®,[98] as well as from reference publications.[99–102]

Ecological risk characterization requires the calculation of the quotient between the measured or predicted environmental concentrations (for each compartment, *i.e.* aquatic (surface water and sediment) and terrestrial (soil)) and the predicted no-effect concentration (PNEC). If this quotient is lower than 1, then the chemical of concern is considered to present an acceptably low risk to the environment; if equal or higher than 1, measures to reduce the risk should be taken.

In human risk assessment two different methods are used, according to the type of effects the chemical of concern is known to pose: (i) non-carcinogenic end-points (measured effects) and (ii) carcinogenic end-points. In the first case, a chemical is considered to pose no risk to human health if the daily ingested amount (daily intake or exposure) is lower than the no-observable adverse effect level (NOAEL). Both quantities are indicated in *mass of chemical per unit mass of human body weight per day*. When the ratio between the daily intake and NOAEL is higher than 1, the risk assessor will need to decide whether to consider the situation as of risk, according to a pre-established margin of safety, *i.e.*, and then decide how much lower the exposure should be. The margin of safety will change according to the confidence of the data that supported the calculation of both exposure and NOAEL. For low concentrations, cancer risk is considered to relate linearly to exposure, the slope of the linear curve defined as the "slope factor". Hence, if the level of exposure is within the range considered valid for the linear relation, unitary (per person) health risk can be calculated by multiplying the slope factor by the exposure level (daily intake). The option here was to present the values of the NOAEL for humans, for non-carcinogens, and PNEC for non-human species instead of reference doses or environmental quality standards, as these latter depend on empirical decisions taken about the margins of safety. Note also that the values indicated by different institutions for both NAOEL and PNEC may vary significantly if the studies from which they were calculated are not the same. Consider, for instance, the value of PNEC for the PAH fluorene: the *Institut National de l'Environnement Industriel et des Risques*, in France,[103] indicates a value of 77 μg kg^{-1} (dry weight) in soil, while Jensen and Sverdrup[104] propose a value of 800 μg kg^{-1} (dry weight) for the establishment of ecotoxicological soil quality criteria in Denmark. The option in the present article was to use the most conservative (lowest) values found in the literature.

3.2. Results and discussion

Results for NERI are presented in Fig. 3. Regarding the large amount of references consulted and data obtained for the calculation of the PNEC and NOAEL values, they are provided in Table S3†. Health hazards were ranked in three levels, from the most hazardous, to the least: Level 1 for proved carcinogens and endocrine disruptors; Level 2 for probable carcinogens/endocrine disruptors; and Level 3 for contaminants with mild toxicity. Levels 1 and 3 include contaminants for which the risk assessment studies are sufficient for classification with minor uncertainty. Level 2 was introduced to accommodate contaminants for which there is still some uncertainty about their hazards. As more complete studies become available, contaminants in Level 2 can be reclassified in one of the other two levels. Health hazards are used as proxy for environmental hazards, *i.e.*, for both humans and ecosystems. The combination of the NERI and the ecological and human health hazards provides a measure of risk. Contaminants are ranked first by the level of toxicity and then by the value of NERI, resulting in a final scale of risk (Table 8).

For fuels, among the most important soil and groundwater contaminants at airports (see Section 2 and Fig. 2), animal median lethal concentrations tests demonstrated a low order of acute oral and dermal toxicity.[105] Gasoline, including aviation gasoline, is possibly carcinogenic to humans, but jet fuel and diesel are not classifiable as to their carcinogenicity to humans due to limited evidence.[106] For mineral lubricating oils and processing oils there is sufficient evidence for the carcinogenicity of untreated and mildly treated mineral oils in experimental animals.[107] Of the lighter monoaromatic hydrocarbons (BTEX), benzene poses the highest risk, due to its relatively high mobility (hence high probability to reach distant receptors) and carcinogenic potential (resulting in high hazard, Table 8). In contrast, most PAHs, including the most hazardous ones, rank in the middle of the potential risk scale (Table 8), due to their low mobility (negative NERI values, Fig. 3).

Regarding the solvents, largely detected in soil and groundwater (Fig. 2), the chlorinated solvents TCE and CCl_4 are probable human carcinogens, while petroleum solvents,[108] DCE and PCE present some mild toxicity at concentrations usually found in contaminated soil and groundwater. On the risk scale the chlorinated solvents rank fourth and fifth (Table 8), due to their relatively high mobility.

ADAFs appear primarily in the form of ethylene glycol, propylene glycol, or diethylene glycol as the freezing point depressant and proprietary additives. The latter are considered the most toxic.[109,110] Several additives are found in ADAF, namely (benzo)triazoles, which constitute a group of chemicals with similar structure and similar physicochemical and toxicological properties. They include 1*H*-benzotriazole,

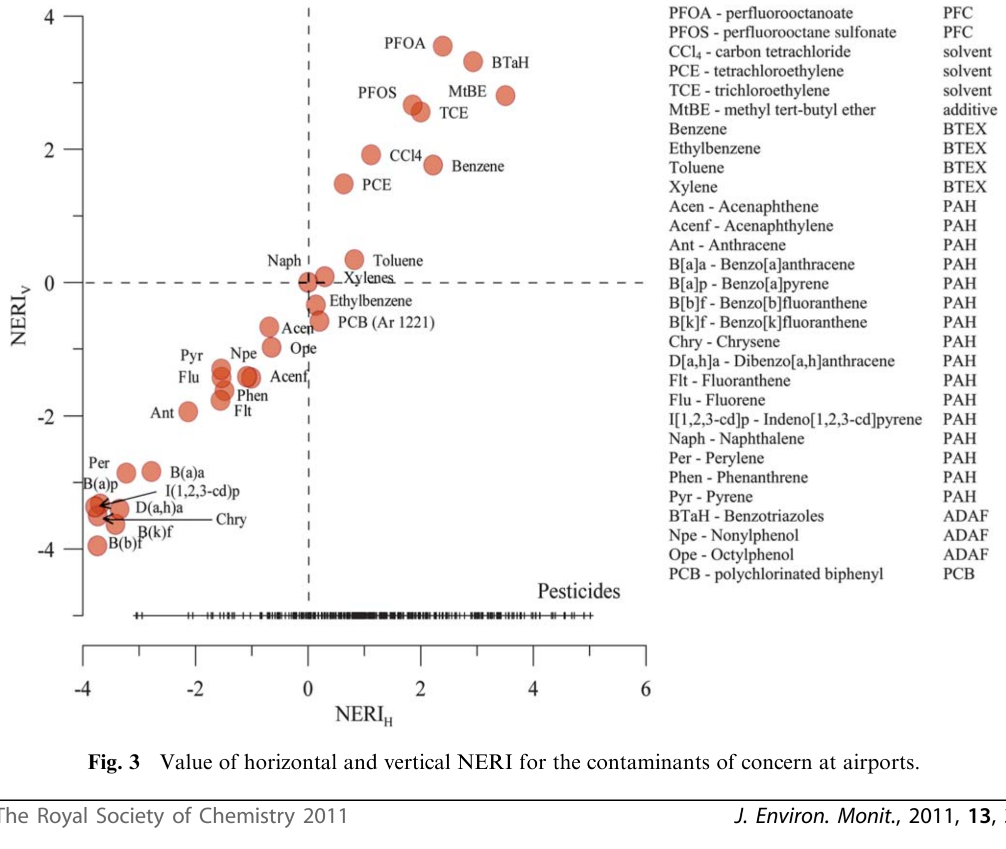

Fig. 3 Value of horizontal and vertical NERI for the contaminants of concern at airports.

Table 8 Ranking of risk of groundwater contamination for the contaminants of concern at airports[a]

	Hazard level		
	Level 1	Level 2	Level 3
	Carcinogen/endocrine disruptors	Probable carcinogen/endocrine disruptors	Mild toxicity
Increase risk->	1—Perfluorooctanoate (PFC) (2.4) 2—Benzene (BTEX) (2.2) 3—Perfluorooctane sulfonate (PFC) (1.9)	4—TCE (solvent) (2.0) 5—CCl_4 (solvent) (1.1) 6—PCB (0.2) 7—Octylphenol (ADAF) (−0.65) 8—Nonylphenol (ADAF) (−1.1) 9—B[*a*]a (PAH) (−2.8) 10—D[*a,h*]a (PAH) (−3.3) 11—B[*k*]f (PAH) (−3.4) 12—B[*a*]p (PAH) (−3.7) 13—Chry (PAH) (−3.7) 14—I[1,2,3-*cd*]p (PAH) (−3.8)	15—MtBE (additive) (3.5) 16—Benzotriazoles (ADAF) (2.9) 17—Toluene (BTEX) (0.82) 18—PCE (solvent) (0.63) 19—Xylene (BTEX) (0.30) 20—Ethylbenzene (BTEX) (0.14) 21—Naphthalene (PAH) (0.00)

[a] $NERI_H$ values are presented in brackets.

4-methyl-1*H*-benzotriazole and 5-methyl-1*H*-benzotrizole. These substances have long half-lives as indicated by results from the former Oslo airport Fornebu, in Norway, where triazoles were found in the soil two years after cessation of ADAF application.[31] These results, along with their detection in groundwater, demonstrate that these substances can migrate long distances in the subsoil, particularly if the soils have low organic and clay content, as adsorption will be minimal.[111] Other additives include alkylphenol ethoxylates (APEO), of which the most prevalent are nonylphenol ethoxylates (NPnEO), used as surfactants.[112] ADAF nonylphenol ethoxylates have been shown to degrade to byproducts, namely nonylphenol and octylphenol, known endocrine disruptors in animals and humans.[113–115] Benzotriazole is classified as toxic to aquatic organisms that can cause long-term adverse effects in the aquatic environment.[116] Skin and respiratory allergic reactions in humans have been reported also.[117,118] Octylphenol and nonylphenol rank seventh and eighth on the scale of environmental risk (Table 8), but with low probabilities of reaching distant receptors due to low mobility (negative value of the risk index, Fig. 3).

Regarding the environment risks of PFCs, for PFOS there seems to be no risk for the aquatic, terrestrial and atmospheric compartment.[119] However, there is still much uncertainty about the real effects and the same author refers that there is evidence that PFOA shows developmental toxicity in experimental animals. From general human health studies there is a suggestion of a negative association between estimates of maternal exposure to PFOA and fetal growth or fertility in humans. From epidemiological occupational exposure and general human health studies there is only an association between PFOA and prostate cancer, but the evidence is not conclusive. Some increases in prostate cancer have been seen, but the cause is not certain. These substances have been classified by some authors as endocrine disruptors.[120–124] As the production of PFOS and PFOA is being phased out, their concentrations will tend to decrease in the future, though global spread is expected to continue. According to the potential risk method, these substances rank first and third due to their hazard potential and very high mobility (positive index values, Table 8 and Fig. 3).

Despite the absence of robust toxicity datasets for longer chain PFCAs (>C8), these substances are reasonably expected to display even greater adverse human health impacts than PFOA as a result of their known slower clearance rates and higher bioaccumulation potential,[59] though more investigation is still needed to validate these results.[52] Perfluorinated surfactant toxicity testing for health effects identified endocrine disrupting, immunotoxicity, development and reproduction disrupting and neurotoxicity potential.[120–124] There is no indication that supplementary agents pose any relevant risk to water and organisms, except in very high concentrations and in the vicinity of the emission.

PCBs were classified as probable carcinogens by several international agencies[125–127] and have been associated with poor reproductive success, impaired immune function of aquatic species and developmental deformities, as well as with cancer development.[125] Environmental hazards of pesticides depend on the active principle, some being carcinogens or endocrine disruptors. Many have severe acute toxicity. PCBs rank sixth on the potential health risk scale (Table 8), due to a very high residence time in the environment and intermediate retention in the soil matrix.

Pesticides have very high potential risk if they are very hazardous and simultaneously very mobile (high index value), or have very low risk otherwise. Individual pesticides are not included in Table 8, but the value of NERI is presented in Fig. 3 for a list of 336 pesticides, where the high variability of their mobility and exposure risk values becomes clear. Finally, some of the heavy metals found at airports are proved carcinogenic, *e.g.*, Cr and As, or are suspected to be, such as Pb and Cd. This is particularly relevant as these metals are among the most frequently detected, as shown in Fig. 2.

4. Final considerations

Results presented here showed that soil and groundwater contamination at airports is mainly associated with: (i) fuel storage, (ii) stormwater runoff and drainage systems; (iii) fuel hydrant systems; (iv) fuel transport and refuelling;

(v) atmospheric deposition; (vi) rescue and fire fighting training areas; (vii) winter operations; (viii) electrical substations; (ix) storage of chemical products by airport owners or tenants; and (x) maintenance of green areas. The ranking of environmental risks was made based on potential exposure and contaminants' hazards. This ranking and the locations where contaminants are most frequently found should provide a basis for helping establishing the planning and checking phases of environmental management systems (EMS), such as ISO 14001 and EMAS. Results show that the contaminants with the highest risks are the perfluorochemicals (PFCs), benzene, trichloroethylene and CCl_4. The review made to existing regulatory and technical support documentation revealed important gaps in what regards soil and groundwater contamination, which the present text is expected to contribute to reduce. Many governmental and non-governmental organizations have produced guidelines, manuals and regulations for the assessment of impacts of airports on water resources.[7,128–131] However, these guidelines are too generic to serve as practical tools for designing systems for assessing environmental management in airports, namely because no priority as to what substances and where to evaluate is given. As a consequence, many of the implemented monitoring systems around the world are not targeting the most relevant substances. This is easily confirmed by the consultation of airports' annual environmental reports made under the EMS. Environmental objectives should be set for the identified contaminants, and the assessment should include means to evaluate the compliance to environmental targets, at least at the locations where contamination is more frequent. Information provided here may help in the best design of pollution prevention measures by choosing the best set of procedures, practices, techniques, and materials to avoid, reduce or control pollution in order to avoid or reduce significant environmental impacts of existent or planned airports.

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