Original Research

Contaminants in Airport Runoff Water in the Vicinities of Two International Airports in Poland

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Received: 17 October 2011
Accepted: 8 December 2011

Abstract

The general aim of the study was to evaluate environmental quality associated with the operations (combustion of fuels, cleaning of aircraft and airport aprons, aircraft and ground vehicle maintenance and repairs, fueling operations, de/anti-icing operations) of international airports located in central (Warsaw) and northern (Gdańsk) Poland. These two monitoring areas were set up to monitor PAHs, PCBs, formaldehydes, phenols, detergents (cationic, anionic, non-ionic), metals and other compounds, cations (Ca^{2+}, Mg^{2+}, K^+, Na^+, NH_4^+, Li^+) and anions (F^-, Cl^-, Br^-, NO_2^-, NO_3, PO_4^{3-}, SO_4^{2-}, CN^-), as well as pH, conductivity, and total organic carbon (TOC). Our paper presents the results obtained during three years (2008-11) in stormwater events in winter. The results of these studies of runoff water samples can be treated as a basis for evaluating the influence of airports on the environment.

Keywords: airport, runoff water, pollutants, water quality monitoring, chemical analysis

Introduction

Despite the positive aspects resulting from the intensive development of aviation, airports are associated with detrimental environmental effects [1-4]. Everyday activities at airports, such as combustion of aviation fuels, cleaning of aircraft and ground vehicles, aircraft maintenance and repair, fueling operations, engine test cell operations, de/anti-icing operations, ground vehicle maintenance, and removal of weeds and other vegetation from the airport apron are all sources of waste [5-10]. One of the more important problems in this respect is the runoff waters that form when precipitation or atmospheric deposits flush the airport surface during its operation.

A variety of chemical agents (cationic, anionic and non-ionic detergents, formaldehyde, phenols, polycyclic aromatic hydrocarbons (PAHs), and polychlorinated biphenyls (PCBs), as well as other cations and anions get into the environment with airport runoff waters [11-16]. Table 1 lists these types of airport pollutants and their effects on the environment.

Most airport water quality problems caused by pollution occur during winter. Typically, the winter season at airports lasts from October to April. In cooler climates this period may be longer, in warmer ones it is usually shorter [17].

During winter, conditions require the use of greater quantities of deicing salts, detergents and other compounds than at other times of the year.

Most airports do not possess their own wastewater treatment plants, so that all effluents carrying petroleum compounds, surfactants, the de-icing agents used in winter, and other organic and inorganic pollutants run off together with rain water or snowmelt into drainage ditches, whence they

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Table 1. Types of airport industrial wastes and a short description of their impact on the environment.

Compounds emitted	Type of pollutant	Origin of pollution	Environmental impact	References
PAHs	Combustion gases Fuel, oil, grease	· combustion of aviation fuels · combustion of engine fuels · vehicle maintenance shop operations · fueling operations · engine test cell operations	· mutagenic, carcinogenic · the resistance of trees to pests and disease · impairs growth of biomass and lowers its quality · adverse effect on fungi, algae, lichens · contamination of surface waters and soils · the consumption of dissolved oxygen · hinders re-oxygenation of streams · may form sludge deposits that could interfere with stream self-purification processes	[8, 28, 30-33]
PCBs	Chemical stabilizers	· aircraft maintenance operations (heat exchanger fluids, chemical stabilizers, and in hydraulic systems) · plasticizers in natural and synthetic rubber products such as adhesives, installation materials, flame retardants, lubricants, chemical stabilizers in paints, pigments and oil varnishes at airports	· highly toxic · carcinogenic	[9-10]
Cationic detergents Anionic detergents Non-ionic detergents	Detergents	· cleaning of aircraft, ground vehicles and airport aprons · repairs to aircraft engines and ground vehicles	· may cause foaming in aeration basins · may cause partial sludge flotation through release of carbon dioxide	[6]
Cations Anions	· De/anti-icing chemical wastes · Cleaning wastes	· de/anti-icing operations · cleaning of aircraft and ground vehicles · paint application and removal · steel hardening · metal plating	· may interfere with biological activity · consumption of dissolved oxygen · are toxic to human beings, livestock, and aquatic life	[34-36]
Phenols Formaldehyde	Combustion fuels	· partial oxidation of fuel (phenols) · photochemical reactions with unburnt fuel such as benzene, xylene, toluene (formaldehyde)	· consumption of dissolved oxygen · may form sludge deposits that could interfere with stream self-purification processes and with biological activity	[28]
Metals	Corrosion pollutants	· chromium plating · copper stripping · anodizing operations · corrosion of aircraft parts and ground vehicles	· may interfere with biological activity and may complicate sludge disposal are toxic to human beings, livestock, and aquatic life	[6]

Table 2. Characteristics of runoff sampling sites at Gdańsk and Warsaw airports.

Site number	Sampling site characteristics	Sample numbers
Gdańsk Airport		
1	Airport aprons, taxiing areas	1-7
2	Service road to the runway for ground staff, fire brigade, rescue teams	8-13
3	Airport aprons close to the passenger terminal	14-18
4	Machinery park – parking and garages for ground staff, fire brigade, and rescue team vehicles	19-23
5	Entrance gate to the airport premises	24-25
6	Car park	26-27
Warsaw Airport		
1	Inflow of Służewiecki stream	1-5
2	Outflow of Służewiecki stream	6-10
3	Municipal catchment and MPS	11-15
4	CARGO catchment.	16-20
5	Airport aprons, drainage system	21-25
6	Car park	26-30
7	Aircraft deicing pads	31-32
8	Aircraft refueling points and parks	33-34

enter the soil, surface waters (rivers, lakes, ponds), and ultimately ground waters. The contaminants resulting from airport operations penetrate all elements of the environment [6, 18-27]. However, their most destructive effects are on people and animals [28]. So it is crucial to monitor levels of contaminants emitted into the environment on a continuous basis.

To date there are not a great deal of data on runoff water samples. Most cases of pollution by airport runoff waters are defined using just basic total parameters such as chemical oxygen demand, biological oxygen demand, total organic carbon and total suspended solids [29]. In many countries such environmental samples have never been analyzed. Nonetheless, in recent years there has been a noticeable increase in interest in the problem of runoff waters because of the possibility of assessing the pollutant load entering the environment from this source.

The present work deals with the determination of pH, conductivity, total organic carbon (TOC), metals (Be, B, Al., V, Cr, Mn, Co, Ni, Cu, Zn, As, Se, Rb, Sr, Mo, Ag, Cd, Sn, Sb, Cs, Ba, Tl, Pb, U, and Fe), detergents (cationic, anionic, non-ionic) and formaldehyde, total phenols, PAHs, PCBs, metals, as well as cations (Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}, NH_4^{+}, and Li^{+}) and anions (F^{-}, Cl^{-}, Br^{-}, NO_2^{-}, NO_3^{-}, PO_4^{3-}, SO_4^{2-}, and CN^{-}) found in airport runoff waters from the Lech Walesa Airport in Gdańsk and the Frederick Chopin Airport in Warsaw. The results of the analyses of runoff water samples from these locations are an excellent qualitative and quantitative index of contaminants produced as a result of all kinds of activities at both airports.

Experimental Procedures

Sampling Site and Sampling Method

Runoff water samples were collected from two airports: the Lech Walesa Airport in Gdańsk and the Frederick Chopin Airport in Warsaw. Samples were collected in winter from 2009 to 2011. The runoff samples were taken from sites where rain water collected (depressions in the terrain), from the airport drainage system and from in front of the main entrance gate. Table 2 provides information on the runoff sampling sites at the two airports and Fig. 1 shows the locations of these sites.

Airport runoff waters at each location were collected manually with a plastic syringe (100 ml) with tubing. The material for analysis was then poured into 500 ml watertight plastic bottles (for determination of inorganics) or into 1000 ml dark glass bottle (analysis of organics). Prior to use, the syringes and tubing were rinsed with MilliQ water and then with the water to be sampled.

Chemicals

The reagents and standards for determining analytes present in runoff samples are listed in Table 3.

Preparation of Samples for Analysis

The samples were transported to the laboratory as quickly as possible. Bottles were stored at 4ºC in the dark

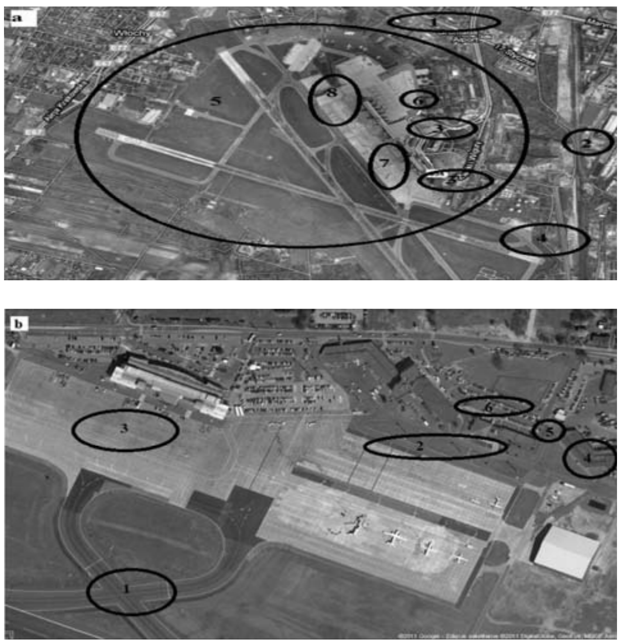

Fig. 1. Location of runoff water sampling sites at Warsaw (a) and Gdańsk (b) airports.

Table 3. Chemicals used during studied analysis.

Analytes	Reagents	Standards
PAHs (naphthalene, acenaphthylene acenaphthene, fluorene, phenanthrene, anthracene, fluoranthene, pyrene, chrysene, benzo(b)fluoranthene, benzo(k)fluoranthene, benzo(a)pyrene, benzo(a)anthracene, indeno(1,2,3-cd)pyrene, dibenz(a,h)anthracene),benzo(g,h,i)perylene)	· Dichloromethane, MERCK, Germany · Methanol, Riedel de Haen, Germany · Milli-Q deionized water	Internal standards: · Naphthalene-d8, Benzo(a)anthracene-d12, Supelco, USA · Mixtures of 16 PAHs (2000 µg/ml in dichloromethane), Resteck Corporation, USA
PCBs (PCB 28, PCB 52, PCB 101, PCB 118, PCB 153, PCB 138, PCB 180)	· Dichloromethane, MERCK, Germany · Methanol, Riedel de Haen, Germany · Milli-Q deionized water	· PCB standards, IUPAC Nos. 28, 52, 101, 118, 153, 138 and 180 (10µg/ml in isooctane), Restek Corporation, USA · Certified standards of ^{13}C- labelled PCB 28 and PCB 180 (40µg/ml in nonane), Cambridge Isotope Laboratories, USA
Formaldehyde, Phenols, Cyanide Ions, Cationic, Anionic and Nonionic Detergents	· Milli-Q deionized water · Reagents for the spectrophotometric determination of formaldehyde, phenols, cyanide ions, anionic/cationic/non-ionic detergents, Spectroquant, MERCK, Germany	-
Anions (F^-, Cl^-, Br^-, NO_2^-, NO_3^-, PO_4^{3-}, SO_4^{2-})	· Milli-Q deionized water	·F^- (sodium fluoride), 1001±2 mg/dm^3 ·Cl^- (sodium chloride), 1000± 2 mg/dm^3 ·NO_2^- (sodium nitrite), 1001±5 mg/dm^3 ·Br^- (sodium bromide), 1001±2 mg/dm^3 ·NO_3^- (sodium nitrate), 1004±5 mg/dm^3 ·PO_4^{3-} (potassium dihydrogen phosphate), 1002±2 mg/dm^3 ·SO_4^{2-} (sodium sulphate), 1002±2 mg/dm^3, MERCK, Germany
Cations (Ca^{2+}, Mg^{2+}, K^+, Na^+, NH_4^+, Li^+)	· Milli-Q deionized water	·Na^+, (sodium nitrate), 1001±5 mg/dm^3 ·NH_4^+ (ammonium chloride), 1001±2 mg/dm^3 ·K^+, (potassium nitrate), 996±5 mg/dm^3 · Ca^{2+}, (calcium nitrate), · Mg^{2+}, (magnesium nitrate), 1000±2 mg/dm^3, MERCK, Germany

until analysis. Samples badly contaminated with solid material (sand, leaves, insects) were filtered (filtration, decantation). Prior to quantitative analysis, samples were treated in such a way as to isolate and/or preconcentrate PAHs/PCBs. Fig. 2 shows a flow chart for sample preparation.

The procedure shown in Fig. 3 was applied to runoff water samples for the determination of PAHs and PCBs.

Analytical Laboratory Methods

For final quantification, the concentrations of organic and inorganic compounds, metals, cations, and anions in water runoff samples were determined by various methods. Table 4 sets out the features of the techniques for determining selected parameters/analytes.

Measurement Ranges, and Limits of Detection and Quantification of the Analytical Procedures Used

Table 5 shows the measurement ranges, limits of detection (LOD), and limits of quantification (LOQ) of all the analytes tested for using ion chromatography (IC), gas chromatography coupled with mass spectrometry (GC-MS), inductively conjugated plasma mass spectrometry (ICP/MS), and spectrophotometric methods.

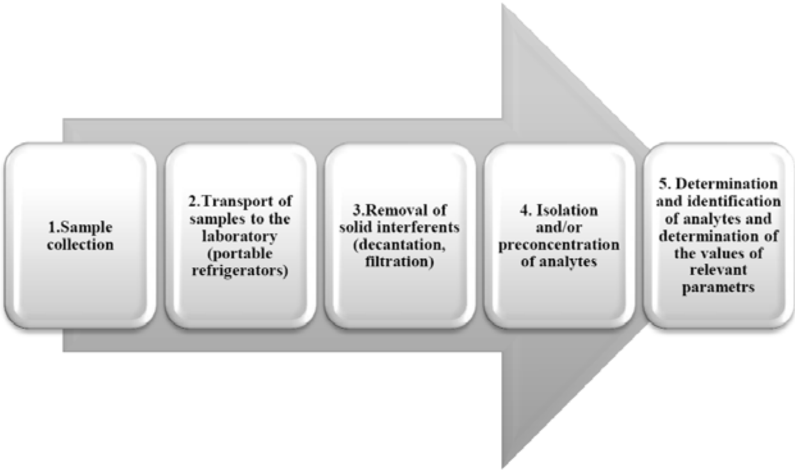

Fig. 2. Steps in the preparation of airport runoff water samples for analysis.

Results

Tests Carried out at Gdańsk and Warsaw Airports in 2008-11

Physicochemical Parameters and Inorganic Compounds

Figs. 4-7 show the mean values of physicochemical parameters (pH, conductivity), as well as ion and total metal concentrations in samples of runoff and precipitation collected at Gdańsk Airport in 2008-11 and at Warsaw Airport in winter 2010-11.

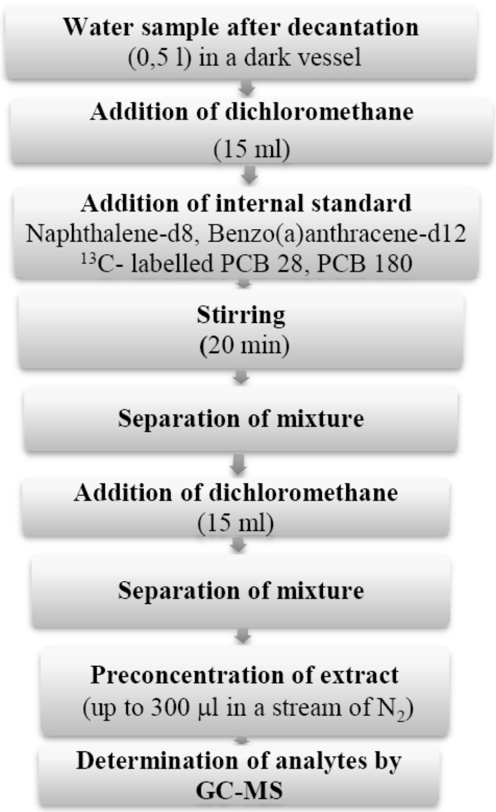

Fig. 3. Flow chart showing the procedure for determining PAHs and PCBs in samples of airport runoff waters.

The plots show the relevant values divided according to season. In each season the successive columns refer to the sampling sites. Table 6 sets out information that can be treated as a preliminary discussion of the results.

Organic Compounds

Fig. 8 shows histograms of the mean contents of TOC (Fig. 8a), anionic detergents (Fig 8b), cationic detergents (Fig. 8c), and formaldehyde (Fig. 8d) in samples of runoff and rainwater collected from Gdańsk and Warsaw airports in 2008-11 and from Warsaw in winter 2011.

Table 7 lists information that can be treated as a preliminary discussion of the results. Table 8, on the other hand, compares the values of the parameters investigated and analytes in samples of runoff and rainwater from the airports at Gdańsk and Warsaw. The levels of the parameters/analytes are classified as follows: ++ high; + medium; – low, or below the limit of detection (LOD).

Comparison of our Results with Literature Data

The subject literature boasts only a few research papers on the composition of runoff and precipitation water samples collected from airport premises. Such studies have been carried out at two airports in Poland – Gdańsk [37] and Warsaw[38], and at some other airports elsewhere in the world [19, 35, 39-42]. Figs. 9 and 10 show the mean concentrations of selected parameters and analytes in samples of runoff water collected from Polish (Gdańsk and Warsaw) and U.S. airports.

The highest levels of total organic carbon are reported for winter samples from Bradley Airport (USA) (35,000 mgC/dm^3). In contrast, at Gdańsk Airport in the winters of 2009 and 2011 and at Warsaw the respective TOC levels in runoff water samples were lower: 1,920, 1,390, and 2,784 mgC/dm^3. These values are much higher than those recorded at Newark Airport (USA) – 563 mgC/dm^3. Even though the number of passengers at Polish airports is much smaller than at US airports, the quantities of organic contaminants in runoff water samples are comparable.

Table 4. Characteristics of techniques for determining selected parameters and analyte contents in samples.

Analyte / parameter	Analytical technique	Measurement instrumentation
pH	Electrochemical technique	Multifunctional measuring instrument CX-401 (ELMETRON) with an ERH-11 electrode (measurement cell consists of a glass half-cell and a saturated chloro-silver half-cell).
Conductivity		Multifunctional measuring instrument CX-401 (ELMETRON) together with a CD-21 conductometric sensor
Total phenols	Spectrophotometric method	UV/VIS Spectrophotometer (6300)
Cyanides		
Formaldehyde		
Anionic detergents		
Cationic detergents		
Nonionic detergents		
Cations: Na^+, NH_4^+, K^+, Mg^{2+}, Ca^{2+}	Ion chromatography (IC)	DIONEX 3000 chromatograph (DIONEX, USA): → conductometric detector → column: AS22 (anions) CS16 (cations) → supressor: ASRS and CSRS 300 flow rate: 0.38 ml/min (cations) 0.36 ml/min (anions)
Anions: F^-, Cl^-, NO_2^-, Br^-, NO_3^-, PO_4^{3-}, SO_4^{2-}		
Polycyclic aromatic hydrocarbons (PAHs)	Gas chromatography coupled with mass spectrometry (GC-MS)	Gas chromatograph 7890A (Agilent Technologies) coupled with a mass spectrometer (5975C inert MSD – Agilent Technologies) → column (Agilent 190915-433, Rtx – 5MS (30 m, 0.25 mm, 0.25 µm) → detector (Agilent Technologies 5975C) with electron ionization (EI) operating in SIM mode → automatic sample injector (7683B – Agilent Technologies) → carried gas: helium → injection volume: 2 µl → time of analysis: 60 min
Polychlorinated biphenyls (PCBs)		
Total organic carbon (TOC)	Coulometric method	Module for determining total carbon: CM 5300 Furnace Apparatus Version 1.0 with a CM 5014 CO_2 coulometer (UIC INC. COULOMETRICS)
Metals	Inductively conjugated plasma mass spectrometry (ICP/MS)	Elan DRC, PerkinElmer, USA gas fed to the atomizer → Ar: 0.98 l/min, plasma gas→ Ar: 15 l/min

Table 5. Measurement ranges , LOD, LOQ of the analytes tested for using IC, GC-MS, ICP-MS, and spectrophotometric methods.

Group of compounds	Analyte	Measurement range	LOD	LOQ
Cations (mg/dm^3)	Li^+	0.01-500	0.01	-
	Na^+		0.01	
	NH_4^+		0.01	
	K^+		0.01	
	Mg^{2+}		0.01	
	Ca^{2+}		0.01	
Anions (mg/dm^3)	F^-	0.033-500	0.011	-
	Cl^-	0.03-500	0.009	
	Br^-	0.02-500	0.02	
	NO_2^-	0.16-500	0.055	
	NO_3^-	0.04-500	0.014	
	PO_4^{3-}	0.12-500	0.041	
	SO_4^{2-}	0.046-500	0.016	
PCBs ($\mu g/dm^3$)	28, 52, 101, 118, 153, 138, 180	-	-	0.05
PAHs ($\mu g/dm^3$)	Naphthalene, Phenanthrene	-	0.35	1.05
	Acenaphthylene, Chrysene		0.50	1.50
	Acenaphthene, Fluorene		0.60	1.80
	Anthracene		0.45	1.35
	Fluoranthene, Benzo(k)fluoranthene		0.75	2.25
	Pyrene		0.60	1.80
	Benzo(a)anthracene		0.55	1.65
	Benzo(b)fluoranthene		0.80	2.40
	Benzo(a)pyrene		0.05	0.15
	Indeno(1,2,3-cd)pyrene		1.40	4.20
	Dibenzo(a,h)anthracene		0.90	2.70
	Benzo(g,h,i)perylene		1.10	3.30
Metals ($\mu g/dm^3$)	Ag, Cu, Pb, Sb, Tl, Ba, Be, Cd, Co, Mo	0.05-1,000	-	-
	Al, Mn, Ni, Sn	0.5-1,000		
	U, V	1.00-1,000		
	Sr	0.10-1,000		
	As, Cr, Se	2.00-1,000		
	B	5.00-1,000		
Cationic detergents (mg/dm^3)		0.05-2.00		
Anionic detergents (mg/dm^3)		0.05-2.00		
Non-ionic detergents (mg/dm^3)		0.10-7.50		
Sum of phenols (mg/dm^3)		0.1-2.50		
Cyanides (mg/dm^3)		0.002-0.25		
Iron ions (mg/dm^3)		0.05-5.00		
Formaldehyde (mg/dm^3)		0.02-1.50		

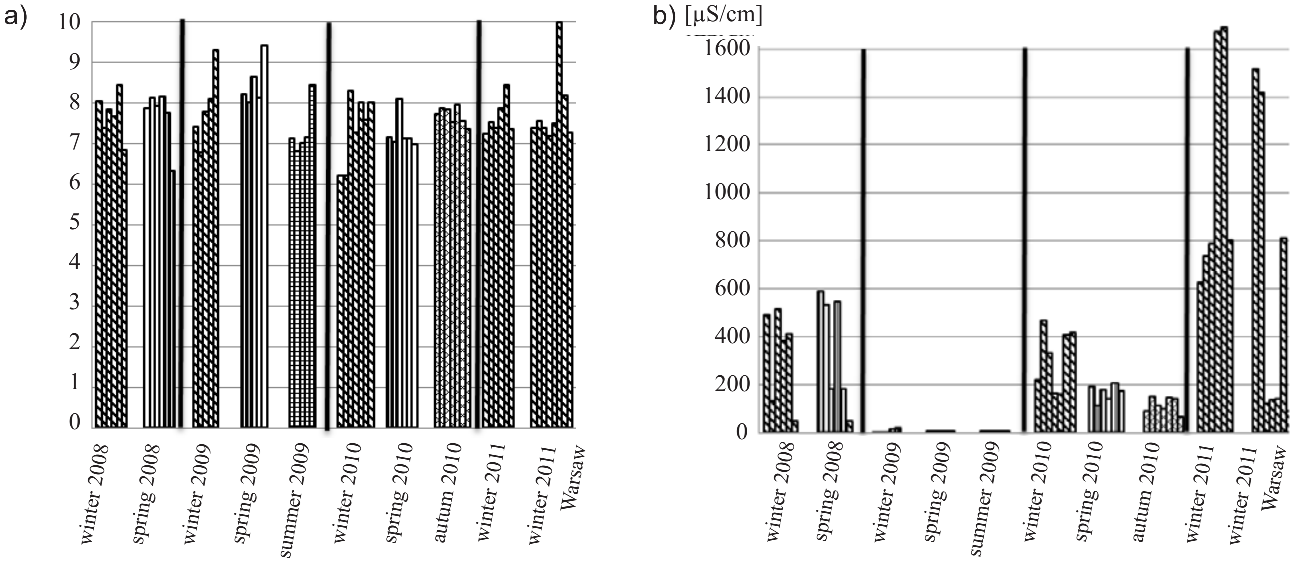

Fig. 4. Mean values of pH (a) and conductivity (b) of samples of runoff and precipitation from the airports at Gdańsk and Warsaw (2008-11). Spring, summer, autumn, winter.

The highest PAH levels were recorded at Gdańsk Airport in winter 2008 (852 µg/dm^3); at Louisville Airport this value was 150-200 µg/dm^3. Comparison of these airports with regard to the levels of naphthalene in runoff water samples indicates that they were the lowest at Warsaw Airport in winter 2011.

Conclusions

The results of contaminant analyses indicate that airport runoff waters do affect the environment around the airports at Warsaw and Gdańsk. We can draw the following conclusions from our research:

- Runoff waters at Gdańsk and Warsaw airports are qualitatively similar but quantitatively different.
- Samples of runoff and precipitation contained high levels of fluoride, chloride, phosphate, and sulphate anions, and of ammonium, sodium, potassium, magnesium, and calcium cations.
- In winter at both airports there were large concentrations of sodium and potassium cations in samples taken directly from the airport aprons and taxiing areas, and also from the aircraft parking spaces, deicing pads, and the machinery park. This would indicate that in the period 2008-11 deicing agents were based on the acetates and formates of potassium and sodium.
- At Gdańsk Airport the highest pollutant load was recorded in runoff samples from the machinery park, whereas at Warsaw Airport the highest such loads were found in samples from the refueling points and aircraft parking spaces.
- At both airports the levels of anionic detergents for washing/cleaning aircraft and car windscreens were the highest on the aprons, aircraft parking spaces, deicing pads, machinery park and the airport entrance gate for ground staff vehicles.
- The highest pollutant loads were recorded at both airports in winter, when deicing agents were being applied and when rain or snowfall was intense. Such loads were

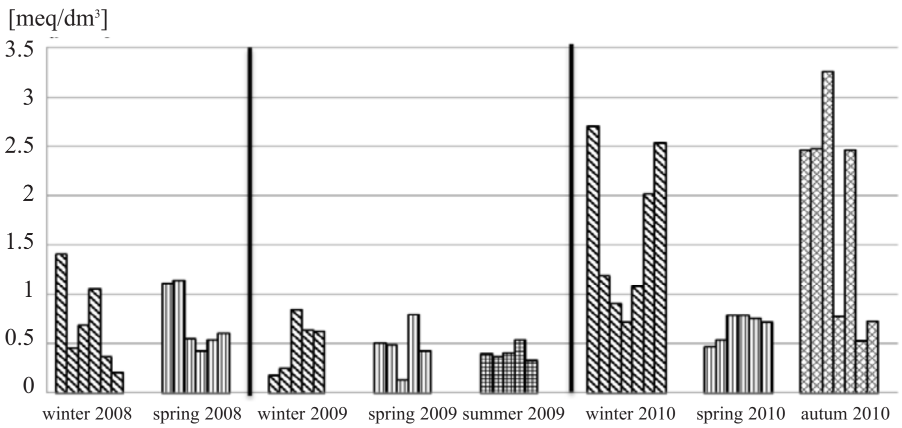

Fig. 5. Mean concentrations of calcium ions in samples of runoff and precipitation at Gdańsk Airport in 2008-10.

recorded in water samples collected directly from the airport aprons, taxiing areas, deicing pads, and refueling points. This may be due to the need to ensure the safe movement of aircraft across airport surfaces.

- PAHs were found in all samples collected from Warsaw Airport – the main source of these compounds was the combustion of liquid fuels. In contrast, the PAHs present in water samples taken from Gdańsk Airport turned out to be of both pyrolytic and petrogenic origin.
- High levels of metals were recorded: at Gdańsk Airport in samples from the machinery park, entrance gate, and car park, and at Warsaw in samples from the inflow and outflow of a natural watercourse in the airport's vicinity. This means that contaminants from Warsaw Airport are getting into water bodies, which poses a hazard to the wildlife inhabiting them.

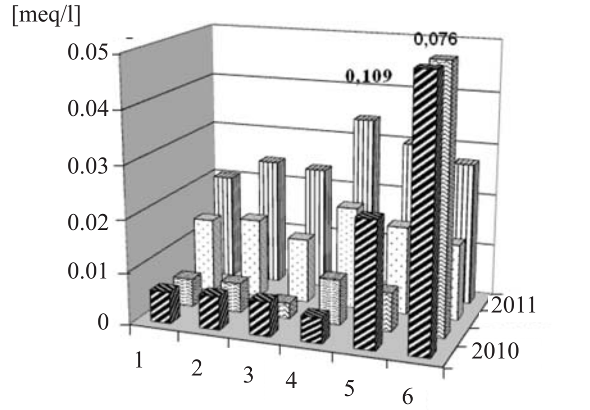

Fig. 7. Mean total metal concentrations in samples of runoff and precipitation taken from Gdańsk Airport in 2010-11.

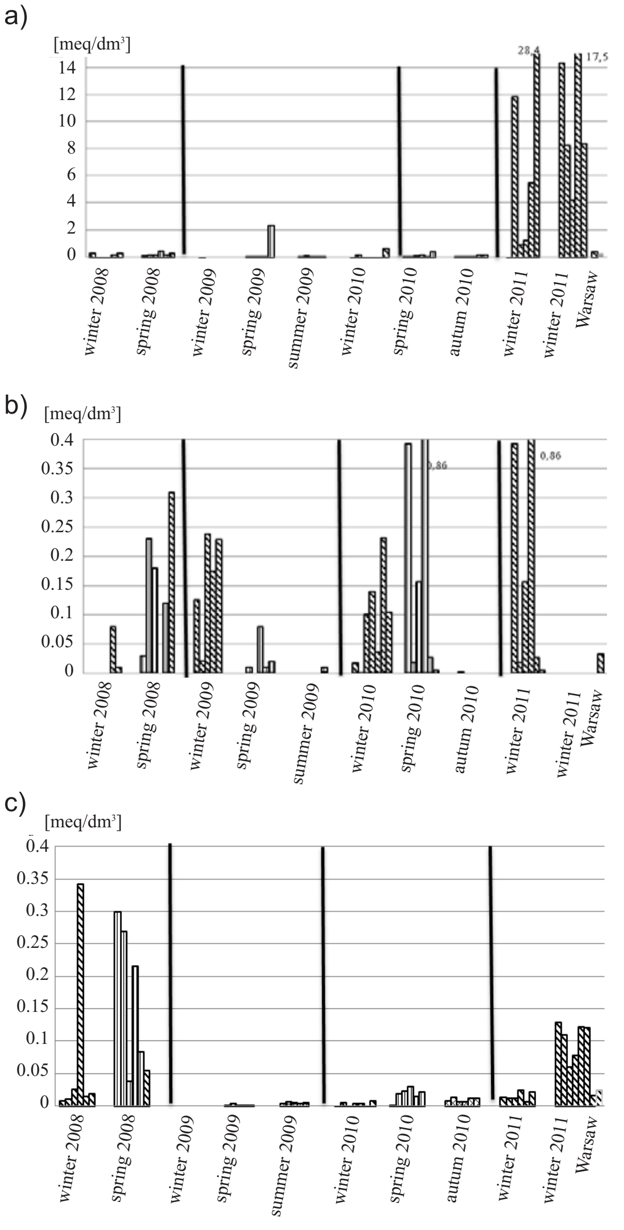

Fig. 6. Mean concentrations of chloride ions (a), phosphate ions (b), and sulphate ions (c) in samples of runoff and precipitation taken from Gdańsk Airport in 2008-11.

- At Gdańsk, contaminants were recorded all over the airport premises (airport operations carried out in different places) whereas at Warsaw the highest pollutant levels were recorded at sites where particular operations are carried out.

The results enable the effect of airport operations on and the pollutant loads emitted to the environment to be assessed. Runoff waters generated by airport operations pose a serious hazard to the environment, contributing as they do to the contamination of the air, soils, and water in the vicinity of airports.

Analysis of the contaminants present in samples of airport runoff waters provides a clearer picture and understanding of the xenobiotic cycle in the environment. It is therefore crucial that samples of runoff waters from airports should be monitored and analyzed for the largest possible number of contaminants. Only monitoring of this kind can supply data that can be used to assess the intensity of the effects of airport operations on the biotic and abiotic environment.

Acknowledgements

The authors express their gratitude for the scholarship awarded within the framework of the interdisciplinary project "The development of interdiscplinary PhD studies in modern technologies at the Gdańsk University of Technology," and for the scholarship in the project Human Capital Project "Innodoctorant IV edition" co-funded by the European Union. The authors would like to thank the National Science Center for the grant awarded within the framework of the Project No. 2011/01/N/ST4/01913 for financing this investigation.

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Table 6. Conclusions drawn from a preliminary analysis of the measurement data.

Parameter/analyte		Conclusions	Fig.
pH		· The pH of all runoff water samples was basic	4a
		· Highest pH: Warsaw – 9.97 (winter 2011) Gdańsk – 9.41 (spring 2009)	
		· Lowest pH: Gdańsk – rainwater – 6.33 (spring 2008) and runoff water (winter 2010) collected directly from the airport apron close to the terminal (site 1) and from the service road to the runway for ground staff vehicles (site 2) Warsaw – the lowest pH values were recorded in samples taken from the machinery park	
		· Only in 2008 was pH<7 for precipitation; in all the other seasons this parameter was in excess of 7.00	
Conductivity		· Conductivity at Gdańsk Airport was the highest in samples collected in winter 2011 at the machinery park (Site 4) and the car park (Site 6): 1,673 µS/cm 1,691 µS/cm, respectively	4b
		· At Warsaw Airport conductivity was the highest at the river inflow (Site 1)	
		· In 2009 conductivities were the lowest in the entire research period (< 7.57 µS/cm)	
		After 2011 there was a dramatic rise in conductivity values at both airports	
Cations	Ammonium ions*	· Ammonium ion concentrations were lowest in the winters of 2008 and 2009	-
		· In winter 2010 ammonium ion levels were highest (2.10 meq/dm^3) in runoff water samples from the airport aprons and taxiing areas (Site 1)	
		· In the springs of 2008-10 ammonium ion concentrations in samples did not exceed 0.10 meq/dm^3	
	Calcium ions*	· Levels of calcium ions in runoff water and precipitation samples were high in comparison with those of other ions	5
		· The highest level of calcium ions was recorded in water samples taken directly from the airport aprons and taxiing areas (> 2.50 meq/dm^3)	
	Potassium ions*	· In winter 2009 potassium levels were highest (81.7 meq/dm^3) in water samples taken from the entrance gate to the airport.	-
		· At all the other sampling sites potassium concentrations were always low (< 5.00 meq/dm^3)	
	Sodium ions*	· In winter 2009 sodium levels were the greatest in samples from the machinery park (site 4) and from the entrance gate. The respective Na^+ levels at these sites were 162 and 173 meq/dm^3	-
		· In other seasons Na^+ levels did not exceed 4.50 meq/dm^3	
	Magnesium ions*	· The highest levels (2.12 meq/dm^3) were recorded in winter 2010 in samples from the airport aprons and taxiing areas (site 1), and in autumn 2010 (1.40 meq/dm^3) in samples from the service road to the runway for ground staff vehicles (Site 2)	-
		· In 2008-09 Mg^{2+} levels were low (< 0.40 meq/dm^3) compared to 2010	
Anions	Fluoride ions	· Fluoride ion levels in the samples from both airports were very low in comparison with the concentrations of other anions.	-
		· The highest F^- concentrations were recorded in samples from the airport aprons and taxiing areas (Site 1), and also from the deicing pads (Site 3) in winter	
		· No F^- were recorded in samples taken in summer or autumn	
	Formate ions	· Formate ions were present in low concentrations in runoff samples from both airports	-
		· The highest levels were recorded in winter 2009 at Gdańsk Airport at the de-icing pad (139 meq/dm^3) and in the samples taken from the machinery park (159 meq/dm^3)	
	Chloride ions	· In 2011 there was a dramatic increase in chloride ions in runoff waters at both airports in comparison with the previous 3 years	6a
		· The highest mean Cl^- concentration was recorded at Gdańsk Airport in winter 2011 (28.4 meq/dm^3)	
	Nitrite ions	· The content of nitrite ions in water samples from both airports in 2008-11 was low; the highest levels were recorded in rainwater samples (0.29 meq/dm^3)	-
		· Maximum NO_2^- levels were determined in runoff samples from the car park at Warsaw Airport (45 meq/dm^3)	
	Phosphate ions	· Phosphate levels varied widely in runoff waters (0.12-0.66 meq/dm^3) throughout the measurement period	6b
		· The highest mean levels (0.86 meq/dm^3) in runoff waters were found in samples taken in spring 2010 and 2011 from the machinery park at Gdańsk Airport.	

Table 6. Continued.

Parameter/analyte		Conclusions	Fig.
Anions	Sulphate ions	· In ca 56% of samples the sulphate level was < 0.10 meq/dm³	6c
		· The highest sulphate concentrations were recorded in runoff samples at Warsaw Airport in winter 2011 (0.25-1.3 meq/dm³)	
	Cyanide ions	· The highest CN^- levels (0.11 mg/dm³) were recorded in winter 2011 in runoff samples taken directly from the airport apron near the passenger terminal (Site 5)	-
		· In autumn 2010 CN^- levels were 0.003-0.010 mg/dm³, and in winter 2011 they ranged from 0.02 to 0.11 mg/dm³	
		· In ca 83% of samples from different sites, cyanide ion concentrations were always less than 0.06 mg/dm³	
	Total metals	· The highest total metal concentrations were measured in runoff samples from the car park (Site 6) at Gdańsk Airport throughout the study period, and from the deicing pad, aircraft refueling points, and aircraft park in Warsaw (0.15 meq/dm³)	7
		· From 2010 onwards the total metal content increased	
		· In 2008-09 runoff and rainwater samples were not analyzed for their metal contents	

* This refers to samples of runoff water and precipitation collected at Gdańsk Airport. Cations in the samples taken at Warsaw Airport in winter 2011 could not be determined because of a breakdown in the IC apparatus.

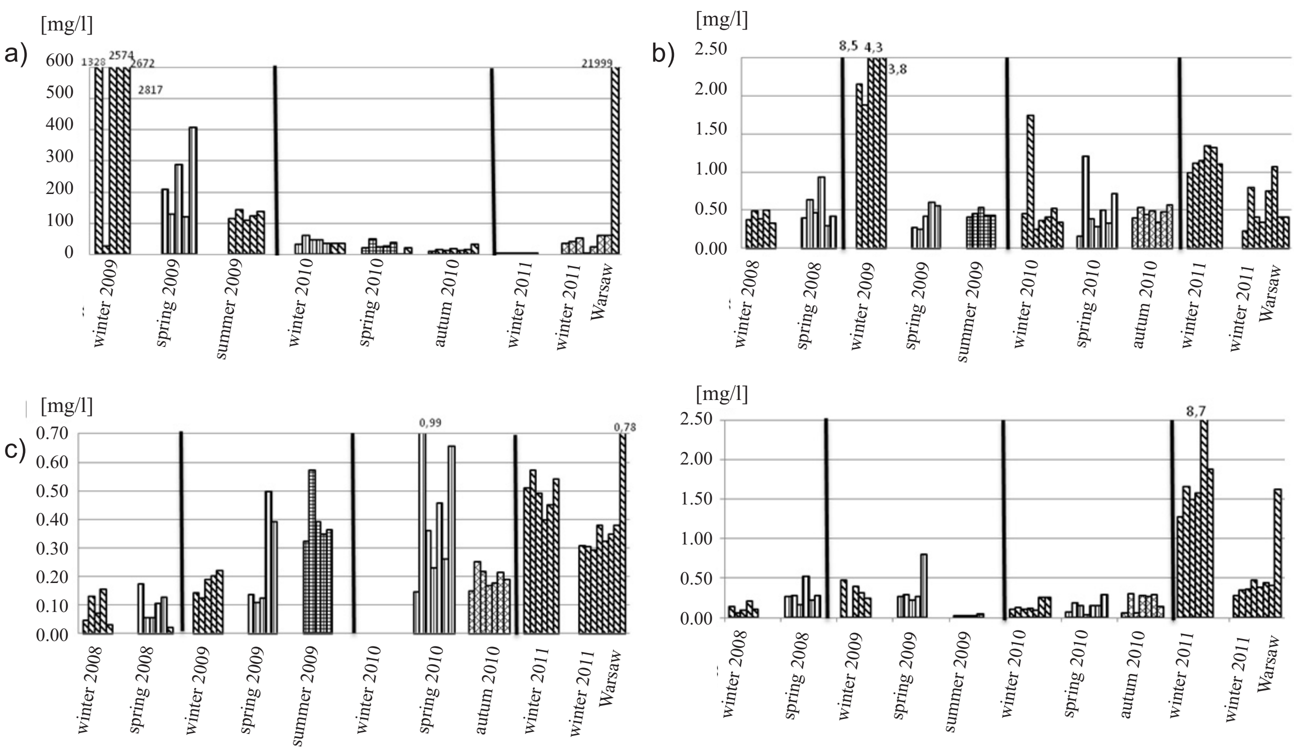

Fig. 8. Mean contents of total organic carbon (a), anionic detergents (b), cationic detergents (c), and formaldehyde (d) in samples of runoff and rainwater collected from Gdańsk and Warsaw airports in 2009-11.

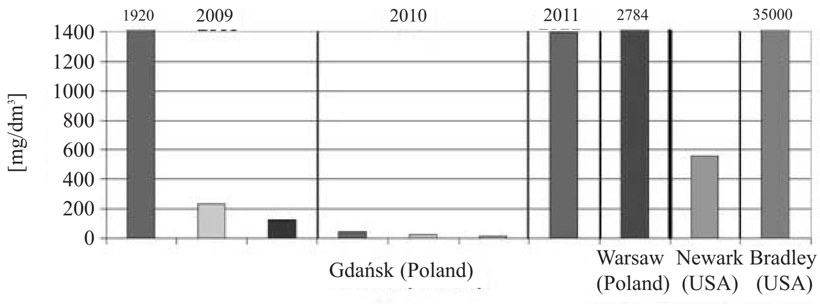

Fig. 9. Mean levels of total organic carbon in runoff water samples collected in winter from the airports at Gdańsk and Warsaw (Poland) and Newark and Bradley (USA).

Table 7. Information that can be treated as the results of the preliminary analysis of the measurement data obtained.

Parameter/ analyte	Conclusions	Fig
TOC	· The highest TOC levels were recorded in water samples from Warsaw Airport. This parameter reached dramatically high levels at refueling points and aircraft parking spaces (21.999 µg/dm³)	8a
	· The highest TOC values at Gdańsk Airport were recorded in winter 2009 and 2011 (2,672 and 3,162 mgC/dm³, respectively) in samples from the machinery park (Site 4).	
	· At both airports in 2009 and 2010 TOC levels were high in all the samples from different sites	
Anionic detergents	· Anionic detergent concentrations at both airports were the highest in winter, particularly in 2009 and 2011	8b
	· Anionic detergent levels in ca 55% of samples taken between spring 2008 and winter 2011 did not exceed 1.00 mg/dm³	
Cationic detergents	· Levels of cationic detergents (used mainly for washing aircraft and ground service vehicles) were distinctly higher in winter 2011 than at other times during the research period	8c
	· The highest levels of these detergents were determined in runoff water from refueling points and aircraft parking spaces at Warsaw Airport (0.78 mg/l)	
Non-ionic detergents	· Samples collected from spring to winter 2008 and in winter 2010 were not analyzed for non-ionic detergents.	-
	· Levels of these analytes varied widely throughout the study period at both airports.	
	· The highest mean levels of non-ionic detergents (7.50 mg/dm³) were recorded in samples from refueling points and aircraft parking spaces at Warsaw Airport in winter 2011	
Formaldehyde	· Formaldehyde levels at both airports in winter 2011 were as high as those recorded in previous study periods	8d
	· A record high level was found in a sample from the apron at Warsaw airport (a refueling point and an aircraft parking space)	
Total phenols	· In general the total phenol content in the samples from both airports was highest in winter and spring	-
	· Most phenols were determined in a sample from Warsaw Airport (a refueling point and an aircraft parking space) (3.33 mg/l)	
PCBs	· Higher PCB levels were recorded in water samples from Gdańsk than from Warsaw	-
	· The highest PCB levels recorded in samples taken from Gdańsk between spring 2008 and winter 2011 referred to PCB 153 (samples from the car park – Site 6)	
	· The concentrations of PCB 138 (0.30 µg/dm³) and PCB 101 (0.13 µg/dm³) were the highest in samples taken directly from the runway and taxiing areas	
	· Levels of all PCBs in winter precipitation samples were higher than in the corresponding spring samples. They ranged from 0.014-0.017 µg/dm³ (winter) to 0.002-0.006 µg/dm³ (spring)	

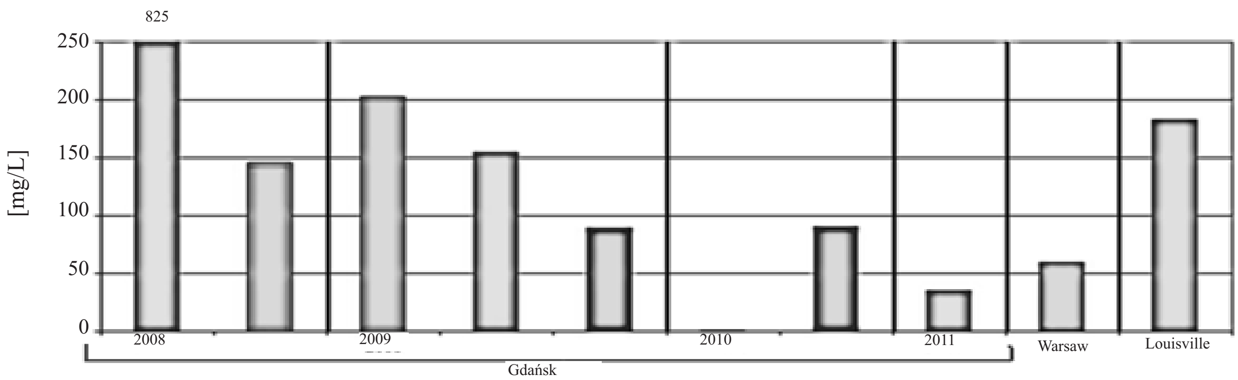

Fig. 10. Mean concentrations of naphthalene in runoff water samples collected from the airports at Gdańsk and Warsaw (Poland) and Louisville (USA).

Table 8. Comparison of analyte levels determined in runoff water samples collected from two Polish airports (Gdańsk and Warsaw) in winter.

Parameter /analytes		Gdańsk 2009-2011 (winter)							Warsaw 2011 (winter)							
		Sampling sites														
		1	2	3	4	5	6	7	1	2	3	4	5	6	7	8
pH		alkaline							slightly alkaline					alkaline	slightly alkaline	
Conductivity		+	+	+	++	++	+	+	++	++	+	+	+	++	+	+
Anions	F^-	++	+	++	++	++	+	+	-	-	-	-	-	-	+	++
	Cl^-	+	++	+	+	++	++	-	++	+	+	++	+	-	-	-
	NO_2^-	-	-	+	+	-	+	+	-	-	-	-	-	++	+	+
	Br^-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	NO_3^-	-	+	-	+	-	-	-	++	-	-	+	-	++	-	-
	PO_4^{3-}	+	+	+	++	+	+	+	-	-	-	-	-	-	-	-
	SO_4^{2-}	+	+	+	++	+	+	+	++	++	+	+	++	++	+	+
Cations	Na^+	++	-	++	++	++	-	-								
	NH_4^+	++	++	-	++	+	+	-								
	K^+	++	-	++	++	++	-	-								
	Mg^{2+}	++	+	+	+	+	+	-								
	Ca^{2+}	++	+	+	+	+	++	-								
Sum of phenols		+	+	+	++	++	++	-	++	++	-	-	-	-	+	+
Cyanides		+	+	+	+	++	++	-	+	+	++	+	+	+	+	++
Formaldehyde		+	+	+	+	++	++	-	+	+	+	+	+	+	+	++
Anionic detergents		+	+	++	++	++	+	-	+	++	+	+	++	++	+	+
Cationic detergents		+	+	+	-	-	++	-	+	+	+	+	+	+	+	++
Non-ionic detergents		-	+	-	+	++	++	-	+	+	+	+	+	+	+	++
TOC		+	+	+	++	+	++	-	+	+	+	-	+	++	++	++
PCBs		++	++	++	+	+	++	+	+	+	+	++	+	+	+	++
PAHs		Origin: pyrolytic and petrogenic							Origin: petrogenic							

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