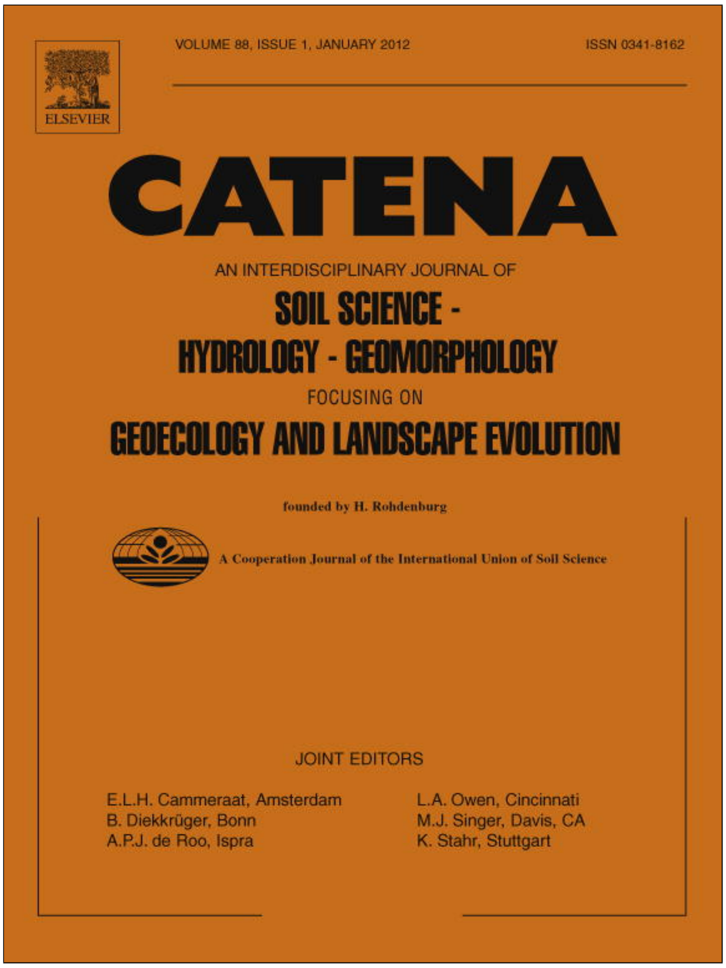
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Impact of cemeteries on groundwater chemistry: A review

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A B S T R A C T

Studies on the impact of cemeteries on groundwater quality were initiated by van Haaren in 1951, and were occasionally undertaken in the 1970s and 1980s in Germany, the United Kingdom, Canada and South Africa. Regular studies only began in the late 1980s and were continued in the 1990s in Brazil, South Africa, Australia and Poland. On a smaller scale, this kind of research was also undertaken in other countries such as the USA, Portugal, and France. An overview of the results of those studies and focuses on the environmental conditions is presented, which according to current research, highlights the hazards associated with the significant chemical contamination of water.

Contents

1. Introduction

If inappropriately located or insufficiently protected, cemeteries pose a significant health problem for people (Fisher and Croukamp, 1993). Several countries do not have appropriate legal regulations with regard to this problem, and it is also being overlooked by national governments.

In Christian countries, cremation was abandoned in the 5th century and was opposed by Christians for 15 centuries. Only the Instruction [with regards to] cremation of bodies endorsed on 8 May 1963 by the Supreme Sacred Congregation of the Holy Office, allowed this form of burial. Above all, the Church values the custom of interment and permits the cremation of human remains provided that the process does not contradict certain principles of Christian faith.

In Hinduism or Buddhism, cremation is the basic form of burial, whilst it is not practised in Islam or Judaism. A large proportion of the world's population accepts inhumation on separate burial grounds and these locations accumulate significant amounts of organic matter.

Modern research highlights two types of impact that necropolises have on the environment; namely: in the short and long-term. In groundwater, the impact is associated with increased concentrations of intestinal flora (Dent and Knight, 1998; Matos, 2001), ions (Knight and Dent, 1995; Pacheco et al., 1991), amino acids (Żychowski et al., 2002; Żychowski et al., 2003) and other organic compounds (Żychowski, 2007); ptomaine and various chemical elements in soils (Spongberg and Becks, 2000a, 2000b; Forbes, 2002; Żychowski, 2000; Żychowski et al., 2006), and gases such as PH_3, P_2H_4 and C_2H_4 in the air (Żychowski, 2009). The concentrations of these contaminants are usually measured using ion chromatography systems (water), gas chromatographs (air) and an atomic absorption spectrometer (solid particles) (Forbes et al., 2003; Stuart et al., 2000, Żychowski, 2008, 2009). This paper reviews the results of studies on the impact of cemeteries on the quality of groundwater in unsaturated and saturated zones. The studies are usually conducted within or at some distance from the cemeteries (Schraps, 1972; Żychowski et al., 2000b). Monitoring of the groundwater is designated by the researchers or carried out according to officially approved procedures. In the UK, the monitoring of groundwater contamination around cemeteries is undertaken in parallel with groundwater quality monitoring conducted in landfills. Detailed

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methodology is provided in the *Guidance on Monitoring of Landfill Leachate, Groundwater and Surface Water* of Dumble and Ruxton (2000) and *Guidance from the Advisory Committee on Dangerous Pathogens* of Transmissible Spongiform Encephalopathy Agents (2003). The monitoring of soils in cemetery grounds is recommended at a depth of between 0.5-1 m below the interment level (Creely, 2004; Environmental Agency, 2002).

The circulation of groundwater is often difficult to determine, especially in impermeable bedrock (Dent 2005; Knight and Dent, 1998). Archaeological and geophysical techniques are increasingly used in these studies (Bastianon et al., 2000; Braz et al., 2000). Most expert studies are based on piezometers, which should be placed along the hydraulic gradient. Some researchers use ditches, or wells in cemeteries, drainage wells or wells located in farms close to cemeteries (Chan et al., 1992; Żychowski et al., 1996; 2000a,b; 2003). Study results are also influenced by factors other than cemetery-related ones, both natural and anthropogenic (Dent, 2000a,b; Trick et al., 1999), and especially the quality of shallow groundwater (Rodrigues and Pacheco, 2003).

Over 40% of cemeteries in South Africa contaminate water resources (Fisher and Croukamp, 1993). Local authorities seem oblivious to the problem. Both legal regulation and the determination to act in a way which would limit the threat are lacking (Alfoldi and Croukamp, 1988; Bitton et al., 1983). Most researchers assess the impact of interment on the environment by comparing study results from cemeteries with data from reference sites. This type of assessment is satisfactory despite some possible errors. These errors are usually related to the heterogeneity of substrate properties in cemeteries and reference sites, or insufficient hydraulic gradients (Creely, 2004; Knight and Dent, 1998).

Most studies treat cemeteries as *black boxes* (Dent, 2000b). Decomposition products accumulated within a cemetery constitute the "inputs" to the model, while decomposition products migrating out of a cemetery represent the "outputs". The impact of burial grounds on groundwater has been extensively examined in Australia (Knight, Dent, Forbes, Stuart), Brazil (Pacheco, Matos, Bastianon, Silva, Mendes, Batello, Gamba, Pellizari), South Africa (Croukamp, Fisher, Richards, Tumagole), the UK (Trick, Noy, Klinck, Coombs, Chambers, West, Williams, Moore, Reeder), Portugal (Rodrigues), Kanadzie (Chan, Scafe, Emami), USA (Spongberg, Becks) and Poland (Żychowski, Lach, Pawlikowski, Kolber). Some researchers have published reports on the subject (Creely, 2004; Morgan, 2004; Ucisik and Rushbrook, 1998).

The Bereavement Services Management Centre in the United Kingdom commented on the report by Ucisik and Rushbrook (1998): "This review considers the current state of knowledge on the fate of decomposition products from human corpses as they pass through the soil and into the groundwater. This report is intended to provide an introductory briefing on the state of knowledge regarding water pollution from cemeteries and the mechanisms operating to ameliorate the pollution potential. Some suggestions are provided on the siting and design of future burial sites." (Rotherham, 2011).

The Creely Report (2004) describes the results of a literature review undertaken for the British Institute of Embalmers (BIE), in order to determine the infection risks to which funeral directors and embalmers are exposed from embalmed or unembalmed cadavers. The report assessed the effectiveness of embalming fluids on the viability of infectious organisms, and considered strategies for preventing infections. Other topics relating to the disposal and decomposition of human remains are also highlighted.

Morgan in his research/study (2004) reviewed the existing literature in order "to assess the risks of infection from dead bodies after a natural disaster occurs, including who is most at risk, what precautions should be taken, and how to safely dispose of the bodies".

2. Impact of burial on groundwater chemistry

Studies on the impact of burials on groundwater carried out in different countries, at different times and under diverse environmental conditions, give a range of results. The influence of cemeteries on the groundwater regime was first investigated by van Haaren (1951) who measured, though without an assessment of the soil properties, high concentrations of some ions in shallow groundwater (e.g. chlorides - 500 mg/l, sulphates - 300 mg/l, bicarbonates - 450 mg/l) and high conductivity (2300 μS/cm). High ion concentrations in the immediate neighbourhood of graves, especially 50 cm below the interment level, were confirmed by Schraps (1972) in Germany. Schraps focused on the variability of ion concentrations depending on the distance from the burial ground and the inclination of its surface, with respect to chemical oxygen demand (COD), nitrate and ammonium concentrations, carbon dioxide and gaseous ammonia.

High concentrations of these contaminants quickly decreased with distance from the burial sites. Schraps (1972) also found evidence of bacteria near cemeteries in groundwater. Bouwer (1978) reported the sweet taste of water and foul odour from wells in the vicinity of cemeteries in Paris. In 1863–1867, a higher incidence of typhoid fever was noted in communities living near cemeteries in Berlin (Bouwer, 1978). This kind of contamination was not confirmed by studies in Hamburg, where the lower contaminant concentrations resulted from a thicker (0.7 m) unsaturated zone under the graves and lower permeability of the soil (Hanzlick, 1994).

A reduction in contamination levels with distance from cemeteries was also measured by Gray et al. (1974). These results were promptly followed by a major research programme funded by the UK's Department of the Environment entitled "The behaviour of Hazardous wastes in Landfill Sites". British researchers noted a slow decrease of ion concentrations between 100 and 200 m from a cemetery and a rapid decrease beyond 200 m. Studies carried out in England and Wales point to the high concentrations of chlorides close to and under burial sites. The additional reason behind such high levels of contamination was the unfavourable hydrogeological setting - natural high permeability and supposedly poor attenuation characteristics of geological barriers in the subsurface, primarily excessive sand, and sandstone (Gray et al., 1974). The impact of cemeteries on groundwater was then brought to the attention of the UK Parliament and especially the Environment, Transport and Regional Affairs Committee (Memorandum (CEM 56), 2000). Studies on the environmental impacts of cemeteries were commissioned by the UK government and completed by the British Geological Survey and the Environment Agency (Trick et al., 1999, 2001, 2005a,b). One of the research sites was the Carter Gate Cemetery in Nottingham, which opened in 1813, and remained in use until 1875 (Trick et al., 1999). The study at Carter Gate Cemetery demonstrated low groundwater contamination with sulphates, chlorides and sodium ions, and higher concentrations locally of carbolic acid and zinc, which was associated with the considerable thickness of the unsaturated zone (max. 9.4 m at the time of the study). Pigmented soil in this zone showed increased concentrations of P, Ca, Cu and Zn. A solution sampled from the soil at depths of 2–3 m contained, with neutral pH, relatively higher concentrations of sulphates, chlorides, potassium, manganese, sodium and calcium as well as large amounts of TOC and ammonia. Ammonia was considered to be the main product of decomposition, being more mobile than chloride, sulphate and sodium ions which are thought to migrate through the unsaturated zone for up to 20 years. Some of the contaminants are also derived from other sources e.g. sandstones and sewage leaks. Manganese is leached from Triassic sandstones, while bromine (0.49 mg/l) and phosphorus (3.06 mg/l) may come from sewage leaks. Higher concentrations of organic substances from anthropogenic sources (e.g. chlorinated hydrocarbons, phthalates and volatile fatty acids) were found in the unsaturated zone below the graves. The concentrations of the acids, increased content of ammonia and other substances suggest the limited environmental impact of this cemetery (Trick et al., 1999).

Trick et al. (2001, 2005a) found relatively increased concentrations of chloride, sulphate, sodium and calcium in the lower part of a cemetery in Wolverhampton, while in the middle part of the cemetery, nitrate, sulphate, bicarbonate, carbonate, potassium and magnesium ions were abundant. Significant contamination was found in water sampled from piezometers in shallow groundwaters, typified by the highest temporal variability of sulphates, sodium, chlorides and TOC content. At times, the water also contained high concentrations of organic carbon and other ions (e.g. ammonium, copper, manganese, zinc, iron and occasionally also arsenic). High concentrations (16 mg/l) of volatile fatty acids were detected in only one piezometer, whilst another showed increased levels of trichloroethane and tetrachloroethane. Diethylhexylphthalate was found in nearly all sampled piezometers and was probably supplied during the study.

Studies by Young et al. (1999) in Northwood Cemetery in West London revealed high concentrations of formaldehyde (8.6 mg/l) close to the recent interment site. Young et al. (1999) drew attention to the rarely-studied occurrence of pesticides, natural fertilizers and herbicides in the cemetery environment. A report by the UK Environment Agency indicates controls on decomposition - include depth of burial, embalming and type of caskets used and points to nitrates, phosphorus, calcium, mercury, formaldehyde and bacteria as potential dangers from the cemeteries (Hart and Casper, 2004). Hart and Casper (2004) assume that total decomposition is completed after 100 years. In Europe, the impact of cemeteries on groundwater is best studied in the United Kingdom, although it seems, however, that the reports outnumber genuine research projects (Young et al., 1999).

This kind of research is also carried out in Poland. The results of such studies were presented, for the first time, by Żychowski et al. (1996). These authors measured the concentrations of various ions, amino acids and bacteria in groundwater close to or under cemeteries. Most of the studies involved the assessment of bedrock conditions in the burial grounds.

The quality of groundwater in the cemeteries of south-eastern Poland is satisfactory where the aquifers are fairly deep, such as in the uplands and in the Beskidy Mountains. At these sites, the contents of the studies ions rarely exceeded allowable levels. The latter case includes manganese and iron. However, significantly increased concentrations of several ions (nitrates, nitrites, sulphates, ammonia, phosphates, chlorides, potassium and sometimes fluoride) were reported from the cemeteries located along valley floors, in the marginal zone of the Carpathian Mountains and the Cracow Upland, as well as on the slopes of the Carpathian Mountains. Contamination is facilitated by the presence of sandy and gravelly deposits underlain by impermeable Miocene clays, as in Niepołomice near Cracow (Żychowski 2011; Żychowski et al., 2000a).

Studies by Żychowski et al. (2000b, 2002, 2005, 2007), Żychowski (2008, 2009) stress the significance of local geology and topography, weather conditions and water table oscillations upon the adverse impact exerted by the cemeteries on groundwater.

Polish studies demonstrated that the least contaminated sources were the waters sampled from cemeteries located on nearly impermeable alluvium and on gentle slopes (Żychowski et al., 2000b). Both in the cemeteries and their surroundings (under the same conditions) the waters contained increased sulphate and potassium concentrations, while increased phosphate levels were less common. Sporadically, relatively higher ammonium and fluoride concentrations were noted. Nitrate concentrations usually increased close to the cemeteries, in wetter periods and on alluvial terraces.

Based on 11 analyses, Żychowski (2008) assessed the quality of groundwater within or close to 26 mass graves from WWI and WWII. Concentrations of phosphates, iron, manganese and, to a lesser extent, copper, zinc and aluminum ions were at higher concentrations compared to the hydrochemical background. The values for the mass graves were typical of the surroundings areas of the largest mass graves from WWII, located on the terraces of the Vistula, Dunajec and Raba rivers, especially where the graves are located on sandy material underlain by impermeable deposits (Table 1). Contamination of the groundwater was more common on landslide slopes such as in Biecz, where the samples of water had been collected from a well situated on the landslide zone below the cemetery (Table 2). The water sampled from under a WWII mass grave in Niepołomice near Cracow, had concentrations of nitrates, ammonium, phosphates, fluoride, chlorides and sulphates between 2 and 5 times higher. The water table in the sandy deposits above Miocene loams was shallow and subject to fluctuations (Żychowski et al., 2007). The variability of water quality corresponds to these water table fluctuations.

Except for iron and manganese, Żychowski (2008, 2009, 2010) did not find increased levels of other indicators in deep aquifers below cemeteries located on the top of hills, gentle flat slopes or on alluvial fans (Table 2). Other studies, such as in Nottingham, also confirm the importance of the thickness of the aeration layer (Trick et al., 1999).

The studies conducted by Żychowski (2008) indicated the high variability of the chemical composition of groundwater close to cemeteries, especially with respect to phosphate ions which migrate with infiltrating water resulting from major downpours or rapidly melting snow. A fairly novel approach was introduced by Żychowski et al. (2002, 2003, 2005) who tested the content of some amino acids; namely lysine, glutamic acid, glycine, leucine and isoleucine, in the groundwater taken from some cemeteries in south-eastern Poland. The content of lysine in the water sampled from cemetery wells is

Table 1
Analyses of groundwater sampled in and close to cemeteries and mass graves, and their hydrochemical backgrounds.

Cemeteries and mass graves	Analytes [mg/l]								Depth of water table [m]
	NO_3^-	NH_4^+	SO_4^{2-}	PO_4^{3-}	F^-	Cl^-	Fe^{3+}	Cu^{2+}	
Cerekiew, cm.	12.32	1.02	185.32	0.72	0.56	89.36	0.36	0.05	5-6
Cerekiew, background	5.21	0.52	115.21	0.63	0.22	85.21	0.52	0.01	5-6
Wojnicz, cm.[a]	8.36	5.23	82.21	0.81	0.72	56.36	1.22	0.01	4-5
Wojnicz, background	4.52	2.22	77.21	0.63	0.56	53.33	1.07	0.01	4
Gorlice, below m.g.[b]	8.26	1.05	89.36	0.26	0.21	75.22	0.72	0.02	4-5
Gorlice, background	7.36	1.14	92.32	0.34	0.09	72.21	0.52	0.04	4-5
Glinik, close to m.g.[b]	5.21	2.21	100.11	0.92	0.22	56.33	1.52	0	4-5
Glinik, background	4.25	0.85	52.21	0.72	0.14	45.21	1.32	0	6
Niepołomice, m.g.[c]	28.27	1.11	248.8	2.9	1.54	204.31	2.97	0.09	2-2.5
Niepołomice, background	4	0.24	61.17	0.94	0.6	47.21	1.64	0.02	1.5-2.0

Water sampled in October and November, 2004.
[a] cm. - cemetery.
[b] m.g. - mass grave from WWI.
[c] m.g. and WWII.

Table 2
Ion concentrations in groundwater sampled in or close to cemeteries and mass graves.

Cemetries and mass graves	Analytes [mg/l]									Depth [m]	Date
	NO_3^-	NH_4^+	SO_4^{2-}	PO_4^{3-}	F^-	Cl^-	Fe^{3+}	Cu^{2+}	Al^{3+}		
Nowy Sącz, cm.[a]	68.89	1.98	268.32	26.33	1.2	251.36	0.85	0.29	0.35	5-6	28.06.02
Oświęcim, close to m.g.[b]	180.14	6.32	624.25	89.99	2.28	602.33	2.82	0.36	0.69	3-4	9.12.04
Rakowice, cm.[a]	1.55	0.06	30.21	0.17	0.06	80.21	0.13	0	0	7.5	28.10.04
Niedzieliska, cm.[a]	18.98	0.23	284.21	1.96	0.52	225.21	0.92	0	0.08	1.5- 2	31.05.02
Gorlice, below[c]	49.32	1.03	79.36	5.36	2.36	82.06	1.02	0.25	0	5	19.05.02
Biecz, below[c]	87.25	1.82	276.32	12.05	5.01	312.12	3.92	0.3	0.001	1.2	19.05.02
Szczepanów, cm.[a]	15.89	0.31	75.21	1.82	0.24	85.23	0.15	0.17	0	5-6	16.06.02
Mikluszowice, cm.[a]	32.87	0.96	56.32	12.02	0.96	102.14	0.11	0.01	0.39	5-6	9.06.02

[a] cm. - in a cemetery.
[b] m.g. - mass grave from WWII.
[c] below - below mass graves from WWI.

approximately one third higher than background values in sandy, alluvial and loess substrates (Żychowski et al., 2002). Only in clay bedrock was the concentration of lysine and glycine low, and often lower than the background values. Polish authors i.e. Żychowski et al. (2002, 2003, 2005) suggest that glycine concentrations exceeding 12 ppm indicate that it originated during decomposition.

Żychowski (2007) also determined the levels of other organic compounds, such as cadaverine, bromodichloromethane, chlorfenvinphos, ethanolamine, chlorinequat chloride and phosphamidon in groundwaters under a mass grave in Niepołomice. Piezometer samples confirmed the presence and a relatively high concentration (2.41 μg/l) of toxic chlorinequat chloride which is corrosive towards metals. The concentration of health-threatening cadaverine was low.

Rodrigues and Pacheco (2003) emphasized the problem of chemical and bacterial contamination of groundwater in three Portuguese cemeteries: Luz de Tavira, Querenc and Seixas. All groundwater samples from these cemeteries, irrespective of climatic conditions, contained heavy metals including zinc and lead (Rodrigues, 2002).

Studies by Chan et al. (1992), commissioned by the Ministry of Environment of the Province of Ontario in a Toronto cemetery, noted the contamination of groundwater with formaldehyde. Groundwater collected from six cemeteries had concentrations of formaldehyde at the level of 1–30 μg/litre. According to Levine et al. (1984) in Ontario, the danger to humans from formaldehyde is limited, although the measured concentrations could not be compared to legal norms as these have not yet been established. Chan et al. (1992) also indicated bacterial, nitrate, nitrite and phosphate contaminations in cemetery groundwater. With one exception being that the concentrations of the ions were very low (<10 mg/l) at all the sites. Studies in North America demonstrated contamination at burial sites resulting from materials used in casket production, including polychlorinated biphenyls (PCBs), methanol and solvents (Beak Consultants Ltd., 1992). Beak Consultants Ltd. (1992) observed slightly higher, compared with legal norms, concentrations of copper and zinc, whereas increased 5-day biochemical oxygen demand levels most probably resulted from the former existence of a pond. The study results were in part interpreted in relation to the substrate type and groundwater levels. The depths of watertables in the two cemeteries studied in Toronto were mostly about 12–13 m and sporadically about 3–5 m. The substrate was composed of fine sands and silts.

The negative impacts of cemeteries on drinking water quality have been noted by experts and high ranking officials (Schneider et al., 1993). A White House report of 1980 mentions cemeteries as a potential source of environmental pollution, however, it does not indicate formaldehyde as a major hazard (Cook, 1999). American researchers associate a higher risk with arsenic (Konefes and McGee, 1996; Spongberg and Becks, 2000b). Studies in Iowa revealed 30 ppm of arsenic in water from two out of 14 sampled wells; a concentration level that exceeds the norms for drinking water in the United States (Konefes and McGee, 1996). Spongberg and Becks (2000b) reported the presence of metals in soil in the vicinity of 14,610 graves, in a cemetery which functioned between 1800 and 1999 in northwestern Ohio. These authors also point to arsenic as the largest cemetery-related hazard for human health; other potential dangers are associated with mercury, lacquers, seals, preservatives, lead, zinc, copper and iron. The migration of those substances outside of a burial site can be limited by appropriate soil texture (Spongberg and Becks, 2000b). However, there is no research on the cemeteries in the USA, and the relevant norms on the allowable limits of contaminants in water, e.g. formaldehyde, have not yet been established.

The largest numbers of studies on the impact of cemeteries have been carried out in Brazil, with the most prominent group led by Professor A. Pacheco of the Instituto de Geociências, Universidade de São Paulo (Matos et al., 1998; Migliorini, 1994; Pacheco, 1986, 2000; Pacheco and Batello, 2000; Pacheco and Matos, 2000; Pacheco and Mendes, 1990; Pacheco et al., 1999; Pequeno Marinho, 1998; Rodrigues, 2002; Silva, 1998). The studies focus on the influence of cemeteries on the groundwater depending on local conditions (Mendes et al., 1989; Miotto, 1990; Pacheco et al., 1991; Pedley and Guy, 1996), with the majority of projects examining the occurrence of bacteria and viruses close to burial grounds and their migration beyond the cemeteries (Bastianon et al., 2000; Martins et al., 1991; Matos, 2001; Matos and Pacheco, 2000; Matos et al., 1997a, 1997b, 1999; Rodrigues et al., 2000). Matos (2001) described patterns of migration of microorganisms from the Vila Nova Cachoeirinha cemetery near Sao Paulo, and reported higher, in comparison with the reference sites, concentrations of chlorides and bicarbonates, sodium, calcium, iron, aluminium, lead and zinc in groundwater sampled near the cemeteries (Table 3). Matos and Pacheco (2002) found concentrations of bicarbonate ions exceeding 100 mg/l. Higher concentrations

Table 3
Ion concentrations in groundwater sampled from 4 of 20 piezometers in de Vila Nova Cachoeirinha, Sao Paulo, Brazil (after Matos and Pacheco, 2002, shortened).

Ions	Ion concentrations in selected piezometers with date of sampling [mg/l]			
	P5 (01/9/99)	P5 (28/11/99)	P8 (28/11/99)	P10 (26/10/99)
Na^+	27.5	11.8	3.9	5.8
Ca^{2+}	20.8	30.0	3.8	34.4
Fe^{total}	35.73	19.84	1.07	81.3
Al^{3+}	5.46	9.35	4.59	33.59
Pb^{2+}	0.62	b.d.[a]	0.34	0.38
Zn^{2+}	0.49	0.29	0.08	1.54
Cl^-	10.4	12.33	2.35	6.23
NO_3^-	0.65	0.03	21.62	b.d.[a], n.a.[b]
PO_4^{3-}	0.06	0.060	0.009	0.11
HCO_3^-	188.0	120.0	34.0	109.0

[a] b.d. - below detectable range.
[b] n.a. - not analysed.

Table 4
Typical physico-chemical properties of groundwater under the Botany Cemetery, Australia against a hydrogeochemical background (Knight and Dent, 1995, shortened).

Parameters and concentrations [mg/l]	Selected contaminants		
	Hydrogeochemical background	Cemetery hydrogeochemical background	Groundwater within the present cemetery limits
EC μS/cm	320.0	194.0	740.0
Eh mV	235.0	295.0	65.0
Cl^-	49.00	27.00	58.5
Fe^{3+}	0.29	0.27	5.00
Na^+	25.49	14.00	70.55
Mn^{2+}	0.007	<0.2	0.214
K^+	2.50	3.20	9.56
Zn^{2+}	0.692	0.170	0.103
HCO_3^-	7.20	11.00	0
NO_3^- - N	14.00	6.05	6.16
NO_2^- - N	0.01	0	0.07
PO_4^{3-}	0.10	0.9	3.4
NH_3 - N	0	0.13	1.24
SO_4^{2-}	24.20	15.00	57.0

of chlorides, nitrates and sodium, as well as iron and aluminium were also detected (Table 3).

The quality of groundwater within and close to cemeteries has been studied by M.J. Knight and B.B. Dent (Dent, 1995, 2000a,b, 2003, 2004, 2005; Dent and Knight, 1998; Knight and Dent, 1995, 1998). Knight and Dent (1995) found increased concentrations of several ions (e.g. ammonium, nitrate, orthophosphate, chloride, iron, sodium, magnesium and potassium) and high conductivity in groundwater sampled near recent interments in the Botany Cemetery, Sydney (Dent, 1995). Other ions (e.g. bicarbonates and zinc) also displayed relatively higher concentrations in comparison to the hydrochemical background (Table 4).

Later, the research concerning the influence which the soil properties and hydrogeological conditions had on the process of decomposition and migration of products was extended to other cemeteries in Adelaide, Sydney, Melbourne and Perth (Dent, 2000a,b; Dent and Knight, 1998; Knight and Dent, 1998). Dent (1998), Dent and Knight (1998), Knight and Dent (1998) confirmed the occurrence of *Pseudomonas aeruginosa* in groundwater near burial grounds. High temporal variability concerning the extent of the contamination was also indicated. The measured concentrations were usually relatively low (Table 5) but some measurements pointed to the detrimental effects of cemeteries on groundwater quality. Dent (1998), Dent and Knight (1998) consider the levels of nitrates, phosphates and bacteria in groundwater under cemeteries to be relatively high. However, some parameters like chlorides and sulphates, TOC, BOD_5 and electrical conductivity (EC) showed values lower than background levels.

Dent and Knight (1998) reported higher concentrations of nitrates, nitrites and chlorides and the presence of sulphates in the groundwaters of the Necropolis Cemetery in Melbourne. No increase in the concentrations of ammonium and orthophosphate ions was found in the Necropolis Cemetery. Higher phosphate levels were found in the Woronora Cemetery in Sydney and Guildford Cemetery in Perth. Most contamination indicators had low values, and only sulphates showed higher levels in background sites than in the sources within and beneath the cemeteries. This might have resulted from low precipitation totals during the study period. Other studies by Knight and Dent (1998) in the Cheltenham cemetery in Adelaide indicated increased concentrations of orthophosphates and carbon dioxide, but lower BOD_5 and TOC.

Physical and chemical properties such as conductivity or redox potential (ORP), oxygen and carbon dioxide content measured during the studies, showed temporal variability. Beneath the cemetery in Adelaide, the groundwater contained relatively higher concentrations of ammonia, TKN, TOC, and BOD_5. Knight and Dent (1998) suggest that fast tissue decomposition in this environment may be responsible for such values of the measured parameters.

Another study by Dent (2000a) - at the Botany Cemetery in Sydney and at the Guildford Cemetery in Perth - demonstrated high concentrations of nitrates in groundwater close to recent interments. However, the migration of these contaminants is not a long-distance one. More recently, various nitrogen ions have been included in the group of the most significant (30.6%) contaminants of the unsaturated zone in cemetery groundwater. The saturated zone is dominated by sulphates, chlorides, sodium, magnesium and strontium ions which constitute nearly 35.3% of the studied contaminants (Dent, 2003, 2004). Another significant contaminant is phosphate ions (20%). Dent (2004) noted the presence of heavy metals close to burial sites in nine necropolises. He also determined bacteria contents and ion concentrations in 305 samples from 83 boreholes.

Forbes et al. (Forbes and Stuart, 2004; Forbes et al., 2002; Forbes et al., 2003; Forbes et al., 2004a,b) investigated the products of fat decomposition, including primarily saturated fatty acids (adipocere). Their studies also investigated the processes of saponification and the controls on the adipocere formation (Forbes, 2002; Dent et al., 2004). According to Forbes et al. (2004b) the process depends on the presence of triglycerides, enzymes produced by an intestine bacteria *Clostridium perfringens*, and the sodium and potassium contained in human tissue and oxygen content.

Formation of adipocere also depends on pH, temperature and soil moisture. Several factors limit the formation of adipocere; namely low temperatures, the presence of calcium and high oxygen levels (Dent et al., 2004; Forbes, 2002; Forbes and Stuart, 2004; Forbes et al., 2004b). Other controls on decomposition processes include the state of the remains and their enclosure, physical aspects of decomposition, evaporation and mobility of gases produced during decomposition, burial environment, climatic zone, penetration of atmospheric gases, local flora and soil fauna, infiltration and circulation of groundwater and the duration of the decomposition process (Dent et al., 2004).

Table 5
Physico-chemical properties of groundwater in three cemeteries and their surroundings in Australia (Dent and Knight, 1998, shortened).

Analytes mg/l	Cemeteries in Australia					
	Woronora in Sydney		Necropolis in Melbourne		Guildford in Perth	
	Background	2 internal seepage wells	Comparative seepage well	3 internal seepage wells	Background	2 piezometers below cemeteries
EC μS/cm	509-922	236-684	241-263	608-2204	60-1127	216-667
NO_2 -N	0-0.001	0-0.003	0-0.002	0-0.056	0.002-0.315	0-0.015
NO_3 -N	0.2-0.3	0-1.16	0-2.2	0-14.3	0.4-6.3	4.1-33.2
NH_3 -N	0-0.39	0.2-4.72	0-0.79	0-0.22	0.1-0.45	0-0.50
PO_4^{3-}	0	0-0.85	1.6-2.55	0.5-1.6	0-1.9	0.06-4.7
Cl^-	85-170	24-41	40-45	42-390	133-160	20-33
SO_4^{2-}	57-77	17-56	3.2-3.7	48-290	66-95	0-21
TOC	2.0-19	1.6-12	2.0-4.0	0-30	58-73	4.0-23
BOD	5-21	3-16	4-6	0-9	<5-22	<5

Table 6
Standard indices of groundwater contamination in the vicinity of a cemetery in Western Cape, South Africa (Engelbrecht, 1993).

Contamination index ions mg/l	Typical concentrations	Measured concentrations
Potassium	2.1-2.5	0.3-37
Ammonia-N	<0.1-2.0	<0.1-88.9
Nitrate and nitrite-N	<0.1	<0.1-55.4
Phosphate	<0.1	<0.1-0.99
TOC[a]	0.1-10	1.8-218.4
Electrical conductivity μS/cm	75-134	14-1360
pH	6.5-6.9	6.5-7.9

[a] Total organic carbon.

In South Africa, research on the impact of cemeteries on the groundwater is carried out in association with the Council for Geoscience (Croukamp and Richards, 2002). In the early 1990s, Engelbrecht (1993) investigated a cemetery established on loose sands in Western Cape province, South Africa. He found the indices of groundwater contamination to be significantly increased in the form of TOC or nitrogen containing ions (Table 6). The results were typified by high temporal variability.

Tumagole (2009) found significant chemical and microbial contamination of shallow groundwater in a cemetery in Ditengteng, north of Tshwane, South Africa. Frequent water table oscillations in sandy deposits caused modification of typical physical properties, including for example, an increase in turbidity, colour, intense odour and unpleasant taste. Increased concentrations of iron and manganese were also reported. Only one well had water with very high nitrate levels (1522.8 mg/l) and water in two sampled wells exhibited high concentrations of lead ions (35.7 mg/l).

South African authors consider bacteria and viruses a major hazard connected with cemeteries (Fisher and Croukamp, 1993; Engelbrecht, 1998, 2000). The negative impact of cemeteries on the groundwater can be limited by specific environmental conditions, such as type of substrate and its reactions with decaying products, organic matter, chemical and biological substances, as well as water circulation and its variability (Engelbrecht, 1998; Wright, 1999).

3. Summary of contamination characteristics

The environmental impact of interments depends largely on the conditions in the surrounding environment. Substrate, land relief, weather conditions, and fluctuations in the groundwater table are of major importance when assessing the adverse impact on the environment. These issues have been highlighted in studies carried out in Poland. However, researchers in North America suggest that the distribution patterns of contamination are affected by such factors as depth of burial, embalming of remains, and the type of coffin, as the production of the latter involves the use of various chemical compounds. According to them, there are more potential contaminants, such as: mercury, lacquers, sealing agents, conservants, lead, zinc, copper, and iron. On the other hand, English researchers have attached great significance to the presence of pesticides, natural fertilizers, and herbicides in the environment in cemeteries.

No comprehensive research has been carried out near cemeteries worldwide. The published results pertain to studies carried out in different geographical and climatic settings, in different types of cemeteries, and the like. The contamination of groundwater in the surroundings of cemeteries results from the presence of increased levels of various ions, including:

- nitrate, nitrite, and phosphate in Canada,
- chloride, nitrate, bicarbonate, sodium, calcium, iron, aluminium, lead, and zinc near graves in Brazil,
- heavy elements, including lead and zinc under various climatic conditions in Portugal,
- nitrate and phosphate as well as ammonium, nitrate, orthophosphate, chloride, bicarbonate, iron, sodium, magnesium, zinc, and potassium, near new interments in a cemetery in Sydney,
- nitrate, nitrite, chloride in Melbourne as well as phosphate ions in Sydney and in Perth, with small amounts of precipitation,
- the total nitrogen, organic carbon, and increased 5-day biological oxygen demand of water as well as ammonia below a cemetery in Adelaide,
- ortophosphate and carbon dioxide found in other studies carried out in Adelaide,
- sulphate, chloride, sodium, magnesium, and strontium – 35.3%, as well as ions containing phosphorus – ca. 20% of the contaminants studied in Australia,
- nitrate – during the rainy seasons on river terraces; sulphate, phosphate, and potassium – in a much smaller number of cemeteries; ammonium and chloride – in a small number of cemeteries as well as, sporadically, fluoride ions in the surroundings of cemeteries in south-eastern Poland,
- phosphate, iron, manganese, and – to a lesser extent – copper, zinc, and aluminium ions in the surroundings of WWI and WWII mass graves in Poland.

The highest indices of contamination are found in cemeteries situated in sites with warm and humid climates, e.g. in RSA and Brazil. The majority of researchers believe that the highest risk from cemeteries comes from ions containing nitrogen and phosphorus, and also from bacteria and viruses. The specialists from England regard ammonia as the main product produced in decomposition and it migrates very quickly compared with slower-moving chloride, sulphate, and sodium ions. Formaldehyde is also a potential threat from cemeteries, as suggested by researchers from Toronto in Canada, as well as those working in the UK Environment Agency. The American scientists (Cook, 1999; Konefes and McGee, 1996), however, do not include it among the principal risk factors. In their opinion, arsenic is a greater threat.

Yet another product of the decomposition of dead body fat is adipocere. Its production is limited by a number of factors, such as low temperatures, presence of Ca, and good aerobic conditions. The Australian researchers regard the process of adipocere production as depending chiefly on the presence of triglycerides, the N and K contained in the fluids of human bodies, and low oxygen levels, as well as on the pH, temperature, and moisture level in the substrate.

In Poland, the impact of cemeteries on the environment is assessed on the basis of the content of selected amino acids and organic compounds in underground waters. Lysine turned out to be a significant indicator for this type of contamination. Its concentration in water taken from wells in cemeteries was some one-third higher compared with the hydrochemical background concentrations in sandy, alluvial or loess substrates. The concentrations of glycin exceeding 12 ppm, is another indicator of the decomposition-related origin of contamination. Also found in the underground water lying below a mass grave, were relatively high concentrations of toxic compounds, including: chlorocholine chloride, and cadaverine.

Markedly increased concentrations of contamination indicators, for example, ions containing phosphorus, nitrogen, as well as sulphate, chloride, and sodium ions, were found in shallow water, particularly in loose sands near burial sites. This issue has been highlighted in RSA, England, and Poland. In these water conditions, for example, in Wolverhampton (England), temporary high concentrations of copper, manganese and zinc ions and the like, have also occurred. Additionally, the contamination indicators obtained under these conditions show great variability over time. Even if the predominantly low concentrations of contaminants (e.g. oxygen and carbon dioxide), as well as conductivity and redox potential were measured in

Adelaide in Australia, the remarkable fluctuations in the water table were the reason for the great temporal variability in these contaminants.

According to a study in Poland, the variability in quantity and relative levels depends above all, on the diversity of precipitation volumes and fluctuations around zero degrees, the variable permeability of the substrate, as well as the diversity in spatial distribution of iron compounds and clayey minerals. Particularly high contamination of underground water is facilitated by a sandy and gravel substrate underlain by impermeable Miocene clays.

The reason for the lower contamination of underground waters is a thick aeration layer below the burials (e.g. in cemeteries in Nottingham and Cracow). According to the English researchers, in this layer itself there were increased concentrations of several elements, including: P, Ca, Cu, and Zn as well as relatively higher concentrations of many ions, including sulphate, chloride, and potassium in the solutions. The lowest levels of underground water contamination were found around the cemeteries situated on low-permeable substrates, and also on alluvia, e.g. in England and Poland.

Land relief is also of considerable importance to the contamination of groundwater, as was proven in Poland, in the studies on a large number of cemeteries (Żychowski, 2008). The quality of groundwater under cemeteries and mass graves situated on hilltop plateaux is mostly adequate, whereas it is not satisfactory in valley floors, in the threshold zone and on the slopes of the Carpathians. The lowest contamination in the studied waters, were noted in cemeteries on mildly inclined areas although not in depressions. Relatively higher concentrations of many ions occurred in lower lying grounds, such as at the Danescourt Cemetery in Wolverhampton. Other ions predominated, however, in the central part of this cemetery. The contamination levels in the studied waters near mass graves were enhanced when a grave was situated on landslip slopes. This issue has been highlighted in the Polish studies.

The studies carried out in England confirmed minor decreases in the concentrations of the investigated ions within a distance of between 100 m to 200 m from the cemetery. With increases in distance, the drop in concentration levels was faster. On the other hand, near contemporary graves in Australia, considerable concentrations of nitrate ions were found in underground waters. These ions, however, did not migrate over great distances. A similar regularity was observed by researchers in England and Wales with regard to high concentrations of chloride ions beneath burials and near them.

4. Recommendations for interments

Implementing the idea of sustainable development also requires interment arrangements that take account of environmental concerns. For this purpose the management boards of cemeteries should, whenever possible, comply with the following guidelines and recommendations:

- interments should be situated in favourable environmental conditions,
- the substrate into which the bodies are lowered must not be of high permeability, e.g. sands underlain by impermeable layers,
- when filtrate is not treated, it is recommended that the substrate contains minerals or decomposition products for improved absorption,
- note that very high impermeability of the substrate can result in adverse excessive moisture content or even waterlogging of the area,
- a thick aeration layer and deeply situated underground water table are advantageous,
- the surface between graves as well as tombs should be made watertight,
- water cycling should be controlled by draining precipitation water from sealed surfaces of cemeteries and tombs through an efficient drainage system, out of the cemetery, in order to limit infiltration,
- the substrate of the cemetery should be separated from the surrounding layers,
- contaminated filtrates from cemeteries should be treated,
- a cemetery should be located on the area of mild inclination but not in depressions without outflows,
- cemeteries should not be situated on landslip slopes,
- the use of chemical compounds (e.g. paints, conservants, metal ferrules etc.) should be limited by granting burial fee reductions,
- the use of chemicals in the plant nursing practices in cemeteries should be reduced,
- too high a density of graves and burying of large numbers of bodies in the same place for years will ultimately increase environmental contamination,
- earth left by digging graves should be treated as anthropogenic waste,
- the area of the cemetery should be covered by low decorative vegetation in order to absorb decomposition products,
- legislation should be enacted to set allowable limits of contaminants in underground water e.g. formaldehyde.

5. Conclusion

Cemeteries adversely affect the quality of underground waters. The highest contamination indicators are found in the cemeteries located in warm and humid climatic conditions e.g. in RSA and Brazil. Ammonia is considered to be the principal product originating from decomposition. Most of the researchers regard nitrogen - and phosphorus-containing ions as well as bacteria and viruses, as the greatest threat posed by the presence of cemeteries.

There is a need for more research assessing such contamination indicators as: amino acids, organic compounds, formaldehyde and arsenic. The issue of the adverse impact of cemeteries must be solved first in large cities where cemeteries are large, shortage of space for burials occur and there are limited opportunities for the acquisition of land. The partial containment of environmental deterioration could be achieved by convincing people to use more humanitarian forms of burials, such as cremation, which could be deemed the lesser evil.

In future, the issue of the adverse impact of cemeteries on the environment should be monitored. There is a need for international cooperation which will allow for the development of research considering various environmental conditions and permit the standardisation of methods.

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