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Spatial distribution of heavy metals in soils and groundwater at the 2000 Olympic Games site, Sydney, Australia

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요 약 문

본 연구는 시드니 포트젝슨(Port Jackson) 내 2000년 시드니올림픽사이트인 홈부시베이(Homebush Bay)를 대상으로 다양한 폐기물의 매립으로 인한 토양 및 지하수 내 중금속 원소들의 농도를 평가하기 위하여 수행되었다. 올림픽게임지역을 3개의 지역, 즉 간척지역(과거에는 강하구였으나 폐기물로 매립되어 있으며 현재는 조수간만 보다 높은 지역), 매립지역(해수면 위에 폐기물을 매립한 지역), 및 자연 상태지역(폐기물의 매립이 전혀 없었던 지역))으로 나누어 조사하였다. 토양코어시료(n=4513) 및 지하수 샘플(n=101) 내 중금속(Cr, Cu, Pb, Zn)을 분석하였다. 본 연구지역의 토양 내 중금속(Cr, Cu, Pb, Zn)의 농도는 간척지역, 매립지역 그리고 자연 상태지역의 순으로 높게 나타났지만 지하수내에서는 납(Pb)을 제외하고 매립지역, 간척지역 그리고 자연 상태지역순으로 나타났다. 올림픽게임사이트 토양 내 평균 납(Pb)의 농도는 간척지역(174 μg/g), 매립지역(102 μg/g) 그리고 자연상태지역(48 μg/g)의 순으로 나타났으며 그 결과 본 연구지역 토양내 중금속의 분산은 농집된 중금속 농도와 메립된 폐기물의 존재와 밀접한 관련이 있음을 나타냈다. 그러나 올림픽 사이트 내 이질적인 폐기물의 매립으로 인하여 토양과 지하수 내 중금속농도의 상관관계를 규명할 수는 없었다.

주요어 : 2000 시드니올림픽사이트, 매립지역, 폐기물, 토양, 지하수

ABSTRACT

The current study was undertaken to evaluate the hydrogeochemical implications of heavy metals (Cr, Cu, Pb, Zn) in both soils and groundwater in reclaimed lands of Sydney's 2000 Olympic Games site at Homebush Bay in Port Jackson, Sydney. The Olympic Games site can be divided into three areas, i.e. 'reclaimed areas' were previously estuarine, and were filled with waste materials and are now above present high tide level, whereas 'landfill areas' are areas where deposition of waste materials occurred above sea level. No deposition of waste took place in 'non-infilled areas'. 4513 soil core samples and 101 groundwater samples were analyzed for Cr, Cu, Pb, Zn. The mean heavy metal (Cr, Cu, Pb, Zn) concentrations in soils of the study area revealed the order of reclaimed (greatest), landfill and non-infilled area (smallest), whereas in groundwater it is all shown the order of landfill, reclaimed and non-infilled area, except for Pb. Mean Pb concentration in soils derived from the three land types at the Olympic Games site revealed the order of reclaimed area(174 μg/g), landfill area (102 μg/g) and non-infilled area (48 μg/g). Results reveal that soils contaminated by Cr, Cu, Pb and Zn in reclaimed/landfill areas are associated with dumped materials. No relationship could be established between soil and groundwater concentrations of heavy metals (Cr, Cu, Pb, Zn) in the landfill, reclaimed and non-infilled areas of the Olympic site, probably due to the varied nature of the materials deposited at the Olympic site.

Key words : 2000 Olympic Games site, reclaimed land, waste materials, soil, groundwater

1. Introduction

The Port jackson catchment has been intensely urbanized and industrialized since colonization in the late 18th century, but the catchment retains 62 km^2 of natural, or undeveloped areas[1]. Drainage systems entering the lower Parramatta River were straightened, narrowed and lined to increase flow of excess water and to reclaim adjacent lands for development. This modification efficiently drains previously low-lying swampy land, but allows contaminants to be

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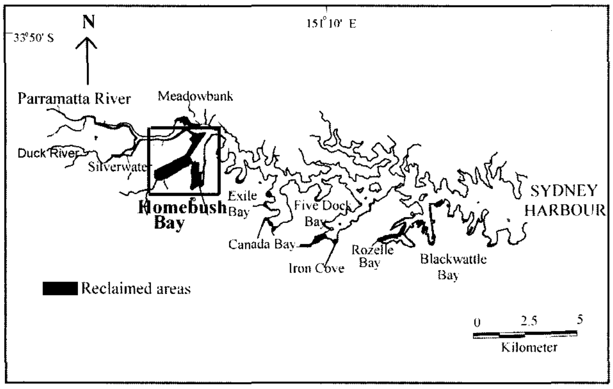

Fig. 1. Reclaimed areas in Port Jackson, Sydney, Australia.

rapidly conveyed from their source to the receiving waters[2]. Human impacts on the Port Jackson include pollution and modifications made to the system through land reclamation, the concreting of tributaries and dredging (Fig. 1). It is believed that the unregulated discharge of oils, organic chemicals, heavy metals and other contaminants over many decades may have had significant effects on the riverine sediments draining into Homebush Bay[3]. Kaoser *et al.*[4] reported that heavy metals can be categorized in three groups according to their mobility in clay soils, e.g. low mobility (Cu, Cr^{3+}, Pb, Zn), moderate mobility (As, Cd, Fe, Ni) and high mobility (Hg, Cr^{6+}). Extensive reclamation has been carried out in Homebush Bay, and the majority of other embayments along the southern shoreline of Sydney Harbour have also been affected by reclamation[5].

The exact number of contaminated sites in Australia is not known, but it is estimated that there are about 400 contaminated sites in Tasmania and in excess of 30000 in the two most populous states of New South Wales and Victoria[6]. The Australian and New Zealand Guidelines for Fresh and Marine Waters provided a framework for managing receiving water quality. The Australian and New Zealand Guidelines for Fresh and Marine Waters are primarily based on the philosophy of ecological sustainable development (ESD)[7]. Regulatory approaches to addressing the definition of a contaminated site have relied on the development of environmental assessment criteria for soils and groundwater against which concentrations at a site can be assessed. It is common to take into account analytical detection limits and background concentrations in establishing such criteria.

The primary aim of this current study was achieved by providing a scientific foundation for the remediation/rehabilitation of natural systems, and to make a contribution to the Olympic Co-ordination Authority's Development Plan and Environmental Management System for the site. The remediated land at this site has been re-vegetated using local native plant species including grasses and rare saltmarsh species (*Lampranthus tegens* and *Halosarcia pergranulata*). At present, all the planned actions have been carried out and both management and monitoring plans for the completed areas have been developed by Waste Services New South Wales who are performing analyses of leachate samples. The results of heavy metal concentrations in leachates to date are highly acceptable. The work assessed the quality of the soils and groundwater previously impacted by waste materials and identifies areas, which might have posed a potential risk to the environment. Sydney's successful bid for the 2000 Olympic and Parolympic Games has provided the impetus for the largest and perhaps the "greenest" single urban remediation project ever undertaken in Australia[8].

2. Study area

The Homebush Bay site is bordered by the Parramatta River, the M4 motorway and Homebush Bay Drive (Fig. 2). The existing landform at the Homebush Bay site is one of low relief, rising to a ridge along the western border of the site. The low-lying areas have been extensively modified and the main topographic features of the site are a 25 m deep excavated brick pit and an engineered landfill which rises more than 25 m above the southern bank of Haslams Creek. About 30% of the Homebush Bay site (7.6 km^2) retains a natural topsoil and topography and remnants of the vegetation present prior to European settlement[8]. Past activities (e.g. reclamation of wetland areas, land clearing, shoreline remodeling) have resulted in an extensive adverse environmental impact on the Homebush Bay site. Until 1986 the site was used for the disposal of about 9 million m^3 of industrial and domestic wastes and consequently, concentrations of chemical

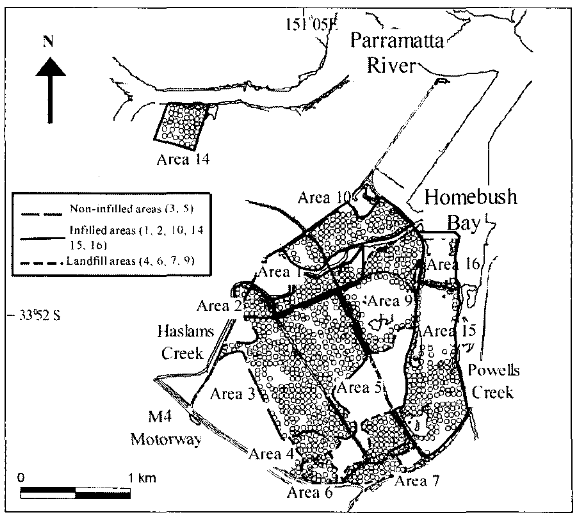

Fig. 2. Study area and soil sampling locations. Circles indicate core soil sample locations.

contaminants in soils were above acceptable levels in some areas.

Before European settlement, Aboriginal people occupied the extensive tidal wetlands and thick woodlands around Homebush Bay[9]. From the early 1800s, large areas of the wetlands were gradually reclaimed and the forests were cleared for farming and industrial use. From the mid-1800s to the 1960s, parts of Homebush Bay were used as a racecourse, brickwork, armaments depot and an abattoir. During the 1960s and 1970s, some areas of Homebush Bay were contaminated through the uncontrolled dumping of household and industrial wastes[8].

3. Materials and methods

3.1. Soil sampling

Field sampling was undertaken between March and December 1990 by Coffey Partners Pty. Ltd. Sampling took place at all intersection points on a 50 m grid from surface soils and fill at regular depth intervals (range: 0.1, 0.5, 1.2, 2, 3.5, 5, 6.5, 8, 9.5, 11, 12.5, 14, 15.5, 17, 18.5, 20, 21.5 m) (Fig. 3). In shallow soil, pits were dug by backhoe, in deeper areas drilling equipment (e.g. pengo augers, hollow flight augers, washboring drilling with rock-roller bits and U50 tubes) was used to collect samples. A total of 4513 soil core samples were collected in 12 areas of the site. All soil samples were sealed with aluminium foil and screwed lids and were immediately stored at 4°C and transported to the laboratory within 24 hours. Soil samples were sieved, crushed to pass through a 2 mm sieve and analysed. Quality control was maintained using a coded sample numbering system and a computer generated chain-of-custody form, which accompanied all samples. Analytical work was performed by Sydney Analytical Laboratories and SGS Australia. Concentrations of four heavy metals (Cr, Cu, Pb, Zn) were determined by flame atomic absorption spectrophotometry (AAS) following a nitric/perchloric acid digestion and reflux with hydrochloric acid[10].

3.2. Groundwater sampling

Representative groundwater samples (Fig. 2) were collected from all parts of the study area during November 1990 to March 1991, using rotary drilling rigs by Coffey and Partners[11]. Two closely-spaced boreholes were drilled at each sampling site, a deeper hole was completed in the underlying hard rock (A series; n=19) and the other hole was completed as a piezometer in fill materials and/or shallow weathered bedrock (B series, n=19). The depth of the A series boreholes varied from 15.2 to 36.3 m beneath the surface, and was terminated after at least 8 m of competent hard rock was penetrated. The depth of B series boreholes

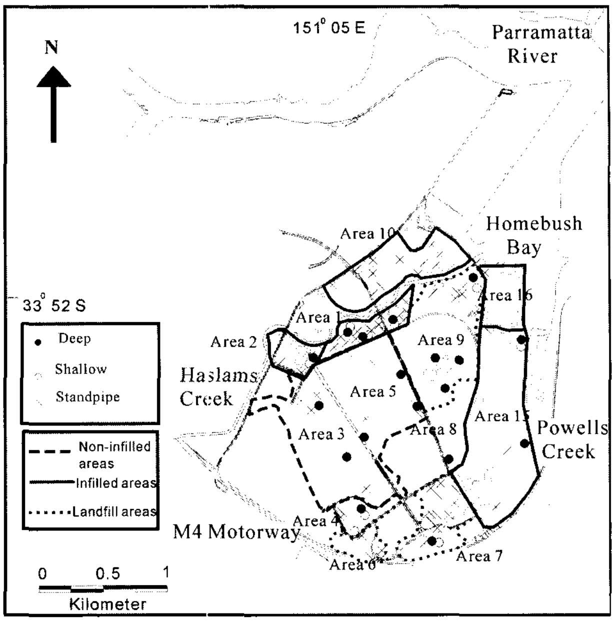

Fig. 3. Study area and groundwater sampling locations.

terminated at between 3.6 and 23.6 m. All standpipes were constructed in fill materials and range from 1.6 to 26 m deep. Unfortunately, during constructing and monitoring, one deep borehole and 11 shallow boreholes did not collect water samples because they were dry, or damaged.

One hundred and one groundwater samples were collected for chemical analyses throughout the study area. All samples were stored in polyethylene containers, labeled and preserved in a refrigerator until processing in the laboratory. Heavy metals (Cr, Cu, Pb, Zn) were analysed by a Perkin Elmer (model 3000) atomic absorption spectrophotometer (AAS). All methods used for the various determinations followed Standard Methods[12]. A quality assurance and quality control (QA/QC) program was carried out during the study. The objectives of this program were to assess laboratory performance, identify deficiencies in data quality and classify the reliability and useability of the laboratory data. Analytical work was divided between two laboratories (Australian Analytical Laboratory (AAL) and Sydney Analytical Laboratory (SAL)) and duplicate samples were sent to both laboratories. All concentrations in Standard Reference Materials (SLRS-1, United State Geological Survey) analysed were within 10% of the recommended concentrations and the analyses are reproducible within 6% relative standard deviation (RSD)[10].

4. Results and discussions

4.1. Site investigation on the Homebsuh Bay site

Prior to taking soil samples in the study area, an interpretation of aerial photography was carried out to locate and estimate

Table 1. Summary of past land use in the study area

Areas	Location	Active period	Fill area (m^2)	Waste composition	Fill types	Fill depth (m)
1	Abattoir Haslams Creek (south-east)	1965-1982	133,200	Municipal garbage, putrescible, building & chemical wastes	R	0-17
2	Abattoir Haslams Creek (south-west)	1951-1978	78,100	Municipal garbage, putrescible, building & chemical wastes	R	0-3.5
4	Former State Rail Authority tip site	1960-1970	12,000	Railway & putrescible wastes	L	1.5-4
3 & 5	Homebush Abattoirs	–	–	–	No filling	–
6	West of State Sports Centre	1965-1981	20,000	Municipal garbage	L	0-5.5
7	State Sports Centre	1965-1981	70,500	Municipal garbage & putrescible wastes	L	0-9
8	Australia Centre	–	–	–	–	–
9	State Brick Works	1979-1982	25,000	Putrescible wastes & municipal garbage	L	0-14
10	Electricity Ash Ponds (Haslams Creek north)	1961-1990	28,000	Household garbage, construction & ash fill	R	3.5-6.7
15	Bicentennial Park	1950-1982	160,300	Dredged sediment	R	0-1.2
16	Bicentennial Park (north part)	1951-1982	32,000	Dredged sediment	R	0-2.4

R; reclamation, L; landfill, –; no data

the extent of fill and the history of infilling was established by the OCA[8](Table 1). Haslams Creek south was completely reclaimed using waste and sediment from the dredging of Homebush Bay. Foreshore reclamation began in 1951 and after 30 years of dumping, a 15 m high stockpile of waste had been created, containing domestic and commercial wastes, oil products and chemical and foundry waste. Haslams Creek North contained many layers of domestic and commercial waste, some power station ash and contaminated substances with builder's rubble representing the bulk of the waste material. Domestic and commercial food wastes were also dumped at this locality. Between 1969 and 1973 domestic, commercial and industrial wastes, including putrescibles, bricks and timber, concrete debris and sandstone blocks, were dumped in the Haslams Creek floodplain. Some hazardous wastes were also dumped in this location, including drums of chemical wastes. The southern area, comprised a municipal dump where uncontrolled dumping occurred for over 20 years. This area contains >780000 m^3 of domestic, commercial and industrial wastes, including hazardous contaminants, such as heavy metals, oil products, asbestos and pesticides[8].

4.2. Spatial distribution of heavy metal concentrations in the three land types

The distribution of heavy metal concentrations in soil samples in the study area revealed a close association between elevated heavy metal concentrations and the presence of contaminated fill materials in each area. Table 2 presents mean and range of heavy metal concentration from the three land types at the Olympic site. Mean Cr concentrations in reclaimed (Areas 1, 2, 10, 14, 15 and 16), landfill (Areas 4, 6, 7, and 9) and non-infilled areas (Areas 3 and 5) were below the interim sediment quality guideline values (ISQG-low; 80 μg/g)[7] (Fig. 4a). Mean Cu and Pb concentrations in reclaimed and landfill areas exceeded the interim sediment quality guideline values (ISQG-low; 65

Table 2. Mean and range of heavy metal concentration in soils derived from the three land types at the Olympic site

Heavy metals	Reclaimed area (n=2382)	Landfill area (n=1252)	Non-infilled area (n=879)
Cu	82	66	30
	21-138	51-90	24-36
Pb	174	102	48
	65-374	78-167	44-52
Zn	288	231	92
	83-694	132-394	87-97
Cr	58	33	25
	25-162	25-40	25-26

Sample values are mean concentration and double figures are the range: n; number of samples: All values in·g g^{-1}

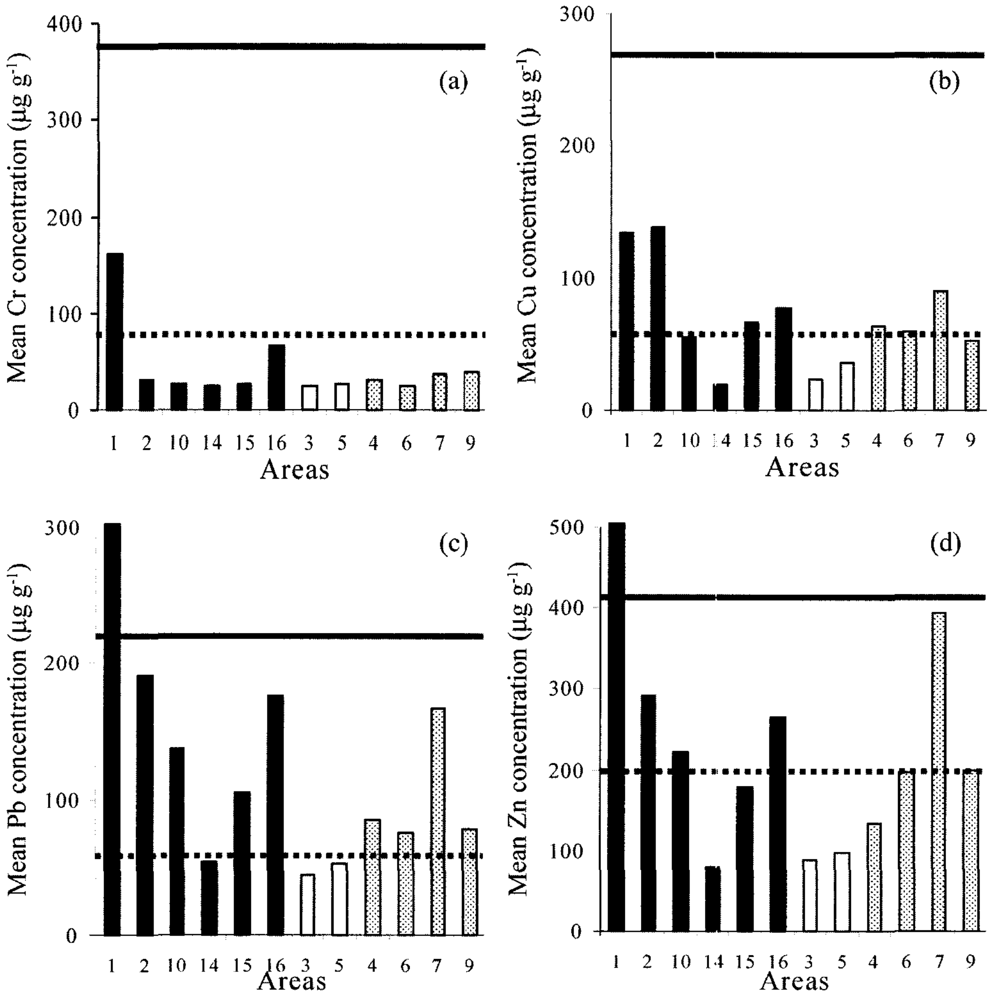

Fig. 4a~d. Mean heavy metal concentrations in infilled (reclaimed 1, 2, 10, 14, 15, 16) and landfill (4, 6, 7, 9) areas) and non-infilled (3, 5) areas with ANZECC and ARMCANZ guideline values. The solid columns, open columns and dotted columns indicate reclaimed areas, non-infilled areas and landfill areas, respectively. Legends indicate line is ISQG-high and dot line is ISQG-low, respectively.

μg/g and 50 μg/g, respectively), but are below the interim sediment quality guideline values (ISQG-high; 270 μg/g and 220 μg/g, respectively) (Figs. 4b-c). Mean Zn concentrations in reclaimed and landfill areas exceeded the interim sediment quality guideline values (ISQG-low; 200 μg/g) (Fig. 4d). However, the mean Cr, Cu, Pb and Zn concentrations in non-infilled areas showed below the interim sediment quality guideline values (ISQG-low). The highest heavy metal concentrations coincide with dredged areas and reclaimed areas at bay ends. Many of waste materials are available at the Olympic site and may reflect the origin of the waste material, in that some of the waste used for infilling the estuary came from dredging the bay and probably contained highly elevated metal concentrations. Results indicate that infilled areas have considerably higher concentrations of heavy metal than non-infilled areas, and that non-filled areas probably reflect background concentrations of heavy metals. This may reflect the origin of the waste material, in that some of the waste used for infilling the estuary came from dredging the bay and probably contained highly elevated metal concentrations.

Fig. 5a~Fig. 5c show the spatial distribution of Pb at the surface, 3.5 m and 9.5 m depth, respectively. The mean Pb concentrations at the surface are low and irregular throughout the study area, possibly due to scattered waste materials. The mean Pb concentrations at 3.5 m and 9.5 m depth, however, exhibit isolated areas east of the State Sports Center and Haslams Creek North, which are highly contaminated with Pb, probably related to activities associated with the abattoir. Cu, Zn and Cr also show similar distribution trend to Pb.

4.3. Trace metals in filled areas

The total mass of trace metals Cu, Cr, Pb and Zn in filled

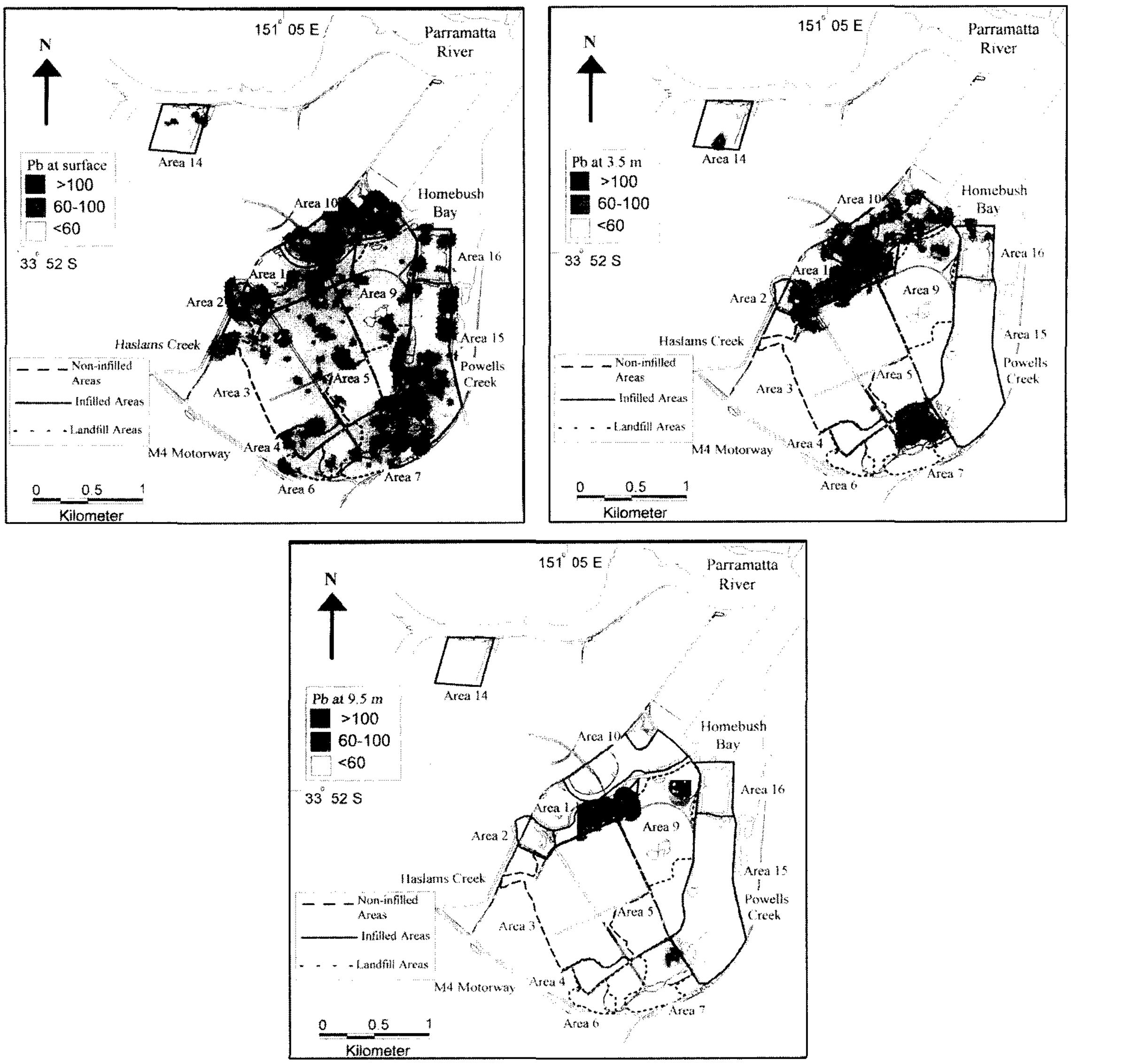

Fig. 5a~c. The spatial distribution of Pb at the surface, 3.5 m, and 9 m depth, respectively.

areas (Areas 1, 2, 4, 6, 7, 9, 10, 15, 16) was estimated using the following relationship:

$$M_m = A\ h\ \rho\ C_m$$

Where Mm is the mass of trace metal m (Cu, Cr, Pb Zn) (in kg), A is the infilled area in m^2, h is the infilled waste height in m, ρ is the average density of municipal waste material (657 kg m^{-3})[13], and C_m is the mean concentration of trace metal m in g g^{-1}. The distribution of the total mass of Cu, Cr, Pb and Zn in the infilled areas (Total area: 0.8111 km^2) shows remarkable differences (Table 3). Although Area 1 comprises only 16% of the total infilled area within the Olympic site, more than 27% of Cr, 53% of Pb and 68% of Zn are contained in the 133200 m^2 area. The depth of infilling (17 m) with waste material which, is highly enriched in Pb and Zn, has resulted in the majority of these two metals being contained in this part of the Olympic site. Similarly, Area 7, which comprises only 8.7% of the total area, contains 28.6%, 10.9% and 17.3% of the total mass of Cu, Zn and Cr, respectively. Area 9 (25000 m^2 area: 3.1% of the total area) contains 9.1%, 17.3% and 10.3% of the total mass of Cu, Pb and Cr, respectively at the Olympic site. In contrast, the other infilled areas (Areas 2, 4, 6, 10, 15 and 16) contain comparatively smaller masses of trace metals, due to the lower mean concentrations of trace metals of infilled waste materials and the shallower depths of infilling. For example, Area 10 (280000 m^2, or 34.5% of the total area) contains only 7.6, 8.6 and 16.5% of the total mass of Pb, Zn and Cr, respectively at the Olympic Games site.

Table 3. Total mass of Cu, Cr, Pb and Zn in the infilled area

Area	Fill area (m^2)	Area (%)	Cu (kg)	%	Pb (kg)	%	Zn (kg)	%	Cr (kg)	%
1	133,200	16.4	199.4	15.2	556.4	53.6	1032	68.2	241	27
2	78,100	9.6	24.8	1.9	34.1	3.3	51.9	3.4	57.5	6.4
4	12,000	1.5	12.6	1	16.8	1.6	2.6	0.2	6.1	0.7
6	20,000	2.5	44.1	3.4	56.4	5.4	14.4	1	18.1	2
7	70,500	8.7	375.2	28.6	69.6	6.7	164.2	10.9	154.2	17.3
9	25,000	3.1	119.6	9.1	179.4	17.3	45.8	3	92	10.3
10	280,000	34.5	323.8	24.7	78.9	7.6	130.1	8.6	147.2	16.5
15	160,300	19.8	197.2	15	44.5	4.3	67	4.4	169.3	19
16	32,000	3.9	16.7	1.3	2.6	0.3	4.5	0.3	6.6	0.7
Total	811,100	100	1313	100	1039	100	1513	100	892	100

4.4. Relationship of Cr, Cu, Pb and Zn concentrations between groundwater and soil

The mean, range and standard deviation of heavy metal (Cr, Cu, Pb, Zn) concentrations in groundwater in the landfill, reclaimed and non-infilled areas were examined in the current study (Table 4). The mean heavy metal (Cr, Cu, Pb, Zn) concentrations in soils of the study area revealed the order of reclaimed (greatest), landfill and non-infilled area (smallest), whereas in groundwater it is all shown the order of landfill, reclaimed and non-infilled area, except for Pb (Figs. 6a~d). In a varied soil matrix, such as exists at the Olympic site, small-scale spatial variance in the subsurface can be expected to be high, resulting in a poor correlation between soil and groundwater compositions. The correlation between heavy metals (Cr, Cu, Pb, Zn) in groundwater and soil are all very low, having r^2 values between 0.001 and 0.1. The inconsistent relationship between metal concentrations in soils and groundwater is due to the varied nature of the materials deposited at the Olympic Games site and the movement of groundwater in the study area.

Hounslow[14] reported that the movement and attenuation of heavy metal pollutants in the subsurface depends primarily on groundwater movement and the sorptive properties of the subsurface solids. The principal sorbents are hydrous oxides of Fe and Mn, insoluble organic matter and clay minerals, and frequently in that order of importance. Heavy metals in groundwater may be dissolved and mobilized by high salt concentrations, changes in pH and redox potential, an influx of natural or synthetic complexing agents, or microbial formation of soluble and toxic alkyl derivatives of heavy metals[15,16]. The mobility of heavy metals will depend on the interaction of soil chemical processes, and individual heavy metal characteristics, while heavy metal ions in solution compete for adsorption sites[17]. An important consequence of metal oxide dissolution in contaminated environments is the release of other heavy metals that may have been scavenged by Fe and Mn[18]. Suh *et al.*[19] also suggested that there are a number of controlling the concentration, and hence migration, in the groundwaters associated with fill materials of the Bicentennial Park site at Rozelle Bay, Australia. First, the redox behaviour of

Table 4. Statistical results of the heavy metal concentrations in groundwater based on past land use

Site		Cu	Pb	Zn	Cr
	Mean	180	60	358	47
Reclaimed area	Range	5-1600	5-1300	30-1900	5-950
	SD	280	180	380	150
	n=49				
	Mean	1254	41	1074	222
Landfill area	Range	5-17000	5-320	5-11500	5.0-3300
	SD	3370	70	2200	660
	n=37				
Non-infilled area	Mean	177	17	562	6
	Range	5.0-2300	5-110	20-3700	5.0-20
	SD	590	30	1130	6
	n=15				

SD=standard deviation, n=number of samples.
All metal values in μg/l.

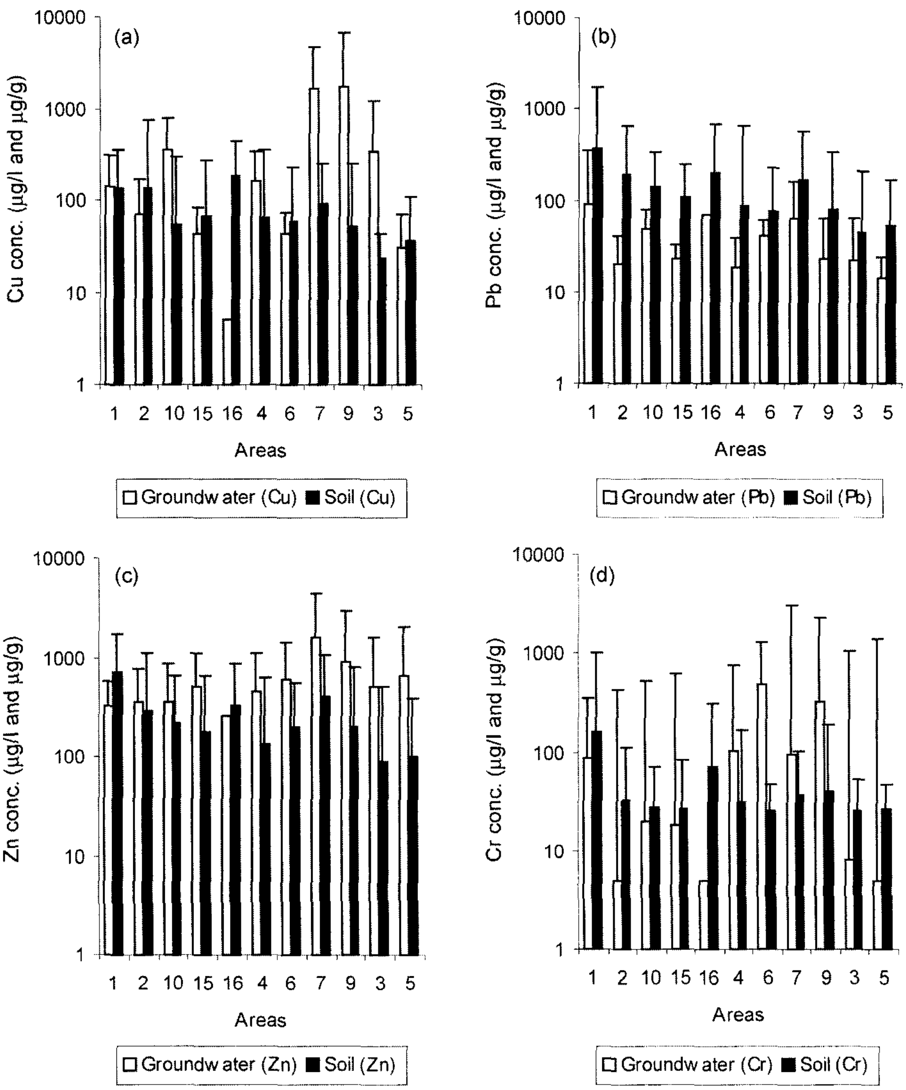

Fig. 6a~d. Comparison of heavy metal concentrations between groundwater and soil in the study area. Reclaimed (1, 2, 10, 14, 15, 16) areas, landfill (4, 6, 7, 9) areas, and non-infilled (3, 5) areas, respectively.

both the groundwater and its associated soil profiles can influence the behaviour of redox-sensitive elements, such as Mn and Fe. Second, during dry periods (Cu, Pb, Zn, As and Cr), where the water table recedes, oxygen ingress can lead to biologically catalyzed oxidation reactions resulting in a reduction in pH and an associated increase in the concentration of some trace elements. Finally, dilution of seawater by the ingress of freshwater from up gradient of the filled area decreases the solubility of some elements (Fe and Mn), relative to that of chloride (As, Cr and Cu), whilst increasing others (Pb, Zn, Ni, Co and Al).

5. Conclusions

This study has established the distribution of heavy metal concentrations in reclaimed areas of the Sydney 2000 Olympic site and has assessed the quality of the soils and groundwater impacted by waste materials. The distribution of heavy metal concentrations in core soil samples in the study area revealed a close association between elevated heavy metal concentrations and the presence of fill materials in each area. Soils contaminated by Cr, Cu, Pb and Zn in reclaimed/landfill areas are associated with dumped materials. Soil metal concentrations are high enough to pose a threat to groundwater and continuous monitoring of the groundwater leachates is necessary to ascertain contaminant retention at the site. The inconsistent relationship between metal concentrations in soils and groundwater is due to the varied nature of the materials deposited at the Olympic Games site and the movement of groundwater in the study area. In the case of metals, the dilute-acid-soluble metal concentration is likely to be a more meaningful than the total value. In addition, changes in redox potential and pH also affect the availability of metals and other contaminants, and should be further studied.

The Olympic Co-ordination Authority (OCA) has implemented strategies to remediate the 2000 Olympic Games site. Having identified risk areas through an extensive hydrogeological investigation involving 4513 soil samples and 101 groundwater samples, a site-wide remediation strategy was developed as waste consolidated and capped, waste material excavated and replaced with clean fill, and material processed, replaced and capped.

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