Phosphorus characteristics of soils treated with sewage effluent using land filtration at Werribee sewage treatment complex, Victoria

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Abstract

The phosphorus (P) content and P distribution in the soil profile, and P adsorption capacity of soil at a land filtration site of the Werribee sewage treatment complex is reported. Sewage irrigation over 50 years has increased the total P in each layer of soil to 100 cm depth compared to an untreated soil. P accumulation was maximum in the 0-10 cm depth and the concentration of P gradually declined with depth in both the sewage treated soil and untreated soil. P that has accumulated in sewage treated soil was mostly as inorganic P. P addition has reduced P adsorption capacity of the upper soil horizons. The high level of P (28 mg/L) in the ground water indicates that currently soil is unable to retain all of the wastewater P applied.

Key Words

Wastewater, Freundlich adsorption isotherm, P adsorption capacity.

Introduction

Melbourne in the state of Victoria, with a population of about 3.5 million produces large amount of industrial and municipal waste in the form of solid, liquid, and/or gases. Solid waste normally is confined in landfills, whereas, city sewage is treated by land application processes at a farm in Werribee, located 50 km southwest of Melbourne central business district (Fig. 1). It is a large-scale land application system that dates back to 1891. Three methods of land treatment are used at Werribee. These are (i) land filtration (irrigation), (ii) grass filtration (overland flow), and (iii) lagoons. Although all three methods of land treatments remove considerable amounts of P from wastewater, due to the soils potential to retain P, land filtration is considered to be the most efficient in removing P from wastewater (Syers and Iskandar 1981). Land filtration occurs on 3,833 ha of the Farm, and treats an average of 30,000 ML of sewage annually (about 60%, Melbourne Water, 1999, unpublished data). The land filtration system involves the periodic application of wastewater on permeable soil and relies on purification by passage through the soil matrix for treatment. The objectives of this application are chemical adsorption, microbial stabilization, immobilization, and crop removal, leading to an environmentally acceptable assimilation of waste (Loehr *et al.* 1979; Iskandar 1982). The farm receives an average rainfall of 488 mm/yr (av. of 84 years) and has a potential evaporation rate of 1456 mm/yr (av. of 5 years).

Melbourne sewage contains many contaminants. Among the pollutants, the high concentration of P in wastewater (Annual average of total inorganic P and organic P is 10 and 0.52 mg/L, respectively) has been identified as a major element for the accelerated algae and water-plant growth in receiving water particularly at Port Phillip Bay. This process can reduce biota diversity resulting in their death, as the masses of dead algae and other organic material undergo decomposition and depletes dissolved oxygen from the water (Bordie 1995). The level of P concentration in solution that could cause eutrophication is not clear, but it could be as low as 20 µg/L (Correll 1998).

In this study, P characteristics of soil which have received wastewater through land filtration system have been investigated. The study includes the quantity and distribution of phosphorus in the soil profile, and changes in P retention capacity of the soil layer. The information obtained will enable better management of land treatment of sewage and more reliable risk analysis to minimize the downstream effects of high P loadings on water quality and eutrophication in sensitive areas.

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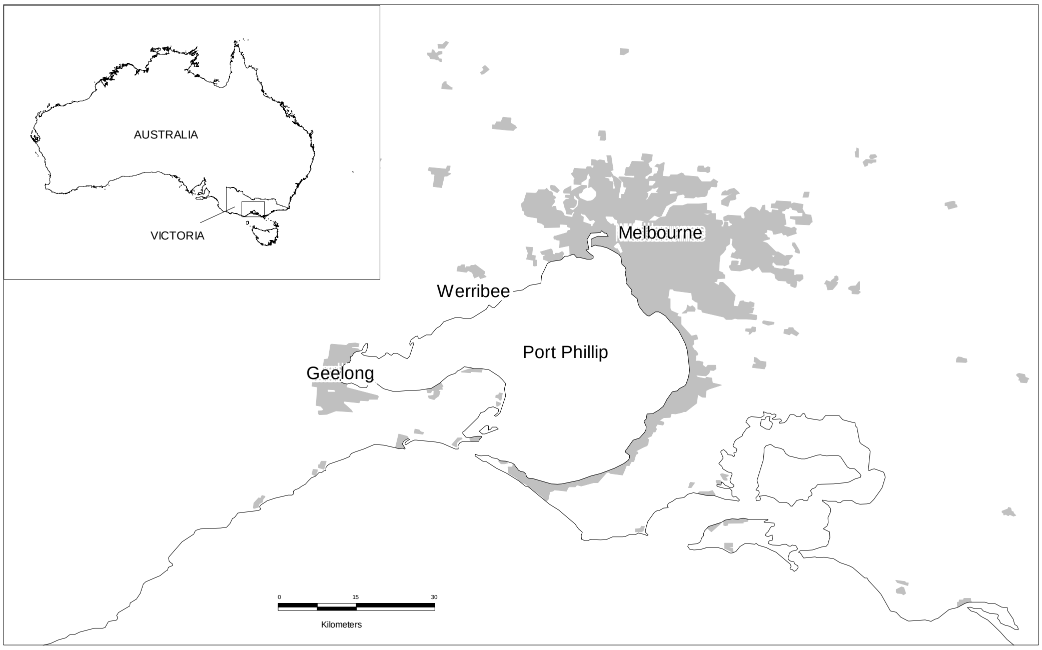

Figure 1 Location of the Werribee Township, Victoria

Methods

Experimental plots

Two sites were selected for the study. One site was a paddock 120m X 80m, which had received sewage by land filtration system for the last fifty years. This site is known as sewage treated soil (STS). On this site sewage irrigation is carried out on a nominal 21 day rotation, involving a watering period of 2 days and a drying time of 5 days. After irrigation and a drying out period, pastures (*Lolium Perenne*) are grazed with livestock (three cows/ha) for about 10 to 14 days before the next watering. In each watering approximately 10 to 15 cm of sewage water is applied. About 10 to 12 irrigations occur over a year during the periods of high evaporation in spring, summer, and autumn. Another site known as control soil (CS) never received sewage irrigation since the farm commenced its operation in 1891 and had been under barley grass (*Hordeum leporinum*). Sewage treated soil and control soil were formed on Quaternary sand and silt deposited in the Werribee delta and overlying a sequence of Cainozoic sediments (Condon 1951). Both the sewage treated soil and control soil are Vetrosols (Isbell 1996), or Vertisols (Soil Survey Staff 1994).

Soil sampling and groundwater collection

Five soil cores from each site (sewage treated soil and control soil) were collected randomly down to 100 cm depth. Soil samples collected from both sites were divided into 0-10, 10-20, 20-35, 35-50, 50-70, 70-90, and 90-100 cm segments for analysis. For bulk density measurements fourteen undisturbed samples down to 100-cm depth were also collected from pits for both the sewage treated soil and the control soil. Ground water was collected from two boreholes situated on the land filtration site under investigation.

Soil properties measurement and groundwater analysis

Soil physical properties include particle size distribution, bulk density, and saturated hydraulic conductivity were measured. Soil particle size distribution was determined by hydrometer method as described by Gee and Bauder (1986). Soil bulk density was determined using the core method (Blake and Hartge 1986). Soil saturated hydraulic conductivity (*Ks*) measurements were carried out on the site of sewage treated soil and control soil by a disc permeameter as described by Perroux and White (1988). To analyze the chemical properties of sewage treated soil and control soil, soil samples collected were air dried and then ground lightly with a mortar and pestle to pass through a 2 mm round-hole sieve. Soil pH was measured in a 1:5 soil/0.01M $CaCl_2$ suspension according to the methods described by Rayment and Higginson (1992). Organic carbon was determined by oxidizing the soil with dichromate ($Cr_2O_7^{2-}$) as described by Walkely and Black (1934) and later modified by Mebious (1960). Total, organic and inorganic phosphorus in soils were determined by extraction methods as described by Mehta *et al*. (1954). Cation exchange capacity was determined as described by Gillman and Sumpter (1986). Phosphorus in groundwater was determined colorimetrically using the vanadomolybdophosphoric acid method after digesting an aliquot in sulfuric acid and nitric acid as described in American Public Health Association (1985).

Soil P adsorption capacity was measured by the Freundlich adsorption isotherms
The Freundlich equation is written as:
$X = KC^{N}$
Where
X = total amount of P in adsorbed phase, mg/kg
K = Freundlich adsorption constant,
a measure of the total number of sites involved in sorption, L/kg
N = empirical constant that provides an estimate of the intensity of sorption ($N < 1$)
C = solution P concentration measured after 16 h equilibrium period, mg/L

The data on P adsorption isotherms were obtained by using a laboratory batch method analysis. One gram of < 2 mm air-dried, sieved soil was shaken in an end over-end shaker for 16 hours with a 20 ml 0.01M $CaCI_2$ solution containing varying amounts of KH_2PO_4-P (0, 5, 10, 20, 40, and 60 µg/ml). The solution was then centrifuged and filtered through Whatman No. 41 filter paper. Phosphorus in solution was determined by the Murphy and Riley (1962) method. The amount adsorbed was estimated from the difference between the amount of KH_2PO_4-P added and that remaining in solution (Rajan 1975a; Ryden *et al.* 1977a).

Results

Physical and chemical properties of the sewage treated soil and the control soil down to 100 cm depth are given in Table 1. The particle size analysis of sewage treated soil and control soil from surface to 100 cm depth shows that both soils have a high clay content, with the control soil having significantly higher clay content. The bulk density in the surface (0-10 cm) of the sewage treated soil was 1.0 g/cm^3 and in control soil was 1.4 g/cm^3. Soil saturated hydraulic conductivity was 3.18 mm/h in the sewage treated soil, that was several orders of magnitude lower than the control soil where it was 23.4 mm/h. At the surface (0-10 cm), sewage treated soil had 13% organic matter compared to 6% in the control soil. Cation exchange capacity (CEC) of the control soil was higher than the sewage treated soil at every depth except at 0-10 cm where the sewage treated soil was 28 meq/100 g compared to 12 meq/100 g in control soil. It is assumed that most of the differences in organic matter content, CEC, and the hydraulic conductivity in sewage treated soil and control soil may be attributed to long-term application of wastewater in soil (Ross *et al.* 1982; Bernal *et al.* 1992; Balks and McLay 1996). However, clay content and possibly plant and land management may also contribute to differences (Campbell *et al.* 1980).

Table 1. Some properties of sewage treated soil and control soil.

Sewage treated soil

Depth (cm)	PH ($CaCl_2$)	Sand (%)	Silt (%)	Clay (%)	Bulk density (g/cm^3)	Organic matter (%)	CEC (mequiv./100 g)
0-10	6.0	20	23	58	1.04	13.08	28
10-20	6.5	16	19	64	1.27	4.83	19
20-35	6.6	10	20	71	1.47	1.77	19
35-50	6.7	11	19	72	1.84	1.03	21
50-70	7.3	12	18	69	1.53	0.76	20
70-90	7.8	16	22	63	1.53	0.48	21
90-100	7.9	15	27	59	1.53	0.34	19

Control soil							
Depth (cm)	pH ($CaCl_2$)	Sand (%)	Silt (%)	Clay (%)	Bulk density (g/cm^3)	Organic matter (%)	CEC (mequiv./100 g)
0-10	6.7	16	9	75	1.0	6.60	12
10-20	7.3	15	8	77	1.6	3.38	22
20-35	7.6	13	9	78	1.6	1.55	30
35-50	7.7	14	7	79	1.6	1.06	33
50-70	7.5	15	7	78	1.6	0.22	38
70-90	7.7	14	6	80	1.6	0.15	39
90-100	7.9	14	6	80	1.6	0.15	39

Sewage treated soil had more P (both inorganic and organic) than the control soil (Table 2) and inorganic P is the principal form of P present in each layer of sewage treated soil and control soil. Concentration of inorganic P was significantly high in the 0-20 cm depth and gradually decreased with depth. At the surface (0-10 cm) sewage treated soil had nearly 10-times that of control soil. These values suggest that about 90% of the total P in sewage treated soil is inorganic P compared to 65% in the control soil. The presence of high inorganic P in sewage treated soil is presumed to be due to the high inorganic P in the Melbourne sewage effluent. High concentration of inorganic P in Melbourne sewage was first observed by Khin (1960).

Table 2. Distribution of inorganic P and organic P (µg/g) in the profile of sewage treated soil (STS) and control soil (CS).

	Inorganic P		Organic P	
Depth (cm)	STS	CS	STS	CS
0-10	2256a	242a	237a	138a
10-20	1061b	86b	157ab	82b
20-35	834bc	72bcd	148ab	71bc
35-50	662bc	55bcd	68b	46cd
50-70	580c	30cd	65b	32d
70-90	471c	13d	72b	18d
90-100	434c	11d	71b	19d

Means followed by the same letter in the vertical column are not significantly different according to Duncan's Multiple Range Test ($p \leq 0.5$).

P not only had accumulated in the surface soil but a significant amount has moved down to 100 cm depths in the profile of the sewage treated soil (Table 2). Movement of P in the soil profile was expected as soil has a finite capacity to hold P. When this limit is reached, as is often the case in soils used in wastewater renovation, P moves in soil beyond the zone of application (Latterell *et al.* 1982; Sharply *et al.* 1994; Simard *et al.* 1995; Nair *et al.* 1995).

Accumulation and movement of P in soil profile can be described by sorption-desorption reactions (Syers and Iskandar 1981). A frequently used sorption equation most to describe P sorption is the Freundlich equation (Rajan 1975a; Earl *et al.* 1979; Holford 1982). The Freundlich measured and fitted adsorption isotherms shows that P adsorption capacity of the sewage treated soil has decreased at every layer of soil compared to control soil. In sewage treated soil, the maximum decrease in P adsorption capacity was observed in the surface horizons (Fig. 2) and a gradual increase in soil adsorption capacity with depth up to 100 cm (Fig. 3). An increase in soil P adsorption capacity with depth was also observed in control soil, but compared to sewage treated soil there was little increase.

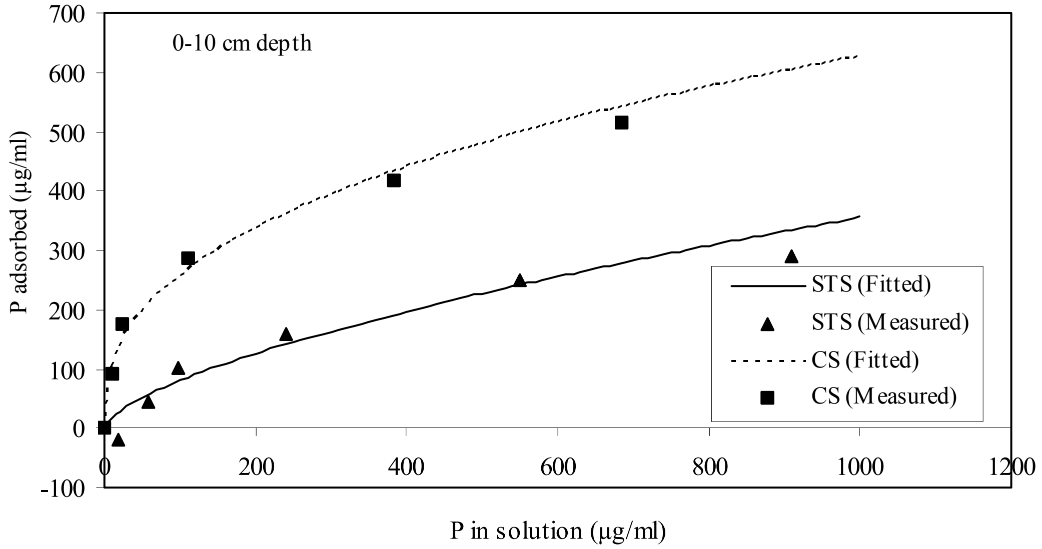

Figure 2. Freundlich fitted and measured adsorption isotherms for both sewage treated soil (STS) and control soil (CS) at 0-10 cm depth.

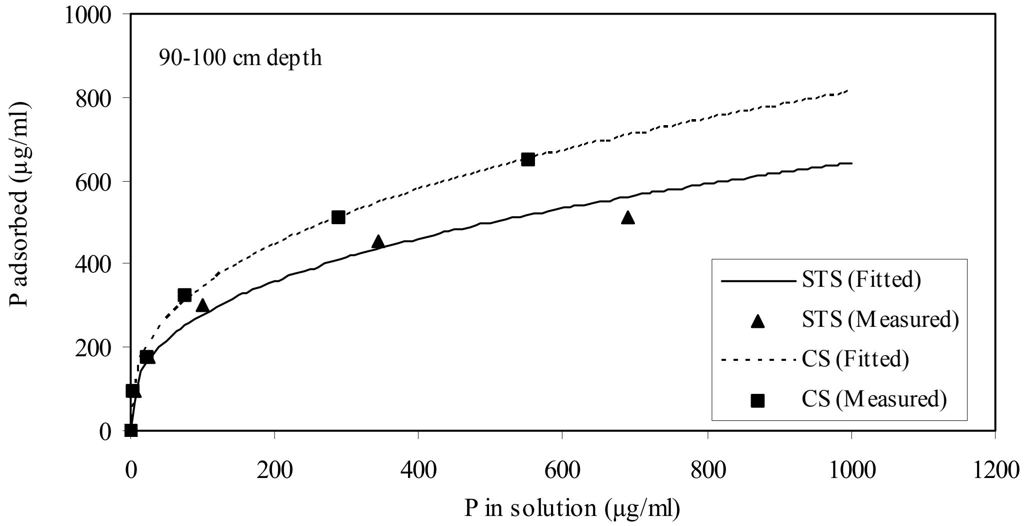

Figure 3. Freundlich fitted and measured adsorption isotherms for both sewage treated soil (STS) and control soil (CS) at 90-100 cm depth.

The Freundlich *K* coefficient (a measure of the total number of sites involved in P sorption), was less at every layer of sewage treated soil than the control soil down to 100 cm depth (Table 3). The *K* value was only 4 on the surface (0-10 cm) of sewage treated soil, compared to 43 in the control soil. These results suggest that P saturation had been reached in the topsoil of the sewage treated soil. Although the number of available P adsorption sites has increased with the increase in depth in both soils, the sewage treated soil still has fewer sites available for adsorption of P. The reduced soil P adsorption capacity of the sewage treated soil is reflected in the high concentration of P (28 mg/L) in the groundwater measured approximately 2m below the soil surface. Ground water containing this amount of P is poses a major threat to any receiving water body.

Table 3. Freundlich adsorption isotherm coefficients at different depth of sewage treated soil and control soil.

	Sewage treated soil			Control soil		
Depth (cm)	*K* (L/kg)	*N*	R^2	*K* (L/kg)	*N*	R^2
0-10	4.13	0.645	0.93	43.54	0.386	0.97
10-20	12.53	0.479	0.96	48.44	0.386	0.99
20-35	20.41	0.406	0.98	57.32	0.389	0.99
35-50	28.22	0.400	0.99	58.96	0.374	0.99
50-70	54.65	0.351	0.97	55.72	0.389	0.99
70-90	67.30	0.344	0.86	72.08	0.343	0.99
90-100	53.00	0.361	0.99	62.55	0.371	0.99

Conclusion

Throughout the sewage treated soil profile more P had accumulated than the control soil. Most (90%) of the P that had accumulated in the sewage treated soil was inorganic form reflecting the high dissolved inorganic P content in wastewater. Accumulation of P is generally restricted to the upper layers of the soil. However, significant downward movement of P in the profile was observed in the study. Movement of P in the soil profile is controlled by inorganic chemistry. The P-sorption capacity of the topsoil of the sewage treated soil had been reduced over time with the application of wastewater. As a consequence the soils ability to retain P against leaching had been reduced in the upper soil horizons. This was reflected in the large amounts of P (28 mg/L) found in leachate at approximately 2m. The results indicate that to continue land treatment of wastewater, and to optimize the soil P removal efficiency there needs to be a change in the present management strategy at Werribee. Challenge is to use the facility without overloading the system. Inefficient use of the system may not only lower the capacity of soil to remove pollutants adequately but also may convert this valuable natural resource into a wasteland.

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