Aust. J. Soil Res., 1995, **33**, 1053–62

Evaluation of the Potential to Dispose of Sewage Sludge. II.* Potential for Off-site Movements of Solids and Solutes

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Abstract

This paper reports a study of the potential for off-site movements of pollutants from sewage sludge broadcast onto the soil surface in *Pinus* plantations established on the coastal lowlands of south-east Queensland.

Laboratory studies of size and settling velocity distributions of rainfall-wetted sludge showed that it is relatively coarse and non-erodible. Field rainfall simulation studies at three sites in pine forests near Beerburrum found no significant increase in interrill erosion due to broadcasting of sludge. (Most or all of the sediment was observed to come from mineral soil exposed when a gutter to collect runoff was installed at the downslope ends of the plots.)

However, there was considerable movement of solutes in runoff from rainfall simulator plots that had received sludge—either freshly applied or 'consolidated' sludge (that had been broadcast on the plots 6 months prior to the rainfall simulation study and exposed to rain and weathering). Electrical conductivity (EC) of runoff from freshly applied sludge was initially high but decreased steadily during the 30 min rainfall event. Runoff from consolidated sludge had lower ECs, though significantly ($P < 0 \cdot 05$) higher than those of runoff from control plots.

Concentrations of nitrate-N and ammonium-N were initially high in runoff from freshly applied sludge, but decreased rapidly during the rainfall event. In contrast, concentrations of mineral N in runoff from consolidated sludge were low throughout the rainfall event. These results indicate a significant risk of off-site N pollution if runoff occurs during the first rains following broadcasting of sludge. By contrast, concentrations of total phosphorus, copper, and zinc in runoff from both fresh and consolidated sludge were relatively high, and showed only small decreases during the rainfall event applied. This suggests that sludge will contribute significant quantities of these elements to runoff for extended periods after broadcasting. The implications of these findings become important in terms of the timing and method of sludge application to the soil.

Keywords: sewage sludge, rainfall simulation, off-site movement, erosion, solutes in runoff, pine forests.

Introduction

Sewage treatment plants servicing the city of Brisbane in south-east Queensland presently produce about 45 t dry weight of de-watered sludge per day. Landfill disposal of this sludge is commonplace, though environmental and land availability problems have stimulated a search for alternative disposal systems. One option

* Part I, *Aust. J. Soil Res.* 1995, **33**, 1041–52.

0004-9573/95/061053$05.00

being considered is to develop a land-based disposal system in the Queensland Department of Primary Industry Forest Service (QDPI-FS) *Pinus* plantations centred on the township of Beerburrum (27° 03′ S., 153° 00′ E.), 50 km north of Brisbane. The intention is for a single broadcast sludge application to be made throughout plantation areas immediately following initial thinning of the *Pinus* crop at age 15–20 years.

Although disposal of sewage sludge on forest land may be of less concern than disposal on agricultural land because forests are a non-food chain outlet, the potential for off-site pollution is a major concern. Off-site movement could occur either in surface runoff (carrying sludge particles and/or solutes) or via movement of solutes to ground water. The Beerburrum State Forest is situated within the Pumicestone Passage catchment, where, in 1991, forestry was the dominant land use, accounting for 39% of the area (Department of Environment and Heritage, DEH, 1993). Pumicestone Passage is a coastal plain or passage-type estuary formed by Bribie Island to the east and the mainland to the west. The longitudinal axis of the passage extends broadly north-south for approximately 45 km. It is less than 2 m deep at mean sea level over 80% of its area, with tidal exchanges at its northern outlet being curtailed by a significant ocean sand bar. Observed changes in estuarine water quality suggest that pollutant exports from its catchment over the period 1978–92 are already well in excess of sustainable levels (DEH 1993). As the catchment is an area of considerable environmental, recreational and economic significance, evaluation of the potential for off-site pollution is essential before large scale sludge disposal can be operational within the catchment.

Existing data on off-site movements of pollutants from land-based sludge disposal systems vary considerably. Research studies of sludge disposal on forest land in the United Kingdom (Bayes *et al.* 1991) have indicated that the rates, timing and frequency of sludge application should be constrained by the ability of the site to accept N loadings that minimize runoff pollution. In agricultural studies, reported effects of sludge application on off-site N and P movement have been variable. In tillage studies, Deizman *et al.* (1989) found that P losses were greater in runoff from surface applied sludge than from incorporated sludge. Dunigan and Dick (1980) reported higher N and P losses in runoff from surface applied sludge relative to incorporated sludge in one experiment, but found variable results in another experiment. Kladivko and Nelson (1979) found higher concentrations of N and P in runoff from sludge-treated soils relative to control sites, whereas Zenz *et al.* (1976) reported no such differences in their studies.

This study was carried out to provide a rapid assessment of the potential for off-site movement of broadcast sewage sludge in the Beerburrum State Forest and is a continuation of the investigation of the hydrology of the site reported by Costantini *et al.* (1995). It includes laboratory examination of the sedimentation characteristics of sludge, and field studies using simulated rain to assess the risks of movement of both sludge particles and solutes leached from the sludge. By identifying likely pathways and rates of off-site movement, the study provided a rapid appraisal of the feasibility of broadcasting of sludge in this area, giving a basis for determining whether further investment in more detailed studies of sludge broadcasting was desirable, and for indicating whether alternative approaches to sludge disposal should be considered.

Methods

Overview

The study consisted of laboratory measurements of sludge properties likely to affect erosion (size and settling velocity distributions), as well as a field rainfall simulator study of movement of sludge in runoff as either solids or solute.

Sludge

Sludge used in the study came from the Luggage Point treatment plant in Brisbane. It was a product of aerobic digestion of domestic and industrial sewage, and had been stored for 12 months following dewatering. Chemical characteristics of the sludge are summarized in Table 1. Gravimetric water content of sludge applied to plots immediately prior to rainfall simulation was $0\cdot39$ g g^{-1}.

Table 1. Chemical characteristics of Luggage Point sludge

All results reported on dry weight basis

pH[A]	EC[A]	Cl[A]	v.s.[B]	Org. C[C]	N[D]	P	NO_3-N	NH_4-N	As	Cd	Cu	Ni	Zn
		(%)					($mg\ kg^{-1}$)						
5·0	8·4	0·18	35	25·4	1·3	2·6	940	1915	10	20	570	107	1130

[A] pH, EC (dS m^{-1}) and Cl determined on 1 : 5 sludge/water extract.
[B] Volatile solids.
[C] Organic carbon determined by method of Heanes (1984).
[D] Total Kjeldahl nitrogen.

Laboratory Measurement of Sediment Properties

In the laboratory, a 30 mm deep layer of sludge was spread over a $0\cdot5\times0\cdot5$ m plot of sand. The plot was then exposed to 10 min of simulated rain at 100 mm h^{-1}, allowed to stand overnight, and then exposed to a further 30 min of simulated rain at 100 mm h^{-1}. Samples of sludge were collected from the plot for determination of a settling velocity distribution by using the settling column technique described by Loch and Rosewell (1992), and for measurement of particle size distribution by wet sieving.

Effectively, these measurements assessed the sediment properties of sludge at the point of entrainment, prior to any deposition or selective transport.

Site Selection, Sludge Application and Field Rainfall Simulation

On the basis of the classification system for sludge application suitability proposed by Foster (1992), three study sites at Beerburrum were selected: Site 1—suitable, Site 2—marginally suitable, and Site 3—unsuitable. The soils at sites 1–3 belonged to the lateritic podzolic, yellow podzolic, and soloth (with gleyed features) Great Soil Groups (Stace *et al.* 1968), and represented upper, mid-lower and lower slope positions respectively. The sites were cultivated about 15 years prior to the study, and supported mid-rotation aged *Pinus caribea* and *P. elliottii* plantations. A more detailed description of the sites and the soils is given by Costantini *et al.* (1995).

The study examined sludge from the Luggage Point Treatment Plant (as described previously), applied at 90 t ha^{-1} (dry weight basis), either freshly applied to the rainfall simulator plots or 'consolidated'. *Consolidated sludge* was sludge that had been applied to simulator plots 6 months prior to experimentation, and consequently had been weathered by, and exposed to leaching from, natural rain. Following application of sludge to the plots in March 1992, subsequent rain was: April 156 mm, May 183 mm, June 15 mm, July 41 mm, August 8 mm and September 31 mm—a total of 434 mm. *Freshly applied sludge* was applied immediately prior to field rainfall simulation (which was carried out in late October 1992). The application rate of 90 t ha^{-1} gave almost complete coverage of the plot surface. Control plots received no sludge, and there were two replicates of all treatments.

The field rainfall simulation work was described in detail by Costantini *et al.* (1995). Briefly, the apparatus applied rain simultaneously to two plots, each 2·0 m long and 0·8 m wide. Drop-size distribution and energy of rainfall was similar to that of natural rain (Loch and Foley 1994). A simulated rainfall intensity of 150 mm h^{-1} was applied for 30 min, which is approximately equivalent to a 1 in 100 year event for the Brisbane area (Australian Rainfall and Runoff 1977). Water used during the study had an electrical conductivity of 0·14 dS m^{-1}, nitrate N concentration of 0·27 mg L^{-1}, and a total P concentration of 0·01 mg L^{-1}.

Runoff reaching the downslope ends of the plots was collected in a gutter, and transferred by suction to collection tanks for measurement of runoff volume. Samples of runoff were taken at 5 min intervals for measurements of sediment and solutes. Samples of runoff were analysed for total sediment (soil, organic matter and sludge) concentrations, and a flow-weighted total sediment loss was calculated. Electrical conductivities of runoff samples were measured at Sites 1 and 3, and N, P and a suite of heavy metal analyses (detailed later) were performed on samples from Site 1. Sediment concentrations in runoff from all plots were so low that it was not practicable to measure sediment size distributions. Limited samples were taken of wetted sludge on the plot surface for comparison with previous laboratory measurements of settling velocity distributions.

The relatively small size of the rainfall simulator plots restricted the study to the consideration of interrill erosion only. However, erosion by overland flow was not perceived to be a major concern in this area, as the sites considered to be most suitable for sludge application had suffered no recent disturbance by machinery, had well developed litter layers on the soil surface, and were located on low slope gradients (ranging from 3% to 8%). There was no observational evidence for erosion by overland flows at this location, which would have been visible due to associated removal of the surface pine needle litter. Therefore, study of raindrop-driven (interrill) erosion appeared to be a reasonable approach.

Analysis of Chemical Composition of Runoff

Subsamples of runoff from Site 1 were stored in acid washed bottles, preserved by acidification with hydrochloric acid and refrigerated before being analysed for Cd, As, Cu, Ni, Zn, nitrate-N, ammonium-N and total P concentrations. Methods of analysis were as follows:

(a) Solutions for metal analyses were centrifuged to remove particles and an aliquot digested with a sulfuric : nitric : perchloric (2 : 2 : 1) acid mixture. Cd and Ni were determined by anodic stripping voltammetry (ASV), Cu and Zn by inductively coupled plasma–atomic emission spectrometry (ICPAES) and As by ICP-hydride generation.

(b) Nitrate-N was determined by automated colorimetric analysis of the unfiltered solutions (buffered at pH 4–5 with ammonium acetate) based on the Griess–Ilosvay reaction after reduction of NO_3 to NO_2 with alkaline hydrazine.

(c) Ammonium-N was determined by automated colorimetric analysis of the unfiltered solutions based on the salicylate isocyanate reaction.

(d) Total P was determined on the digest solutions prepared for metal analysis by automated colorimetry based on the molybdenum blue reaction.

Although the samples were not filtered before storage and preservation by addition of HCl, there is little possibility that desorption of elements from particulate sludge in the samples contributed to the element concentrations reported. Firstly, concentrations of particulate sludge in runoff were extremely low (if present at all), and secondly, element concentrations in runoff were similar to concentrations in samples of leachate from the rainfall passing through the sludge taken at similar times (unpubl. data).

Results

Size and Settling Velocity Distributions

The laboratory wetted sludge had a coarse size distribution, with 35% and 88% of the particles exceeding 5 and 1 mm respectively (Fig. 1). The proportion of fine particles <0·075 mm was negligible. Because of the high water content of wetted sludge (101% gravimetric) and hence, low wet density, settling velocities were slower than would be expected from the actual size distributions obtained by wet sieving. This is indicated in Fig. 1 by the equivalent sand size distribution derived from settling velocity measurements being much finer than the actual size distribution measured by wet sieving. (If particles had had the same wet density as sand, then both equivalent sand size and actual size distributions would have been the same.)

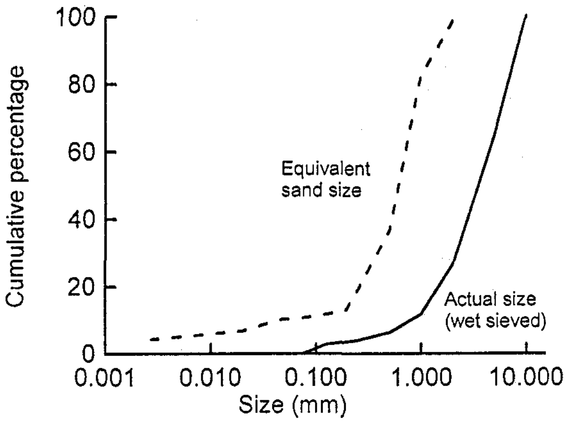

Fig. 1. Equivalent sand size distribution (estimated from measured settling velocities) and actual size distribution (from wet sieving) of Luggage Point sludge.

The settling velocities, however, also indicated a lack of fine, easily transportable particles in the wetted sludge. Samples of freshly applied sludge taken after wetting in the field rainfall simulation study gave similar settling velocity distributions to those measured in the laboratory some months earlier, indicating that size and settling velocity distributions are consistent through time for Luggage Point sludge.

Concentrations of Sediment in Runoff

Sediment concentrations in runoff from the field rainfall simulation plots were uniformly low. Fig. 2 shows changes in runoff rates and sediment concentrations through time for the fresh sludge treatment at Site 1.

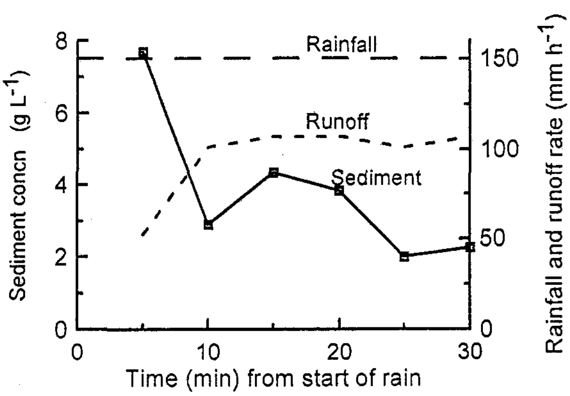

Fig. 2. Changes in runoff rates and sediment concentrations through time for a plot at Site 1 with freshly applied sludge.

Total sediment losses were also low and are summarized in Table 2. The data showed no significant ($P < 0{\cdot}05$) effect of sludge addition on sediment loss. The lack of significant differences between treatments is due to the considerable variability in sediment loss recorded. That variability is not surprising as the data in Table 2 represent small (40–530 g) absolute soil losses per plot. Also contributing to the variability was the fact that much (if not all) of the small quantity of sediment that moved off the plots was observed to come from the lower boundaries of the rainfall simulator plots—i.e., plot installation was a relatively important and variable source of sediment because erosion from the plots was so low. (It was generally impossible to install the lower plot boundary without exposing mineral soil, as the plots were not level.) Particulate sludge was not visible in runoff, nor in dried samples of sediment in runoff.

Table 2. Effects of sludge addition and site on mean sediment loss (t ha^{-1}) from rainfall simulator plots

Site	Sediment loss (t ha^{-1}) for treatments of Nil sludge	Consolidated sludge	Freshly applied sludge
1	1·83	0·71	1·44
2	0·99	1·83	0·68
3	0·71	0·34	1·37

Electrical Conductivities of Runoff

Electrical conductivities (ECs) of runoff from Site 1 are presented in Fig. 3. Similar data (not presented) were obtained for Site 3. At both sites, ECs of runoff from plots with freshly applied sludge were initially high as runoff developed, and then declined rapidly through time. Even after 30 min rain, these ECs were significantly higher ($P < 0 \cdot 01$) than those for the nil and consolidated sludge treatments. For plots with consolidated sludge, ECs were significantly higher ($P < 0 \cdot 05$) than those from plots without sludge.

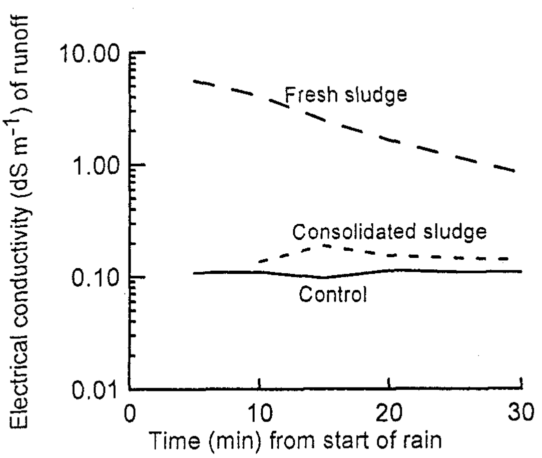

Fig. 3. Effects of sludge on mean electrical conductivities of runoff at Site 1.

Chemical Composition of Runoff

The concentrations of elements found in runoff samples from Site 1 are shown in Table 3. Elevated levels of all nutrients and heavy metals were measured in runoff from both freshly applied and consolidated sludge treatments relative to the control. Runoff from freshly applied sludge had higher concentrations of all elements than runoff from consolidated sludge. For both freshly applied and consolidated sludge, concentrations of elements in runoff typically decreased during the 30 min of simulated rainfall. The largest decreases were observed in the freshly applied sludge treatment where initial concentrations were highest.

Table 3. Mean concentrations of elements in runoff from plots under simulated rain at Site 1

Treatment	Time (min)	NO_3-N	NH_4-N (mg L^{-1})	Tot. P	Cd	As	Cu (μg L^{-1})	Ni	Zn
Control	5	0·95	0·02	0·07	1·7	1·5	16·3	4	125
	20	0·3	n.d.[A]	n.d.	1·2	n.d.	3·1	10·5	74
	30	0·3	n.d.	n.d.	0·7	1·0	3·1	24	90
Fresh	5	330	>330	10·1	20	14	389	138	1783
	10	178	263	10·5	17	16	384	106	1746
	15	77	127	10·3	15	14	344	83	771
	20	43	87	9·4	13	12	299	74	672
	25	23	67	9·6	13	11	296	63	644
	30	16	50	8·5	12	9	100	51	507
Consolidated	10	0·6	2·9	7·4	5·4	15	160	45	347
	15	0·4	0·5	5·7	3·8	10	118	35	260
	20	0·5	1·2	5·3	3·6	7	104	31	249
	25	0·5	0·9	4·3	2·6	7	78	26	203
	30	0·5	0·8	5·0	3·7	n.a.[B]	n.a.	n.a.	n.a.
Recommended limits[C]		0·1		0·1	2	50	5	150	50

[A] n.d., not detected.
[B] n.a., data not available.
[C] Australian Water Quality Guidelines for marine and fresh waters (ANZECC 1992).

Nitrate-N and ammonium-N concentrations in runoff from freshly applied sludge decreased from about 330 and >330 mg L^{-1} to about 15 and 50 mg L^{-1} respectively during rainfall. However, concentrations of both forms of N in runoff from the consolidated sludge were only marginally above background levels, with ammonium N the higher of the two.

Total P concentrations in runoff from freshly applied sludge were relatively high, and only decreased slightly during 30 min of rainfall. Whilst the concentrations were lower in runoff from consolidated sludge, they were also initially high, and decreased at a similar rate during rainfall.

Concentrations of heavy metals in runoff generally followed a similar pattern to that observed for total P, with concentrations decreasing during rainfall. Although concentrations were lower in runoff from consolidated sludge compared with freshly applied sludge, they were significantly higher ($P < 0{\cdot}01$) than those from control plots.

Discussion

Low Erosion and Erodibility

Both the size and settling velocity distributions of wetted sludge indicate a lack of finer size fractions that could be easily eroded. Consequently, any sludge material that is eroded will be predominantly coarse, and rather than move long distances in runoff, will deposit rapidly when flow velocities decrease.

Sludge broadcasting caused no significant increase in erosion from the field simulation plots, from which it can be inferred that the risk of interrill erosion of particulate sludge matter is minimal. During simulated rainfall application to fresh sludge treatments, rain filtered first through the applied sludge, then through the needle litter layer, before reaching the soil surface or the hydrophobic fungal mat commonly associated with needle litter. Any runoff that occurred concentrated first in micro-depressions before moving downslope through the litter layer (Costantini *et al.* 1995). Downslope flows were typically slow, and any entrained particulate sludge would have been filtered out by the pine needles. The situation with consolidated sludge was similar, the only difference being that rain was first filtered through the mat of pine needles that had accumulated on top of the applied sludge.

Movement of particulate sludge by overland flow will not be a significant risk, at least in situations where the depth of runoff is less than the depth of needle litter. The implication for foresters is that a dense needle layer prior to sludge application would be desirable, and areas on steep slopes likely to generate large runoff volumes should not be considered for broadcasting of sludge.

Solute Movement

Interestingly, although the water applied during rainfall simulation had a consistent EC of $0 \cdot 14\,\mathrm{dS\,m^{-1}}$, ECs of runoff from the control plots were consistently in the order of $0 \cdot 10\,\mathrm{dS\,m^{-1}}$. This suggests that the needle litter and other organic matter on the plot surface adsorbed ions from the water.

The EC data in Fig. 3 indicate that freshly broadcast sludge contains highly soluble material that can be rapidly dissolved and removed as leachate. Consolidated sludge by contrast contains much lower concentrations of slowly soluble material that result in a consistent slight increase in runoff EC. This is to be expected because of its exposure to weathering and leaching processes for 6 months prior to the rainfall simulator experiment.

Chemical analysis of runoff from fresh sludge showed high concentrations of mineral N that would be responsible for the associated high ECs. Therefore, a large flush of mineral N (due to mineralization during stockpiling at the treatment plant) can be expected in runoff from the first rains following application.

This suggestion is supported by unpublished data (Barry *et al.*) from a leaching trial involving Luggage Point sludge, which indicated that approximately 25% of the total N in the sludge was leached during the first 5 weeks of the leaching experiment, in which the columns were subjected to rainfall of $35\,\mathrm{mm\,week^{-1}}$.

Under field conditions, depending on whether rain falling on freshly applied sludge infiltrates or runs off, high concentrations of mineral N can be expected in either the soil solution or in runoff water, respectively. If the first rains following sludge application generate runoff, then there is a significant risk of off-site N pollution. This risk could be managed by varying the time of application. If the sludge is applied in winter, when the risk of runoff-generating rains is low in south-east Queensland, most of the sludge-applied N could be expected to be leached into the soil solution.

The situation for total P and for Cu and Zn is more complicated. Applied sludge will release high levels of P, Cu and Zn to leachate/runoff for periods well in excess of 6 months after application. Moreover, release rates are likely to remain high during extended rainfall events. It is therefore not possible to manage the risk of pollution by P, Cu and Zn by varying the time of application. Broadcast sludge application to *Pinus* plantations in the Beerburrum landscape therefore poses a significant risk of off-site pollution, and of accelerated eutrophication of surface waters.

Although application rates of sludge could be reduced, this would not give any certainty of reductions in solute concentrations in runoff. Much lower rainfall intensities than those used in this study could still produce runoff (Costantini *et al.* 1995), and hence, the lower source strength of available solute could be balanced by a reduced rate of solvent flux (rainfall intensity). In fact, higher concentrations of P, Cu and Zn may occur in runoff from natural storms than were recorded in this study.

The elemental concentrations found in runoff in this study can be compared with the Australian Water Quality Guidelines for Marine and Fresh Waters published by the Australian and New Zealand Environment and Conservation Council (ANZECC 1992). Recommended limits for the protection of aquatic ecosystems are shown in Table 3. From the ANZECC recommendations, it can be seen that the elements of greatest potential pollution risk to surface and ground waters are N, P, Cu and Zn. Interestingly, runoff from the control plots exceeded the recommended concentrations for nitrate N and Zn. In the case of nitrate, this is attributed to levels in the water used during simulation.

The risk of runoff pollution by solutes from applied sewage sludge may be reduced by incorporation of sludge into the soil to ensure that the readily soluble pollutants are not exposed to runoff, and are possibly adsorbed or fixed within the soil. Incorporation, however, potentially increases the risks of leaching of N to regional ground water and of erosion.

Conclusions

This study has shown that broadcast sewage sludge will contribute significant concentrations of solutes to runoff and leachate—both from freshly applied sludge and from sludge that has been broadcast for 6 months. Given the potential for generation of surface runoff on the water-repellent soils used for forestry, and the apparent lack of barriers between surface and ground water indicated by Costantini *et al.* (1995), disposal of sewage sludge by broadcasting in forests in the Beerburrum area presents a considerable risk of off-site pollution. As there is already concern that the Pumicestone Passage catchment is receiving unsustainable levels of nutrient pollutants (DEH 1993), the site cannot be considered suitable for that method of sewage sludge disposal.

Together with the previous paper in this series, this study illustrates the potential for rapid appraisal of land management options to provide a timely basis for decisions on land use.

Acknowledgments

This work was made possible by funding from the Brisbane City Council, and permission from the Brisbane City Council to publish this paper is acknowledged.

We thank Dave Osborne and Darryl Goshnick (Forest Service, QDPI) for preparation of plots and Kerry Myers (Natural Resource Management, QDPI) for laboratory analyses.

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Manuscript received 9 May 1994, accepted 5 April 1995