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Evaluation of the Potential to Dispose of Sewage Sludge. I. Soil Hydraulic and Overland Flow Properties of *Pinus* Plantations in Queensland

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Abstract

The studies reported in this paper were designed to evaluate the potential for disposal of sewage sludge in commercial *Pinus* plantations at Beerburrum, 50 km north of Brisbane. Soil descriptions and measurements of hydraulic properties were made in three soils, covering the range of perceived site suitability for sludge application. Disc permeameters and a rainfall simulator were used to characterize surface infiltration properties both with and without sludge, and ponded rings were used to assess permeability of the upper B horizon.

Although surface hydraulic conductivities were potentially high, infiltration into dry soil was reduced by water repellence associated with fungal matting at the soil surface and mycelia extending through the A1 horizon. Surface runoff could be generated from dry soils by relatively low intensity rainfall events, and the rate and volume of runoff was not increased by broadcast sludge application. Hydraulic conductivities of the upper Bt horizons in the lateritic and yellow podzolic soils were high, suggesting that persistent perched watertable development was unlikely. However, the presence of bleached A2 horizons and gleyed Bt horizons with prominent mottling in these soils were interpreted as evidence of periodic regional ground-water intrusion. By contrast, hydraulic conductivity in the Bt horizon of the soloth was low, suggesting that locally restricted drainage occurs.

Likely pathways of water movement were inferred for three representative soil types in the proposed sludge application project. There is potential for both Hortonian runoff when antecedent conditions are dry, and saturated runoff during prolonged wet periods. Potential off-site pollution could therefore occur if either solids or solutes from the sludge are susceptible to transport. In addition, preferential flow paths of water infiltration were demonstrated, and the potential for accelerated water and solute movement to ground watertables was inferred.

The studies reported in this, and the second, paper in the series were used to appraise the potential for either surface water or ground water pollution from land-based sludge disposal.

Keywords: Pinus, sludge disposal, infiltration, rainfall simulation, water repellency.

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 systems. One option considered was to develop a land based disposal system in the Queensland Department of Primary Industries Forest Service (QDPI-FS) *Pinus caribaea* Morelet. var.

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hondurensis Barr. *et* Golf., and *P. elliottii* Engelm. var. *elliottii* plantations centred on the township of Beerburrum (27° 03′ S., 153° 00′ E.), 50 km north of Brisbane. The intention was for a single broadcast sludge application to be made immediately following initial thinning of the *Pinus* crop at age 15–20 years.

The plantations targeted for sludge disposal constitute a significant area of the Pumicestone Passage catchment, an area of very high environmental value in south-east Queensland (Department of Environment and Heritage 1993). Surface waters in the catchment have high conservation and recreation values, the ground water has a potential water supply value, and the Passage itself has high conservation, preservation, recreation and fishing values. It is essential that sludge disposal activities do not degrade these values.

Coaldrake (1961) described the ecosystem of the Pumicestone Passage catchment, noting that vegetation and soil type patterns were largely controlled by topographic and ground water characteristics. Annual rainfall is 1250–1500 mm; topography is low-lying, flat to undulating; and soils are mainly coarse textured, derived from early Mesozoic sediments (sandstones) and some late Cainozoic alluvium. These site characteristics are not considered ideal for broadcast sludge disposal (Ross *et al.* 1991; New South Wales Environment Protection Authority 1994). There was therefore a high risk that either solid or solute material from sludge might pollute ground water, or be transported off-site by surface flow and/or interflow. From a planning perspective, it was desirable to assess the significance of these risks prior to any investment being made in a comprehensive social, environmental and economic feasibility study. A rapid appraisal system was needed to provide managers with good quality information for preliminary decision making.

Pathways of water movement are clearly a major consideration in planning disposal of materials with potential to pollute. The studies reported in this paper were designed to investigate the hydraulic properties of three soils representative of sites that were, (i) suitable, (ii) marginal and (iii) unsuitable for sludge use in the proposed disposal area (Foster 1992). Surface infiltration characteristics, both with and without sludge were determined, and B horizon permeabilities were measured to identify any restrictions to percolation that might result in perched watertable formation.

The study illustrates how strategic measurements of soil hydraulic properties can be used to suggest likely water movement pathways, and predict the potential of these to perform as vectors for transporting sludge solids/solutes either off-site or to the ground water. The second paper in this series reports an investigation of the potential for off-site movement of both sludge and sludge leachates. Together, the papers describe a methodology for rapid appraisal of the potential for sludge disposal to result in either off-site or ground-water pollution.

Methodology

The study was conducted in October 1992. Rainfall simulation was used to characterize surface infiltration at three sites with three levels of sludge application; disc permeameters were used to investigate surface hydraulic properties; and ponded rings were used to assess subsoil permeabilities.

Site Selection and Properties

Foster (1992) developed a classification system for site suitability to sludge application in the Beerburrum *Pinus* plantation estate. The following three sites were selected for study, covering the range of suitability classes defined by Foster (1992): Site 1 (suitable), Site 2 (marginally suitable), and Site 3 (unsuitable) (Tables 1 and 2). In the three soil types studied, gleyed B horizons together with prominent B horizon mottling were interpreted as being indicative of periodic saturation. Because the study was intended to be short-term, by focusing on a rapid appraisal of the potential for off-site and/or ground water pollution, piezometers were not installed. However, observations of soil pits during the wet autumn of 1992 confirmed the presence of a persistent watertable at all sites. Slopes throughout the study area were typically less than 5%.

Table 1. Soil types selected for experimentation at each site

Site	Stace *et al.* (1968)	Northcote (1979)	Slope position	Suitability class
1	Lateritic podzolic	Gn 3·04	Upper	Suitable
2	Yellow podzolic	Dy 5·41	Mid-lower	Marginal
3	Soloth	Dg 4.81	Lower	Non-suitable

The litter layer sites 1–3 comprised 7, 26 and 41 t ha^{-1} respectively of newly fallen and decomposing *Pinus* needles. Litter loads were influenced by both time since controlled litter reduction burning and tree density. Where the litter layer is well developed in Beerburrum *Pinus* forests, basidiomycete fungi are commonly found at the soil/litter layer interface. Felted mycelia bind the surface litter/mineral soil, and extend throughout the surface 100 mm of the soil profile, similar to that described by Bond and Harris (1964) in South Australia.

Forest Establishment and Management

The study sites were located in *P. caribaea* var. *hondurensis* and *P. elliottii* plantations established in 1976 and 1977 (Table 3). The sequence of operations used during *Pinus* establishment was to push and burn the original vegetation, cultivate to a nominal depth of 200 mm, mound if the area had poor drainage, and transplant seedlings with a tractor-mounted planter (Table 3). At Sites 2 and 3, continuous mounds, with consolidated dimensions of 1·0 m width, 0·25 m height at centre and 0·2 m^2 cross-sectional area, were established at the time of planting, and were oriented down the slope. After establishment, mechanical activity was limited to one discing of the inter-mound zone during the first year for weed-control at Site 2 only, and to thinning operations at about age 15 years. The discing increased micro-relief variation in the furrow.

Sludge Application Treatments

The study examined the impacts on surface infiltration characteristics of both freshly applied (fresh) sewage sludge and sludge that had been applied to plots 6 months earlier (consolidated). The consolidated sludge was weathered by, and exposed to leaching from, natural rain following broadcasting in March. Monthly rainfall totals during this period were: April (156 mm), May (183 mm), June (15 mm), July (41 mm), August (8 mm), and September (31 mm)—a total of 434 mm. Fresh sludge was applied 2 h prior to experimentation. Sludge application rates were 90 t ha^{-1}. Sludge used in the study was from the Luggage Point treatment plant in Brisbane, and was the product of aerobic digestion of domestic and industrial sewage. It had been stored for 12 months following dewatering.

Rainfall Simulation

The field rainfall simulator used was based on the design of Bubenzer and Meyer (1965). It used three Veejet 80100 nozzles spraying downwards, with the nozzles mounted on an oscillating manifold so that the fan sprays from the nozzles swept across two plots, each $2{\cdot}0\times0{\cdot}8$ m. Kinetic energy of the rainfall applied was approximately 29·5 J m^{-2} mm^{-1} (Loch and Foley 1994), which is similar to that of intense natural rainfall in Queensland (Rosewell 1986). Forest canopies tend to produce drop size and velocity distribution patterns similar to those of intense natural rain for all intensities (Chapman 1948, Bridge and Ross 1983), as large drops form on the leaves, and fall sufficient distances to reach near terminal velocities.

Table 2. Profile descriptions of representative soils at each site

Site	Depth	Horizon[A]	Texture[A]	Moist colour (dry)	Structure	Primary mottles Abundance	Contrast	Colour
1	1–10	A11	SL	10YR3/3	Medium cast	Nil	—	—
	10–25	A12	SL	10YR3/3	Weak cast	Common	Faint	10YR4/6
	25–40	A13	SL	10YR5/4	Massive	Many	Distinct	10YR3/3
	40–90	A2	SL	10YR6/4 (2.5YR8/3d)	Nassive	Many	Faint	19YR7/3
	90–130	A3	SL	10YR6/6	Massive	Many	Distinct	10YR7/3
	130–145	B1	SCL	10YR7/3	Massive	Many	Prominent	10YR6/8
	145–165	B2	CL	10YR7/3	Moderate[B]	Many	Prominent	10YR6/8
	165–180	B3	LC	2.5Y7/3	Strong[B]	Many	Prominent	7.5YR5/8
	180+	C	MC	2.5Y7/1	Strong[B]	Many	Prominent	10YR6/8
2	0–30	A11	SL	10YR3/2	Massive	Nil	—	—
	30–45	A12	SL	10YR6/2	Massive	Many	Distinct	10YR3/2
	45–65	A2	SL	10YR6/2 (10YR8/2d)	Massive	Many	Distinct	10YR6/6
	65–80	B1	SC	10YR6/2	Massive	Many	Prominent	10YR6/8
	80–105	B21	MC	2.5Y7/1	Moderate[C]	Many	Prominent	2.5YR4/8
	105–150	B22	HC	2.5Y7/1	Strong[C]	Many	Prominent	2.5YR3/6
3	0–20	A1	LS	10YR4/3	Massive	Nil	—	—
	20–45	A21	LS	10YR5/4 (10YR8/1d)	Massive	Nil	—	—
	45–65	A22	LS	10YR7/3 (10YR8/1d)	Massive	Many	Prominent	7.5YR6/8
	65–120	B2	HC	10YR6/1	Massive	Many	Prominent	7.5YR6/8
	120–150	B3	HC	2.5Y7/1	Massive	Many	Prominent	10YR6/8

[A] Horizon/Texture. Conventions follow Northcote (1979).
[B] Polyhedral primary pedality, aggregated in fine polyhedral secondary peds.
[C] Polyhedral primary pedality, aggregated in sub-angular blocky secondary peds.

Table 3. Timing and nature of forestry management operations in the study area

Management operations	Site 1	Sites 2 and 3
Clear original vegetation	May 1977	1975
Disc plough to 20 cm (No. 1)	July 1977	1975
Disc plough to 20 cm (No. 2)	July 1977	—
Mounding (Napier Mounder)	—	Dec. 1975
Planting		
Timing	July 1977	July 1976
Species[A]	PCH	PEE
Stocking[B] (stems/ha)	1356	1304
Inter-row cultivation[C]	—	Dec. 1976 (2 only)
Pre-commercial thin		
Timing	Feb. 1983	—
Stocking (stems/ha)	763	
Commercial thinning		
Timing	Aug. 1992	Oct. 1989
Stocking (stems/ha)	400	600
Control burn (No. 1)	Aug. 1984	Aug. 1984
Control burn (No. 2)	Aug. 1992	—

[A] Species used in pine plantations include *Pinus caribaea* var. *hondurensis* (PCH) and *Pinus elliottii* var. *elliottii* (PEE).
[B] The notional planting espacement was 5×2·4 m, with 5 m between rows of trees and 2·4 m between trees in a row.
[C] Cultivation comprised discing down the furrow to a depth of 50–100 mm.

Preliminary trials showed that soils typically had surface infiltration capacities of 50–120 mm h^{-1}. In order to study both infiltration and runoff, 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 (Institution of Engineers, Australia 1987). Two replications of the three sludge treatments (nil, fresh and consolidated) were studied at each site. Due to technical difficulties in handling the high runoff rates encountered, one nil sludge and one consolidated sludge replication at Site 2 received a 100 mm h^{-1} rainfall intensity. Water used in the study had an electrical conductivity of 0·14 dS m^{-1}. After rainfall, samples of the A1 horizon were collected for water content determination, and surface wetting patterns were noted. Soils were dry (less than 5% gravimetric water content) at the time of experimentation.

Disc Permeameters

Eight disc permeameter (Perroux and White 1988) measurements were made at each site to characterize the hydraulic properties of surface soil without sludge. Test sites were prepared by gently removing the litter layer together with any surface fungal matting. A non-foaming surfactant was added to the permeameter water in order to overcome very strong water repellence. Without the surfactant, water from the permeameters did not enter the soil at all.

The procedure developed by Ankeny *et al.* (1991) and Reynolds and Elrick (1991) was used to determine hydraulic conductivities for saturated and near-saturated soil from a sequence of steady infiltration measurements made at several tensions on a single infiltration surface.

Ponded Infiltration

Ponded ring infiltrometers were used to investigate the saturated infiltration characteristics of the upper B horizons at all sites. The B horizon was exposed by backhoe, surface smearing removed, and 300 mm diameter rings inserted 150 mm into the upper profile were used for measuring cumulative infiltration. Three replicates were used at each site.

Results

Infiltration of Simulated Rain

Surface micro-relief affected the generation of runoff from simulation plots. Rainfall filtered through, and wet, the litter layer (including any applied sludge) before reaching the mineral soil, or if present, a fungal mat. Runoff concentrated first in micro-depressions, before moving downslope through the litter layer. The litter layer had the effect of slowing runoff velocity, with the result that the recession flow from the 2·0 m long simulation plots typically lasted 3 min. The effect of more irregular micro-relief and/or a thicker litter layer was to increase surface storage and further delay runoff. For example, replication 1 of the fresh sludge treatment at Site 2 had the most irregular surface micro-relief of all plots, with an especially thick litter layer. Runoff from this plot continued for 5 min after rainfall cessation, contributing 18% of the total. By contrast, runoff from the second replication of this treatment lasted 3 min, contributing 7% of the total.

The fungal mat at the interface of the mineral soil and litter layer was strongly hydrophobic. Thus soil moisture contents after rainfall simulation were considerably less than moisture contents at saturation (Table 4), and small areas (50–100 mm diameter) of soil surface under the fungal mat remained dry.

Table 4. Water contents of the 0–100 mm layer after rain and at saturation (g g^{-1})

Description	Site 1	Site 2	Site 3
Mean water content after rain (g g^{-1})	0·090	0·194	0·168
Water content range after rain (g g^{-1})	0·059–0·124	0·060–0·256	0·127–0·0217
Water content at saturation (g g^{-1})	0·182	0·263	0·259

Infiltration patterns under simulated rainfall were mostly consistent with conventional theory (Marshall and Holmes 1988). Initial infiltration rates were high, decreasing systematically with time towards a steady rate (Fig. 1). The exceptions were the nil sludge plots at Site 1, and to a lesser extent Site 2, where there was a large decrease in infiltration between 5 and 10 min, followed by a gradual increase (Fig. 1), which was attributed to a decrease in water repellence as the fungal mat gradually wetted. For one replication at Site 1, the infiltration rate reached a temporary low of 5 mm h^{-1} during a single, 1 min measurement period.

Average infiltration rates during the last 10 min of rainfall in the nil sludge treatments were 50, 86, and 91 mm h^{-1} for Sites 1, 2 and 3 respectively (means of two replicates). Across all treatments, analysis of variance showed the infiltration rate during the final 10 min of rain at Site 1 to be significantly ($P < 0 \cdot 01$) lower than Sites 2 and 3.

Fresh sludge application had no significant ($P > 0 \cdot 05$) effect on steady infiltration rates at any site. By contrast, plot runoff was not observed for either consolidated sludge replication at Site 2, indicating an infiltration rate significantly higher ($P < 0 \cdot 05$) than for the other two treatments at that site. At Site 3, steady infiltration rates for the consolidated sludge treatment were higher than for the fresh and nil sludge treatments (Fig. 1*c*), though the difference was not significant ($P > 0 \cdot 05$).

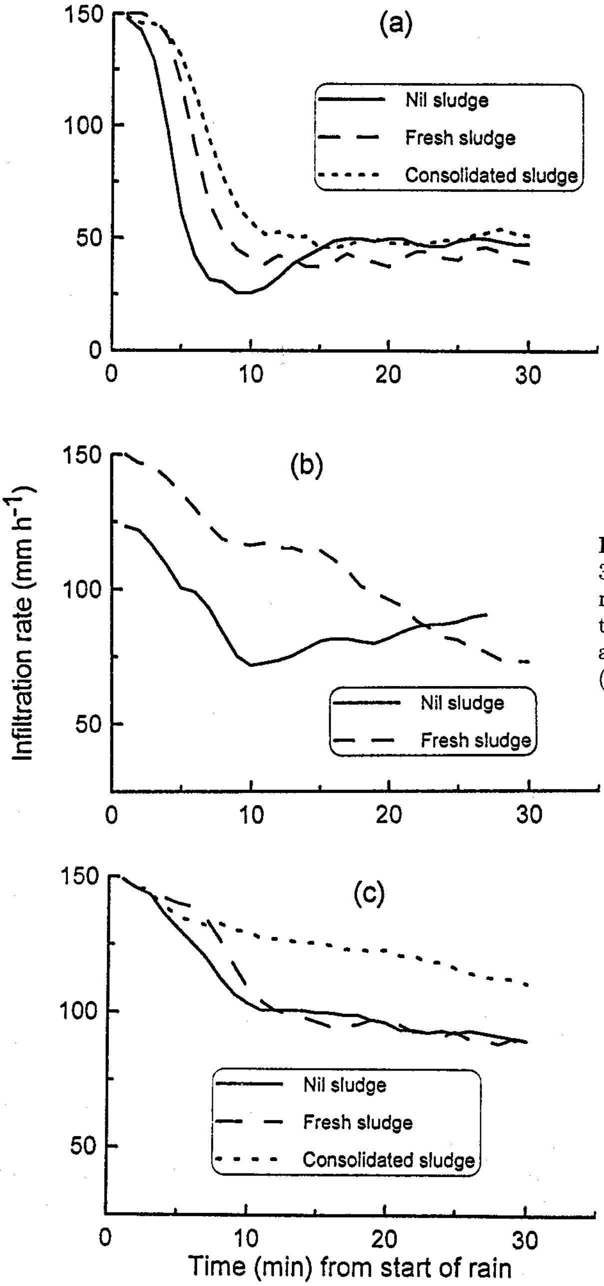

Fig. 1. Relationship between the 3 min moving average infiltration rate and time from start of rain for three rates of sludge application, and for (*a*) Site 1, (*b*) Site 2, and (*c*) Site 3.

Surface Conductivities (disc permeameter data)

Measured hydraulic conductivities for 10, 20 and 30 mm suction are shown in Table 5. The maximum diameters of pores contributing to infiltration at these suctions are approximately 3·0, 1·5 and 1·0 mm respectively. Analysis of variance on log-transformed data showed significantly ($P < 0 \cdot 05$) higher conductivities at 10 mm suction than at 20 or 30 mm suction across all sites. These effects were greatest at Sites 1 and 2. Conductivity at 30 mm suction was significantly ($P < 0 \cdot 05$) higher at Site 3 than at Sites 1 and 2, but there were no significant differences between sites at 20 and 10 mm suctions.

Table 5. Hydraulic conductivities (means of eight replicates) of surface soil

Suction (mm)	Hydraulic conductivities ($mm\ h^{-1}$) Site 1	Site 2	Site 3
30	15	6	166
20	53	10	124
10	245	210	171

B Horizon Conductivities

The B horizon permeability was high at Sites 1 and 2, and significantly ($P < 0 \cdot 01$) lower at Site 3 (Table 6).

Table 6. Saturated hydraulic conductivities ($mm\ h^{-1}$) of the upper B horizons

Site	B horizon conductivities Mean	Range
1	33	26–40
2	24	20–28
3	1	0–2

Discussion

Water Repellence

Water entry into soils at all sites was dominated by repellence, but was also affected by surface micro-relief. Bond and Harris (1964) described the influence of fungal microflora on water repellence in coarse-textured *Pinus radiata* soils of South Australia. Bridge and Ross (1983) reported strong water repellence in similarly textured coastal sands to the north-east of Beerburrum, and identified fungal hyphae mats as the cause. Samples collected from the present study revealed that fungal mats comprised mainly basidiomycete fungi. It was therefore concluded that water repellence in the present study was associated with both the basidiomycete fungal mat and its mycelia which extend into the A1 horizon.

Surface-water repellency at all sites caused simulated rain to enter the soil in preferential flowpaths as shown by the variable wetting patterns indicated by Table 4. Bond (1964) described similar surface wetting patterns for natural rainfall on water repellent sands in South Australia. Dekker and Ritsema (1994) and Ritsema and Dekker (1994) demonstrated that the non-homogeneous wetting of water repellent soils can result in bypass of large volumes of unsaturated soil, and accelerate passage of water and solutes to the ground water. These are sub/optimal characteristics for sludge application, where it is desirable that nutrients and metals will be either immobilized or transformed in the soil, or held in the soil solution in a form available for plant uptake.

Water repellence was significantly stronger at Site 1 than at the other sites. Because fire can increase water repellence in forests (Scott 1993), the stronger repellence at Site 1 may be attributable to the controlled burn in August 1992 (Table 3). The presence of either fresh or consolidated sludge appeared to moderate this initial, very strong water repellence (Fig. 1). A similar trend was evident at Site 2. In addition, consolidated sludge increased steady state infiltration at Sites 2 and 3. Clearly, sludge application can improve infiltration into some soil types in some conditions. Importantly, sludge application did not increase runoff in any of the study soils: sludge did not form impermeable crusts, cause surface sealing, or result in any biological interactions that reduced infiltration.

Differences between Sites

Steady infiltration rates of simulated rain in the nil sludge treatments increased from Site 1 to Site 3. This result was unexpected in these relatively coarse-textured surface soils. It is likely that water repellence accounts for the observed differences. Where water repellence was broken down by a wetting agent, disc permeameter data revealed no significant differences in hydraulic conductivity at 10 mm suction between sites (Table 5).

In the absence of water repellence, surface infiltration rates are high (Table 5), comparable to those of highly permeable agricultural soils (Coughlan *et al.* 1991). In particular, Sites 1 and 2 showed increases in conductivity from 20 to 10 mm suction, implying a dominant role for pores of 1·5 - 3·0 mm in diameter. Typically, these larger pore sizes are associated with faunal activity or decaying plant roots. By contrast, Site 3 showed a relatively high hydraulic conductivity at 30 mm suction, and little overall difference between 30 and 10 mm suction. Pores less than 1·0 mm diameter appear to be dominant at this site.

Potential for Runoff to Occur

At Site 1, a steady infiltration rate of about 50 mm h^{-1} was reached after 10 min in the sludge treatments (Fig. 1*a*). Rainfall in the Beerburrum *Pinus* complex regularly exceeds this intensity/duration. Contrary to expectations for coarse-textured soils, Hortonian overland flow can therefore be expected on the sites that are best suited to sludge application at Beerburrum. If either the sludge, or any sludge leachate, is mobile, then there is potential for off-site pollution.

The potential for Hortonian runoff generation at Site 1 could be expected to be greatest when the soil is dry, and water repellence is greatest. Sites used in this study had low antecedent water contents. Experience in other forests where water repellence has been observed suggests that steady state infiltration rates increase when the soil profile wets (Bridge and Ross 1983), providing there are no restrictions to percolation at depth. In the Beerburrum environment, water repellent soils are slow to wet fully. Even after 35 min, and some 87·5 mm of rainfall, dry patches of soil remained under the litter and surface fungal mats.

Periodic Profile Saturation

At all study sites, A2 horizons are bleached and B horizons are gleyed with prominent bright mottling (Table 2). In these soil types, the gleyed dominant B horizon matrix and the prominent mottling are indicative of periodic reducing and oxidizing conditions. Periodic profile saturation, resulting either from transient perched watertables or regional watertable intrusion, can be inferred.

Only at Site 3 are the B horizon permeabilities sufficiently low to support persistent perched watertable development (Table 6). On this basis, the guidelines of Foster (1992), which would exclude sludge application at Site 3, are sound. At Sites 1 and 2, the B horizons have relatively high conductivities, and would not support the development of persistent perched watertables. The periodic watertable presence at these sites must therefore be controlled by regional ground-water levels. Coaldrake (1961) described similar watertable intrusions in a similar area within the coastal lowlands of south-east Queensland. He described these systems as typically rising to within 30 cm of the surface during wet periods and receding below 4 m during dry periods. If the inferred periodic profile saturation does in fact result from intrusion of a regional ground watertable, evidence of soil profile saturation could be expected to be more significant lower in the landscape, where the watertable would be closer to the surface. The decrease in depths to gleyed B horizons with prominent mottling (Table 2) from Site 1 (upper slope) to Site 3 (lower slope) supports this proposition.

The inferred periodic intrusion of a regional watertable into the Beerburrum landscape poses two potential problems for sludge disposal. Firstly, runoff generation from saturated areas could be expected to occur in wet conditions, reinforcing the risk of off-site pollution if either the sludge, or any sludge leachate, is mobile. Secondly, if nutrients and/or heavy metals are readily leached from any applied sludge, and not absorbed or immobilized by the solum, then the potential for pollution of the regional ground water could be significant.

The Impact of Sludge Application in the Beerburrum Pinus Estate

With the equipment and methodology used in this study, we have been able to infer, and/or demonstrate (i) the potential for both Hortonian and saturated runoff from forested catchments, (ii) the existence of preferential flow paths for infiltration, (iii) the potential for accelerated transport of water and solutes to watertables, and (iv) the potential for periodic intrusion of a regional ground watertable. Clearly, the impact of sludge application in this environment will depend upon the mobility of sludge and sludge leachates, and upon the buffering capacity of the soil. Sludge mobility is addressed in the second paper of this series.

Conclusions

The soil descriptions and hydraulic measurements made were sufficient to characterize likely pathways of water movement in the proposed sludge application project area. This work, together with that reported in the second paper of the series, provide an efficient means for rapid preliminary evaluation of land based sludge disposal proposals.

A soloth soil type was shown to be unsuited to land-based sludge disposal. For a lateritic podzolic and yellow podzolic, water entry into soils was dominated by repellence, but also affected by surface micro-relief. The potential for Hortonian runoff from these soils in a dry condition was demonstrated. It was also inferred that periodic profile saturation occurred, and that regional watertable intrusion was responsible. Saturated runoff generation mechanisms would operate in this environment during wet conditions when the watertable neared the surface. If either solutes or solids from the applied sludge were mobile, then the risk of off-site pollution would be significant on both these soil types.

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References

Ankeny, M. D., Ahmed, M., Kaspar, T. C., and Horton, R. (1991). Simple field method for determining unsaturated hydraulic conductivity. *Soil Science Society of America Journal* **55**, 467–70.

Bond, R.D. (1964). The influence of microflora on the physical properties of soils. II. Field studies on water repellent sands. *Australian Journal of Soil Research.* **2**, 123–31.

Bond, R. D., and Harris, J. R. (1964). The influence of the microflora on the physical properties of soils. I. Effects associated with filamentous algae and fungi. *Australian Journal of Soil Research.* **2**, 111–22.

Bridge, B. J., and Ross, P. J. (1983). Water erosion in vegetated sand dunes at Cooloola, south-east Queensland. *Zeitschrift fur Geomorphologie N.F., Suppl.-Bd.* **45**, 227–44.

Bubenzer, G. D., and Meyer, L. D. (1965). Simulation of rainfall and soils for laboratory research. *Transactions of the American Society of Agricultural Engineers* **8**, 73, 75.

Chapman, G. (1948). Size of raindrops and their striking force at the soil surface in a red pine plantation. *Transactions of the American Geophysical Union* **29**, 664–70.

Coaldrake, J. E. (1961). The ecosystem of the coastal lowlands ('Wallum') of southern Queensland. CSIRO Australia. Bulletin No. 283.

Coughlan, K. J., McGarry, D., Loch, R. J., Bridge, B., and Smith, G. D. (1991). The measurement of soil structure—some practical initiatives. *Australian Journal of Soil Research* **29**, 869–89.

Dekker, L. W., and Ritsema, C. J. (1994). How water moves in a water repellent sandy soil. I. Potential and actual water repellency. *Water Resources Research.* **30**, 2507–17.

Department of Environment and Heritage. (1993). Pumicestone Passage, its catchment and Bribie Island. Draft Integrated Management Strategy—Main Report. Brisbane.

Foster, P. G. (1992). Biosolids management study: Final soil survey report on the availability of suitable sites. Queensland Department of Primary Industries. Report.

Institution of Engineers, Australia. (1987). 'Australian Rainfall and Runoff: A Guide to Flood Estimation. Vol. 1.' Revised Edn. (Institution of Engineers, Australia: Canberra.)

Loch, R. J., and Foley, J. L. (1994). Measurement of aggregate breakdown under rain: comparison with tests of water stability and relationships with field measurements of infiltration. *Australian Journal of Soil Research* **32**, 1125–39.

McDonald, R. C., Isbell, R. F., Speight, J. G., Walker, J., and Hopkins, M. S. (1990). 'Australian Soil and Land Survey Field Handbook.' 2nd Edn. (Inkata Press: Melbourne.)

Marshall, T. J., and Holmes, J. W. (1988). 'Soil Physics.' 2nd Edn. (Cambridge University Press: Cambridge.)

New South Wales Environment Protection Authority. (1994). Interim code of practice for use and disposal of biosolids products—Draft.

Northcote, K. H. (1979). 'A Factual Key for the Recognition of Australian Soils.' (Rellim: Adelaide.)

Perroux, K. M., and White, I. (1988). Designs for disc permeameters. *Soil Science Society of America Journal* **52**, 1205–15.

Reynolds, W. D., and Elrick, D. E. (1991). Determination of hydraulic conductivity using a tension infiltrometer. *Soil Science Society of America Journal* **55**, 633–9.

Ritsema, C. J., and Dekker, L. W. (1994). How water moves in a water repellent sandy soil. II. Dynamics of fingered flow. *Water Resources Research*. **30**, 2519–31.

Rosewell, C. J. (1986). Rainfall kinetic energy in eastern Australia. *Journal of Climate and Applied Meteorology* **25**, 1695–701.

Ross, A. D., Lawrie, R. A., Whatmuff, M. S., Keneally, J. P., and Awad, A. S. (1991). Guidelines for the use of sewage sludge on agricultural land. N.S.W. Agriculture and Fisheries.

Scott, D. F. (1993). The hydrological effects of fire in South African mountain catchments. *Journal of Hydrology* **150**, 409–32.

Stace, H. C. T., Hubble, G. D., Brewer, R., Northcote, K. H., Sleeman, J. R., Mulcahy, M. J., and Hallsworth, E. G. (1968). 'A Handbook of Australian Soils.' (Rellim: Adelaide.)

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