

On-site Systems - Soils, Salts and Solutes.

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ON - SITE SYSTEMS - SOILS, SALTS AND SOLUTIONS

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Abstract

On-site wastewater disposal systems aim to assimilate domestic wastewater into the environment around a dwelling. In Australia, septic tanks and absorption trenches are the most common on-site disposal system. Many parameters combine to influence the environmental performance of on-site disposal.

Most domestic on-site systems are truly 'disposal' systems where wastewaters are partially treated and then dumped into the soil. The soils are used as a simple filter or assimilation system. Soil has a limited ability to adsorb nutrients and therefore cannot be continuously loaded without leakage of nutrients in various solute and salt forms as it approaches saturation. Imbalances in the loading of solutes and salts can also result in failure of the system by biochemical oxygen demand (BOD) overload under anaerobic conditions, or soil structural collapse due to sodicity.

Design approaches to on-site disposal need to be more holistic and focussed on the 'system' health. The design of the on-site disposal systems should be based on, immobilisation capacity, buffering capacity (pH, CEC and phosphate sorption), permeability (hydraulic loading) and organic loading for clay soils. The significance of wastewater chemistry and the ability to reduce chemical loadings within the house should not be dismissed, rather considered part of the holistic approach to on-site wastewater management. The environmental ramifications of a gradual but continuous leakage from on-site disposal systems scattered throughout a catchment need to be investigated and the design criteria shifted towards a method that considers that the disposal area has a limited life.

Keywords

nitrate, phosphate sorption, salinity, salt, septic tank effluent, sodicity, sodium adsorption ratio, wastewater,

1 Introduction

On-site wastewater disposal systems aim to assimilate domestic wastewater into the environment around the dwelling. By its very nature on-site disposal is co-located with all sorts of human activities and in almost all topographic positions, including those lots abutting streams and channels. Therefore, the systems operate across a massive array of climates and soils. Superimposed on this is a third degree of variability created by differences in waste characteristics in terms of quantities and composition of the wastewater or effluent (treated wastewater). The design and operation of any on-site wastewater disposal system requires some consideration of site-specific attributes, usually referred to as land capability. No one system should be uniformly applied to all situations, as not only does the physical receiving environment vary, so too do the activities within each household to generate particular wastewater chemistry.

Septic tanks and absorption trenches are the most common on-site disposal system and Patterson (1993) estimated that more than two million septic systems were in use across Australia. Under most environmental and health legislation, the use of these systems requires that septic tank effluent (STE) should be discharged to land and that wastewater must be treated and retained within allotments (eg Clause 40 State Environment Protection Policy (Waters of Victoria)).

With only primary treatment of all domestic wastewater carried out in a septic tank, the effluent flowing from the system is poorly treated with respect to solids, bacteria, nutrients, and particularly the range of chemicals used within the house. Some wastes are soluble in the wastewater whilst entrained particles include minerals (e.g. clay) and other organic matter (faeces, paper, food wastes). The soluble compounds can be described as solutes and salts and their behaviour and treatment must be considered as part of the overall wastewater management strategy. Patterson (1999) discussed many of the sources of the various chemicals in domestic wastewater and the need to address this within the household rather than in the treatment device.

Solutes and salts are not different chemical compounds *per se*. While they are not mutually exclusive groupings, it is important to define some differences. A solute can be loosely described as any dissolved substance, whereas a 'salt' is a compound of basic and acid radicals where the whole or part of its hydrogen is replaced by a metal or metal-like radicals. An example of a solute is a soluble protein or a sugar, such as glucose or a simple compound like ammonium phosphate. Salts include common table salt (sodium chloride NaCl), which dissociates in water as sodium (Na^+) and chloride (Cl^-) ions, and gaseous ammonia (NH_3), which dissolves readily in water to form ammonium ions (NH_4^+). A significant difference between the behaviour of solutes and salts is their effect upon water chemistry. Sugar, for example is soluble in water but does so without altering the electrical conductivity (EC) of the liquid. Common salt (NaCl), on the other hand, causes a large increase in EC for a small addition of common salt. Salts are, in essence, a subset of solute compounds.

While the above description appears to be clear, the differences can become blurred when we consider the perspectives of a plant physiologist or soil conservationist. In the former case, any ion in the soil solution is considered a nutrient or salt if it is directly taken up by plants and is often simply deemed a 'solute'. In the latter case, salts are those ions which directly affect soil structure. In particular, 'salt' is equated to sodium chloride or in a slightly broader context also sodium bicarbonate or sodium sulphate (gypsum), although this distinction is extremely simplistic and often misleading with respect to both salinity and sodicity. Salinity refers to all the ions influencing electrical conductivity while sodicity refers specifically to the concentration or ratio of sodium ions.

Excessive accumulation of nutrients such as phosphorus (P) in a soil may result in a bleeding of both ionic and organic P to the environment. Nash and Murdoch (1997) found that in intensive dairy pasture systems on sandy loam soils a significant amount of P leaving the soil in leachate was as poorly charged organic P compounds (solutes) rather than the orthophosphate ion or P 'salt'. Mehadi and Taylor (1988) stated that when soluble P compounds are added to soils, much of the P is rendered insoluble within hours through processes of adsorption and precipitation, the former being the most important.

Nitrogen, whether sourced from wastewater or produced naturally from symbiotic relationships of bacteria and plants or soil microorganisms, behaves differently to either phosphorus or salt. It may be a solute in the form of non-ionic organic acids, or in an ionic form as ammonium (NH_4^+), nitrite (NO_2^-) or nitrate (NO_3^-) ions. Thus, mechanisms to prevent the loss to the environment of potential pollutants, or essential biotic nutrients, requires a mixed range of strategies.

The accumulation of sodium in the soil can lead to significant soil structural changes that have the potential to impair the performance of the on-site disposal (irrigation) system. Patterson (1994, 1996) showed that significant loss of soil hydraulic conductivity was associated with small increases in sodium in the percolating solution. At EC and sodium adsorption ratios (SAR) consistent with septic tank effluent, losses of more than 75% were measured in the first few hours of treatment. Over the life of an effluent application area, such losses have significant implications for sustainable disposal.

The mechanisms which must be considered of all wastewater chemicals include cation exchange capacity (CEC), adsorption, fixation and precipitation, solution, dissolution and leaching, volatilisation, mineralisation or immobilisation.

This paper questions some general principles that have underpinned current design and operation of on-site disposal systems. It addresses the need for design to consider 'safe' salt and solute loading rates for on-site disposal (irrigation) systems, based on a consideration of the ability of the soil to sorb (hold, bind) nutrients while remaining structurally stable and biologically active.

2 Domestic Wastewater Characteristics

The quantity of wastewater generated from a household varies significantly with the source of water available and conservation attitudes of the occupants (Carew *et al.*, 1999; Patterson, 1999) even though we typically use a 'ball park' figure of 150-300 litres per person per day (Lpd) (DLG, 1998, Standards Australia, 1994) of generation rates for ST and trench design. However, the public perception is that domestic wastewaters are of all the same quality, yet, nothing can be further from the truth. Table 1 shows the variability that can be found in the quality of household wastewaters.

Table 1. Variability in wastewaters (Data from Patterson, 1997; except noted by * which is cited from van de Graaff *et al.*, 1980).

Parameter	Minimum	Maximum	Mean \pm S.E.	Mass Applied (g) per kL (based on mean)
pH #	6.4	8.7	7.1 \pm 0.1	Not Applicable
EC (dS m ⁻¹) #	0.5	5.0	1.4 \pm 0.1	840 g salts
Hardness	29	217	131 \pm 17	131 g CaCO ₃ equivalent
Nitrogen (TN)	44*	54*	-	49
Phosphorus (TP)	3.7	30.0	14.4 \pm 0.8	14.4
Calcium	7	166	33 \pm 37	33
Magnesium	2	19	12 \pm 2	12
Potassium	14	180	35 \pm 4	35
Sodium	26	318	84 \pm 6	84
SAR (no units)	0.7	9.6	3.6 \pm 0.3	Not Applicable
Chlorine	48	506	182 \pm 16	182

{Note. All data derived from systems with rainwater influent and represent the addition of nutrient to the water from a single household. Values are in mg L⁻¹ unless indicated by #)}

The wide range in the chemical composition of household wastewater underscores the need to consider the potential error associated with the use of mean values for design purposes. The data also show that while wastewater contains the nutrients nitrogen and phosphorus it also significant quantities of the meta-metals Ca, Mg, K and Na, and the anion Cl⁻. The average household will generate about 0.75 kL/day or 0.274ML of wastewater each year. If this is loaded to a an area of about 30 m x 20 m, as per the designed area, (Vic EPA, 1996, p 24 - design calculation), then the equivalent nutrient loads per hectare from the household are significant, as tabulated in Table 2.

3 On-site Disposal

Soils are used in a variety of ways for disposal of many different wastes from domestic wastewater to intensive animal industry effluent and manure. Most domestic on-site systems are truly 'disposal' systems

where wastewaters are partially treated and then dumped into the soil. Soils are used as a simple filter or assimilation system, where sorption capacity is used to attract and hold nutrients, or as a plant support system where the soil is required to attract and hold nutrient and release it to the plant on demand and thus replenish its storage capacity, while the 'waste' water percolates away from the site. While beneficial use of the water and nutrients may be an objective of on-site wastewater application, the chemical load will almost always exceed the demand by plants and organisms for uptake, while the chemical ratios of those nutrients will fail to meet plant requirements.

Table 2. Average mass of nutrient applied to disposal area from a 3-bedroom household

Parameter	Mass Applied (based on mean) g kL ⁻¹	Mass applied to land area per year kg ha ⁻¹
Nitrogen (TN)	49	224
Phosphorus (TP)	14.4	66
Calcium	33	151
Magnesium	12	55
Potassium	35	160
Sodium	84	383
Chlorine	182	830

3.1 Evapotranspiration

The use of evapotranspiration systems is underpinned by a dependency of a plant to take up the water applied to the designated land area. The water is lost to the atmosphere through plant respiration and the to landscape by drainage. Table 1 shows the amount of nutrient applied in 1kL of wastewater. To produce 1 kg of dry matter plants must take up several hundred to several thousand kilograms (1kg = 1L) of water. Most of this water passes through the plant (transpiration) but the transfer of water is responsible for the movement of elements from the soil solution to the plant.

The ability of a plant to grow in soil is dependent upon the soil's capacity to provide both water and nutrients. Any limit in the supply of either component compromises the ability of the plant to transpire and grow. Limiting transpiration increases the dependency of the disposal system on the loss of water by direct evaporation or percolation through the soil, and the assimilation of nutrients by the soil.

3.2 Plant nutrient requirements

The designs of the on-site disposal systems do not specifically consider the optimum amount of nutrient required by the plant to metabolise and indeed respire at a maximum rate. Plant nutrient concentration can be generally described (C4 plants - grasses and crops such as forage sorghum) and these characteristics are defined in Table 3. The data on annual nutrient additions to the soil derived in Table 2 have also been added to this table. These data show that the relative load of nutrient to the salt versus its uptake by plants is mismatched.

Typically a mixed pasture has the ratio of N:P:K:S:Na of 17:2:14:1:1. From this ratio, it can be seen that N:P is 17:2, yet the septic tank effluent in Table 2 above has a ratio of only 3.5:1, far less nitrogen than required to grow to the capacity of the phosphorus. Similarly, the ratio of K:Na (antagonistic elements) in mixed pasture is 14:1, but in STE the ratio is 1:2. Significant plant toxicity must be expected, as well as significant loss of productivity as reduced availability of essential macro-nutrients is encountered.

Table 3. Typical composition of plant tissue (whole plant)

Element	Concentration (% DM)	kg of Nutrient uptake per 10T of Dry Matter (DM)/ha	Amount of Nutrient Applied (kg/yr) - Table 2
N	1.5	150	224
P	0.3	30	66
K	1.8	180	160
Ca	1.2	120	151
Mg	0.7	70	55
S	0.4	40	-
Na	0.01	0	383
Cl	0.05	5	830

To maintain a balance between inputs and outputs of nutrients several processes must occur. These are that (a) plant dry matter produced in the area must be reduced to limit cycling of nutrient back to the soil; (b) nutrients need to be added to the soil to assist in maintaining an adequate nutrient-ratio balance, and (c) some salts can be flushed from the system, by application of excess effluent or by natural precipitation. In the latter case, it has been historically acceptable to allow flushing of sodium from the soil. This requires determination of a leaching fraction which is the amount of percolation required to maintain the cations in balance. Thus, monitoring of the exchangeable sodium percentage (ESP) is required.

3.3 Filtration /Treatment Systems

These types of system rely on the soil to filter out solid matter and dissolved compounds (solutes and salts) from the waste stream. The ability of a soil as a filter is influenced by its capacity to immobilise metals and organic compounds (adsorption) and allow for the breakdown of organic matter by microbial decomposition. These requirements create a real conundrum because clay soils have a high adsorption capacity but low permeability and sandy soils have a low adsorption and high permeability. A compromise must be struck between permeability and immobilisation capacity in the design process. However, the situation is further complicated by the fact that microbial activity is directly influenced by soil chemistry, temperature, abundance of food and most importantly soil moisture content and soil oxygen supply.

Saturated conditions limit oxygen supply through the soil and this in turn restricts aerobic decomposition of the organic material entering the soil in the waste stream. Therefore, the degree of saturation the soil exhibits will limit activity to cope with organic loading. It is fair to conclude that because clay soils have a low permeability they may remain saturated for longer at a similar hydraulic loading. So while they may be able to immobilise components in the wastewater, better than those of sand, their ability to allow rapid decomposition of the organic matter, may be less than a well-drained soil. Sandy soils or loams are comparatively poorly buffered (ie they have less charged sites). Therefore, imbalanced nutrient additions to the soils can quickly alter their physico-chemical state and subsequently limit plant nutrient uptake.

Given the above, the design of the on-site disposal systems should logically be based on;

- ©Immobilisation capacity / Buffering capacity (pH, CEC and phosphate sorption)
- ©Permeability (hydraulic loading)
- ©Organic loading for clay soils.

3.4 Current Design Approaches

Current design of on-site disposal systems is typically focussed on one of only a few parameters, namely; hydraulic load (the amount and rate of water applied), BOD (which can be used to define the amount of readily decomposable organic water applied), and in a limited number of cases nitrogen and phosphorus loads. This is evident in many documents including the NSW Load Based Licensing system (NSW EPA, 1999) and the VIC EPA guidelines for the design and operation of domestic wastewater systems (Vic EPA, 1996). In reality most design criteria do not make such a clear separation between the effects of each parameter on system performance nor require designs using all three factors.

In recent work on effluent disposal in Queensland, Hu (1999) indicates that as phosphorus is the most limiting nutrient (excess nutrients to plant uptake ability) with respect to effluent disposal it is important to measure the phosphorus sorption capacity of the soils in the disposal area. These soils provide the majority of phosphorus removal.

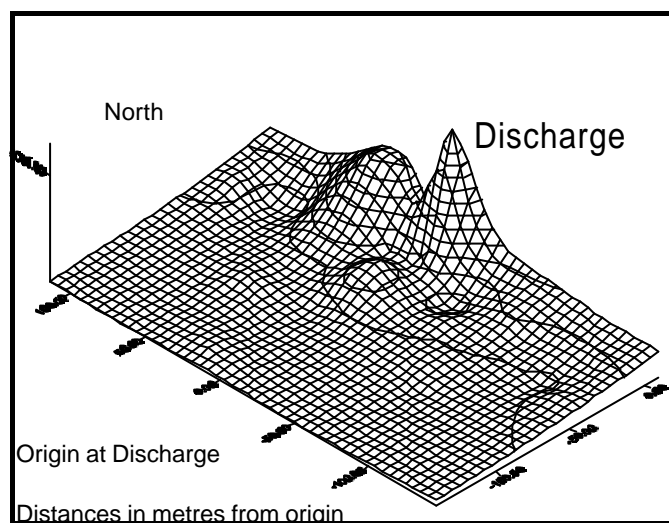


Figure 1. Movement of P is less than 30 m from the discharge

Patterson and Chapman (1998) showed that where effluent had been irrigated for in excess of thirty years onto the same land from a single discharge, movement of phosphorus was restricted by the sorptive capacity of the soil.

Figure 1 indicates the poor movement of phosphorus away from the application area.

However, from the same study, the movement of sodium was pronounced. Sodium salts had moved laterally and were accumulating at downslope sites, as shown in Figure 2, leaching with either excess irrigation water or natural rainfall.

In a similar manner, the phosphates in on-site effluent disposal areas are immobilised by the sorption capacity of the natural soil, or through enhanced soil qualities. However, sodium movement is not restricted by soil adsorption and the detrimental effects of increasing ESP in the soil surrounding an effluent application area may be pronounced.

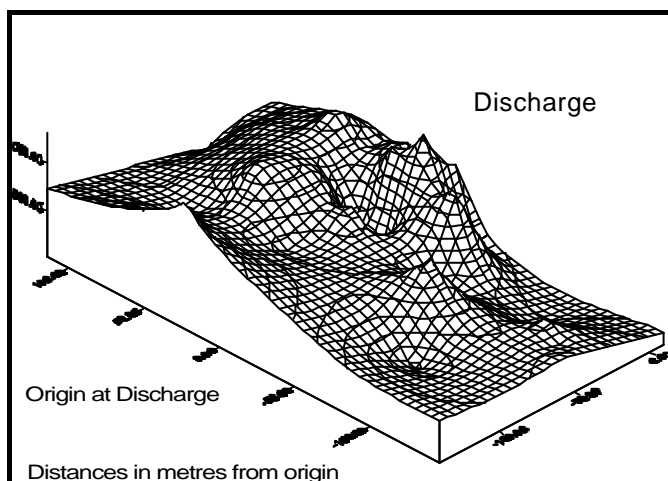


Figure 2. Movement of Na away from the discharge is pronounced compared with P

4 Solutes and Salts

The previous sections showed that many parameters combine to influence the environmental performance of on-site disposal. The critical factors are;

- maintenance of soil water and nutrient storage capacity;
- maximisation of plant growth and transpiration rates;
- removal by plant material; and
- management of percolation so that water accession to groundwater does not raise levels of water tables, and loss of solutes and salts in leachate is limited.

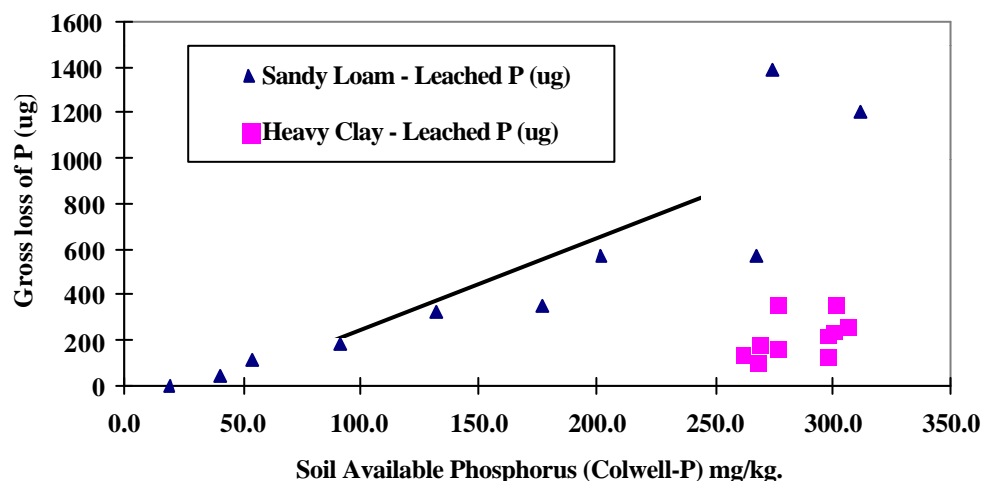
Continued safe on-site disposal of wastewaters is ultimately dependent upon maintaining the health of the soil-plant system receiving the wastewater. The critical determinant is not a single parameter but rather the balance between hydraulic loading, waste loading versus the net removal or loss of nutrient from the system and continuance of a stable soil chemistry. Where excess nutrient occurs then environmental hazard increases.

Many regulations regarding maximum permitted concentrations of nutrients in a soil are based on the measurement of total concentration. However, it is the bioavailable forms of the contaminant that impinges on the environment because they either move off-site in leachate or are translocated to plant tissue. In the latter case this may not represent a problem if tissue concentrations are low. However, if heavy metal salts or solutes such as DDT accumulate in the tissue then consumption of the plant by stock or humans can be a direct threat to their health.

Heavy metals such as copper (Cu) and zinc (Zn) are found in domestic wastewaters. Zinc is derived from products such as shampoo and free copper on the inside of pipework becomes dissolved in inflow water as it is reticulated throughout the household. Over time these metals build up in disposal sites. Heavy metals can move in leachate. The bioavailable forms of the heavy metals Zn, Cu and Cadmium (Cd) are in their salt form. Recent research has shown that the abundance of these free, bioavailable forms is not always directly related to their total concentration in the soil. Quantities measured in leachate have been estimated as a function of total metal concentration, soil organic carbon (OC), pH and CEC (Chaudri *et al.*, 1998). Today bioindicators can be used to monitor these metal salts (McGrath, 1998; Chaudri *et al.*, 1998). The abundance of the metal will follow a curve relationship between total concentration and biological toxicity in any given soil (McGrath, 1998) and this 'break-out curve' can be described by the above variables. Heavier soils (higher clay content) near neutral or neutral pH soils and/or soils containing large amounts of organic matter may reduce the bioavailability of the heavy metals by binding the metals (Mcgrath, *et al.*, 1995). Changes to the soils physico-chemical characteristics may cause release of metals in quantities harmful to the ecosystem. The same factors impinge on the binding and release of all salts in the soil. Clearly the potential hazard of nutrient or salt release ($\text{NH}_4^+ \rightleftharpoons \text{NO}_3^-$ or Zn^{2+}) increases with their accumulation in the soil.

Leakage of solutes from a soil receiving wastewaters is not limited to flushing of 'salts'. All manner of solutes move through soils in leachate. Figure 3 shows that the gross amount of phosphorus lost in leachate from a acid sandy loam can be related to the available soil P (Lott *et al.*, 1997; Klepper *et al.*, 1998).

Figure 3. Gross Loss of P in Leachate from a Sandy Loam and Heavy Clay - Pot Experiment



These soils receive different amounts of beef cattle feedlot manure and wastewater. The increase in soil available P was directly related to the increasing rate of application. The measurement of P in the leachate is for total phosphorus (TP). Speciation of the P found that a considerable amount of the P was in organic form. These complex molecules, or solutes, while dissolved in water are weakly charged and can move in leachate especially where the soil attractive forces (which can be estimated by its CEC) are limited. Figure 3 also shows that the heavy clay soil, which had received the same rates of wastes, did not release P in the same quantities for a given soil available P concentration. The data show that this heavy soil was able to limit loss of both P salts and solutes.

While concrete septic tanks have a 'design life' (Standards Australia and Standards New Zealand, 1998) no such consideration is given to the disposal area which has a limited capacity to assimilate solutes and salts. For instance, the life of a disposal area may be dictated by the time taken to saturate the soil's P sorptive capacity, or by the increase in ESP to levels detrimental to that particular soil texture. Because soils have a finite capacity to immobilise organic and metallic compounds, it can be argued that such systems have a set lifespan, after which another site should be used. The constant addition of solutes and salts to a soil also can have a profound influence on the physico-chemical characteristics of a soil and as a result its ability to assimilate applied wastewater. On many small lots, the ability to move the application area is extremely limited, however, excavation and replacement of soil material is not beyond consideration.

5 Case of - Gradually Varied Flow.

The flow dynamics of a large river system receiving a base-flow along its flow path are complex. The change in flow can only be determined by integrating through space and time the gradual inflows from creeks of groundwater leakage to the main stream. While any individual inflow may be small, the cumulative addition of all inflows through time and space can result in a large continuous outflow at the outfall of the catchment. So too are the leakages of salts and nutrients from a catchment.

On-site disposal systems are not designed to limit nutrient or 'salt' release.

Under the current design system it is likely that leakage of nutrient occurs from "On-site" systems and that the long term health (sustainability) of the systems can be called to question. Clearly where these leaky systems are spaced across the landscape they can constitute a significant hazard to the environment.

The integrated impact of poor design across many systems will have a long term impact on the health of our environment. Already there are signs that this is occurring. In rural residential areas in the Brisbane Valley and in the Sydney basin the quality of surface water resources has diminished. Unfortunately this has not yet precipitated changes to the design criteria such that the systems are optimised for the waste characteristics and the site's climate and soils. One can only hope that the issues we have raised in this paper are better addressed.

6 Conclusions

Soil has a limited ability to sorb nutrients and therefore cannot be continuously loaded without leakage of nutrients in various solute and salt forms as it approaches saturation.

Imbalances in the loading of solutes and salts can result in failure of the system by BOD overload under anaerobic conditions, or soil structural collapse due to induced sodicity.

Design approaches to on-site disposal need to be more holistic and focussed on the 'system' health rather than single parameter empirical design methods. The significance of wastewater chemistry and the ability to reduce chemical loadings within the house should not be dismissed, rather considered part of the holistic approach to on-site wastewater management.

The environmental ramifications of a gradual but continuous leakage from on-site disposal systems scattered throughout a catchment need to be investigated and the design criteria shifted towards a method that considers that the disposal area has a limited life.

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