DEVELOPMENTS IN DETERMINING CRITICAL LOT DENSITY FOR THE PROTECTION OF WATER QUALITY

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Abstract

This paper is divided into two parts. The first part examines methods for determining lot density in unsewered areas. The second part examines the issue of distribution of unsewered development in sensitive catchments.

One factor in determining appropriate minimum lot size for unsewered areas is the potential for pollutants associated with sewage effluent to escape from the lot and enter the stormwater system, or groundwater, causing pollution. Methods for determining minimum lot size (critical lot density) have to date involved either estimating the minimum area required for site soils to remove or retain pollutants, or estimating the mass of pollutant surcharging from failing disposal systems; the critical lot density is then determined by ensuring the mass of pollutant escaping from the development site does not exceed a pre-determined limit based on environmental values for the receiving water. The assimilative capability of a site is related to processes which occur in the ground (permeability, plant uptake, P sorption, NH_3 volatilisation etc). The impact of surcharging is related to system failure rates and processes associated with overland flow. The paper examines important factors relating to each of these two pollutant export routes and provides argument to show that the contribution of pollutants moving through the ground may be negligible when the area between the disposal field and a sensitive watercourse exceeds the "minimum assimilative buffer area" for the site. The "minimum assimilative buffer area" is a function of a number of factors including: soil characteristics; plant uptake capacity; climate; slope; and the pollutant loading. The limiting factor is often the area required for the uptake of nitrogen by plants.

The second part of the paper looks at the export of pollutants from unsewered areas in terms of the total catchment loading, sub-catchment loading and local effects, with each considered equally important. A method is put forward which allows development densities to be set for the overall catchment, for individual sub-catchments and for local areas within sub-catchments. The distribution of densities achieved ensures that the total pollutant loading does not significantly change the pre-development loading on the river system while allowing for local enclaves of development at densities which do not threaten the beneficial uses of any local reach of the river or stream. The approach allows planners to set overall catchment density objectives for sensitive waterways and to distribute the development within sub-catchments and localities such that water quality in local streams or individual sub-catchments is not degraded. The approach is particularly valuable for determining the critical density for clustered or concentrated developments in sensitive catchments, and may be applied to other forms of development as well as unsewered development.

PART A: THE IMPORTANCE OF CONSIDERING BOTH SUB-SURFACE AND OVERLAND ROUTES FOR POLLUTANTS IN THE DETERMINATION OF CRITICAL LOT DENSITIES

1 Introduction

This paper relates to the determination of appropriate lot densities for unsewered development. There is considerable evidence to suggest that the potential for the export of pollutants (mainly pathogens and nutrients) will increase with an increase in the density of development. Density, along with control over the performance of on-site sewage systems, is an important factor affecting the impact of unsewered residential development on water quality. Density may be controlled by Councils through the planning process and is therefore a useful planning tool to control the impact of unsewered development.

In NSW the Department of Health has for some years applied a minimum lot size of 1 hectare, below which the proponent is required to justify how the development will not cause water pollution. As 1 hectare is unlikely to reflect the range of climatic, soil slope and other factors found across NSW, application of this standard may result in larger lot sizes than are needed to avoid water pollution, with consequently larger than necessary environmental footprints, and greater costs in terms of provision of roads and services. In an effort to improve on the 1 hectare criteria this author has previously presented papers which offer a method for determining the "critical lot density" on a catchment and site basis. (Jelliffe 1998). The method outlined in that paper reflects the site soils, slopes and rainfall characteristics, as well as the likely system failure rates. However, for the reasons presented in this paper, the method should only be applied to developments where the proposed density allows for adequate assimilative buffer area within each lot. Where there is inadequate assimilative capacity the export of pollutants through the ground must also be taken into account. The following discussion more clearly defines the applicability of that method and also attempts to clarify the issues which affect determination of critical lot density.

2 Two Routes for Pollution to Enter Water Courses

The major pollutants of concern from on-site sewage disposal systems are pathogens and nutrients (Nitrogen and Phosphorus). There are two routes by which these pollutants may enter a water course from a disposal field:

- As fugitive pollution which percolates through the soil in groundwater (P_{soil})
- By overland flow resulting from surcharging of the disposal field, or illegal direct disposal of effluent or greywater into the overland drainage system. ($P_{surface}$)

Note: P_{soil}, $P_{surface}$ and P_{Total} are the net fugitive pollutant loads (ie total pollutant load minus losses through soil and other processes *en route*). The total pollutant (P_{Total}) loading on a nearby watercourse is therefore:

$$P_{total} = P_{soil} + P_{surface} \qquad \text{Equation 1}$$

Both of these routes may be important. The physical movement of pollutants through the ground will be determined by soil characteristics, existing physical groundwater behaviour, by biological physical and chemical processes within the soil which may attenuate the concentration of the pollutants in the percolating effluent, and of course by distance.

Surveys by Jelliffe (1994) and others (Beavers, 1993) have reported disposal system failure rates of the order of 35% or more in older established developments. System failure resulting in the surcharge of effluent may be a major cause of water pollution and should not be ignored. The illegal direct disposal of effluent into the surface drainage system may also make a significant contribution to water pollution (Jelliffe, 1994).

An analysis of the potential contribution of both routes is essential in determining the critical lot density for planning purposes or for determining and prioritising new management strategies for existing development.

3 Determining the Importance of Soil Processes

The soil is an effective treatment medium for most pollutants in sewage effluent. Contaminants which are not potentially removed by soil processes are limited to conservative ions such as chloride, and some reduced compounds such as hydrogen sulphide. Most other compounds may be removed by processes including: evaporation (water), volatilisation (ammonia), mineralisation (Nitrogen), de-nitrification (NO_3 to N gas), plant uptake (water, ammonia, nitrates and phosphates), adsorption onto soil particles (Phosphate), natural decay (pathogens), predation (bacteria), precipitation (phosphates) and filtration and entrapment (pathogens). The effectiveness of these processes will depend mainly on the soil characteristics, vegetation type and density, and climate of the area immediately down gradient of the disposal field. The underlying geology, hydrogeology, slope and rainfall will affect the rate of movement of effluent through the soil.

Provided there is sufficient buffer area between the disposal field and any bore or surface water down gradient of the disposal field for these processes to effectively remove the pollutant loading, effluent which eventually percolates into the receiving water will no longer be contaminated. It is therefore essential that the buffer area, or assimilative zone between the disposal field and a water course is of sufficient area to be able to assimilate the pollutant loading on a sustainable basis.

If there is sufficient buffer area to assimilate the pollutant loading on a sustainable basis then P_{soil} becomes effectively zero. In this situation $P_{total} = P_{surface}$. The term "sustainable" perhaps needs to be defined for this situation. I would suggest that a time frame of at least 100 years would be reasonable.

There are a number of methods for estimating the required minimum assimilative area for a disposal field. This paper will not delve in detail into these other than to provide an example for the major pollutants, pathogens, nitrogen and phosphorus.

4 Estimating Minimum Assimilative Buffer Areas

Experience has shown that with on-site effluent disposal the critical or limiting pollutant for determining buffer areas is often nitrogen. Nitrogen assimilation is therefore usually used to determine the required minimum assimilative buffer area. However, when determining the minimum assimilative buffer area, consideration needs to be given to both the total area and the minimum length (ie distance down gradient) of the area. For permeable soils the length may be limited by the distance required for the attenuation of pathogens in the groundwater, or where this distance is relatively small, it may be set by the minimum safe set back distance required to adequately attenuate pollutants in overland flow in the event of a system surcharge. The minimum setback distances of 100 m and 40 m set out in the NSW Government Silver Guideline (1998) may in many sites be unrealistically large. Minimum distances of 45 m and 25 m (from permanent and intermittent watercourses respectively) are generally applied in QLD provided it can be shown that the minimum distance required for attenuation of pathogens is no greater than these minima. The setback distance necessary to ensure adequate reduction of nutrient and pathogen content of effluent which may surcharge from a disposal field, may be estimated using methods developed for the treatment of waste waters using "overland flow" treatment. These methods are set out in US Environment Protection Authority Publications (1981 and 1984) and in Reed, Crites and Middlebrooks (1995).

Methods used for determining minimum safe set back distances for underground flows, and assimilative buffer size are:

Pathogens: The Beavers Gardner Virus attenuation method (Beavers and Gardner 1992), provides an extremely conservative (ie safe) method for setting safe set back distances based on the potential movement and survival of viruses in groundwater. The method is widely used as a screening tool for determining safe setback distances for on-site systems. Bacteria and viruses are generally only a limiting factor in soils with high permeability and gradient (ie steeper sandy soils).

Phosphorus: The main processes of phosphorus removal from soil water are adsorption, slow rate precipitation of insoluble Fe and Al compounds, and plant uptake.

Phosphorus sorption capacity of the soil may be obtained from laboratory testing. The effective life of the disposal field and assimilative buffer before P saturation occurs may be determined using the phosphorus isotherm method by Ryden and Pratt (1980).

Phosphorus removal also occurs by slow rate precipitation reactions between phosphate, iron and aluminium. A method for determining the effectiveness of this process is set out in Reed, Crites and Middlebrooks (1995). Distances required to achieve a reduction from 10 mg/L to < 0.05 mg/L in percolate are generally less than the distance for virus attenuation using the Beavers Gardner method. The phosphorus slow rate precipitation model was devised for the US Environmental Protection Authority (1981) and has been tested and found to be conservative in the field (US EP 1984). Slow rate precipitation reactions may extend the life of the disposal field by between 2 and 5 times that determined using the Ryden Pratt phosphorus sorption method.

Plant uptake is also a significant component, particularly where the effluent percolates through the root zone and plants are harvested.

Phosphorus is generally not the limiting pollutant when determining minimum assimilative buffer areas unless the site is a high permeability sand with negligible phosphorus sorption capacity.

Nitrogen: Nitrogen removal occurs through processes of volatilisation (ammonia), nitrification, denitrification, soil micro storage (this eventually reaches an equilibrium), and plant uptake.

Processes of volatilisation are reported to be significant in on-site disposal fields, particularly where disposal is to shallow beds with well aerated soils. The higher soil organic content which will develop within the immediate disposal area will also promote denitrification. A significant proportion of nitrogen will therefore be removed by these processes before effluent moves from the disposal field. Reed, Crites and Middlebrooks (1995) give losses from these processes in the range of 50% to 80% for higher strength wastes such as septic effluent. Geary and Gardner (1996) suggest losses closer to 20% for secondary treated effluent with losses predominantly from de-nitrification. Brouwer *et al* (1979) reported reductions in TKN of 98.6% in soil water within 2 metres of a septic trench in yellow duplex clay soils and around 98% reduction in total nitrogen in soil water 2 metres downslope of a trench in friable red earth. The measurements were taken immediately after installation of the trench in yellow duplex soil. While the age of the trench in the friable red soil was not stated, it was reported to be oversized. The ability of systems to sustain this level of performance is questioned. Gerritse *et al* (1995) also measured losses of nitrogen from septic tank systems. The results from both these papers suggest the Nitrogen reductions put forward by Geary and Gardner are conservative. However, in line with the spirit of the precautionary principle the more conservative values have been adopted in this paper.

Grasses and shrubs growing down gradient of the disposal field will also tap into the effluent. Effluent percolating beyond the disposal field will need to move laterally within the rhizosphere (root zone) in order for plants to remove nitrogen. Plant nitrogen uptake down gradient of the disposal area may be significant and has been the subject of recent work in relation to the reuse of effluent on timber plantations and many years research by agricultural scientists. (Couchman *et al*, 1999, Moss *et al* 1998). Nitrogenous compounds released during decomposition of faecal waste are generally soluble. Provided the effluent percolates through the rhizosphere (the soil horizons which contain plant roots) plants will assimilate N from the soil solution and microbial processes will denitrify the nitrogenous compounds in the soil water. There is active utilisation of nitrogenous compounds in the rhizosphere and their biological half-life is relatively short.

The rate of nitrogen removed from the soil by a plant depends upon the amount of water that the plant abstracts from the soil and the concentrations in that water. The literature reports a range of nitrogen uptake rates by native plants. The lowest reported sustainable plant uptake rate for coastal eucalypt forest viewed by this consultant is an N uptake of 80 to 90 kg/ha/year (Moss *et al* 1998 and Couchman *et al* 1998). Assuming a typical nitrogen concentration in septic tank effluent of 55 mg/L and aerobic sewage treatment plant (ASTP) effluent of 37.5 mg/L, and a daily effluent production of 900 L per household, the annual nitrogen loading will be approximately 55mg/L x 900 L/day x 365 days x $1/10^6$ = 18.1 kg/year for a septic system and 12.3 kg/yr for an ASTP system. Assuming losses from volatilisation and nitrification/denitrification as 20% for ASTP systems and 40% for septic effluent (mainly volatilisation), and plant uptake of 80 kg/ha/yr the minimum area required to take up nitrogen by plant uptake only is:

For Septic Effluent (18.1 kg/yr x (1- 0.4))/(80 kg/ha/yr) = 0.136 ha
For ASTP Effluent (12.3 kg/yr x (1- 0.2))/(80 kg/ha/yr) = 0.123 ha

This example is for a buffer planted with coastal eucalypts and may not be applicable for other situations. For this example, provided the buffer area between the disposal field and a watercourse is greater than approximately 0.123 ha for ASTP effluent, and 0.136 ha for septic effluent, then the site should be able to sustainably assimilate nitrogen from on-site systems. If the area available is less than these critical areas then it can be expected that nitrogen may be exported from the site. Figure 1 shows the predicted relationship between assimilative buffer area and the calculated export of nitrogen from a site for aerobic sewage treatment plant effluent and septic tank effluent.

It can therefore be concluded that for coastal sites with predominantly eucalypt planted buffer areas, provided each site has an assimilative buffer area of at least 0.14 ha between the disposal field and any water course, and the length of the assimilative buffer satisfies set back distances determined for pathogens, then the export of pollutants to the water course via effluent percolating through the ground will be effectively zero and can be ignored in the calculation of critical lot density. It should be noted that this area can only include the zone through which the effluent percolates as it moves down gradient from the disposal field.

As previously stated, if sufficient assimilative buffer area is available the major potential route for the export of pollutants from the site is in effluent that enters a water course by overland flow from either a surcharging disposal field, or by inappropriate disposal of greywater or effluent over the ground.

5 Conclusion - Prediction of Lot Density

In the past methods for the determination of critical lot density have been based on either the capacity of the disposal field and buffer areas to assimilate pollutants, or the contribution of failing systems. It is the conclusion of this paper that it is important to consider the contribution of both sources when determining the appropriate lot density for a development. In the example given the minimum assimilative buffer area required to avoid the export of pollutants in groundwater would need to be at least 1,400 m^2. Studies by Gerritse *et al* (1995) and Brouwer *et al* (1979) suggest that the minimum assimilative area may be significantly less due to greater losses of nitrogen close to the absorption trench than assumed in this paper.

PART B ESTABLISHING LOT DENSITY PLANNING CRITERIA FOR SENSITIVE CATCHMENTS

6 Introduction

It is an objective of most, if not all estuary management plans and catchment management plans that runoff from unsewered areas does not cause a degradation of water quality in water courses. How this can be achieved has been given little attention in the literature, and not surprisingly guidelines which may be applied to the subject are general in nature. The following section offers a method for setting density limits for planning of development in sensitive catchments. The density limits are based on achieving water quality objectives for sensitive waterways and may be adapted beyond unsewered developments.

Catchments for watercourses may be divided into three divisions or levels:

- the overall catchment which includes all areas that drain into the watercourse
- individual sub-catchments of the overall catchment
- local sections or reaches within sub-catchments

When considering the loading of pollutants into sensitive waterways it is possible to have different objectives for the three different divisions, or levels. For example for a sensitive watercourse such as a closing coastal lagoon, an appropriate overall catchment objective for nutrient loading would be for development to cause no change in the overall nutrient loading on the lagoon. This would necessitate a fairly low overall catchment population or development density. However, as it is unlikely that development would be evenly spaced throughout the catchment, a separate objective may need to be established for the individual sub-catchments which, when combined, ensures that the overall objective will be met. For example if one sub-catchment was retained as State Forest it would be possible to have a higher density in other sub-catchments without exceeding the overall density. However, in order to ensure that the waters of the developed sub-catchment were not adversely affected, a density limit would also need to be applied at the sub-catchment level. This density limit could be higher in number than the overall catchment density limit but should not compromise the water quality of waters within the sub-catchment.

Similarly within each sub-catchment it is unlikely that development would be evenly distributed. The most likely scenario is for clusters of development to occur relating to individual development proposals. Clustering of rural residential development is a planning objective for the NSW North Coast by DUAP. If the only criteria applied was to comply with the sub-catchment density limit it would be possible for local clusters to develop which were of sufficient density to threaten local water quality, while still complying with the sub-catchment and overall catchment density limits. Separate local density limits are therefore also needed to protect local reaches of the watercourse.

7 Methodology

The following method allows density limits to be set for the three catchment levels.

Step 1. Water quality objectives are set for the three catchment levels. These objectives will relate to the pollutants of concern and will need to be suitable for modelling. eg suitable objective for total phosphorus for a sensitive catchment might be:

Catchment level: - annual average TP loading (or concentration) not to exceed existing levels determined through baseline monitoring or modelling (eg 0.035 mg/L)

Sub-catchment level: - annual average TP loading (or concentration) not to significantly exceed existing levels determined through baseline monitoring or modelling (eg background plus 10%, 0.039mg/L)

Local level: - annual average TP loading (or concentration) not to exceed a level which would change the local trophic status of the stream (eg 0.05 mg/L). The ANZECC water quality guidelines may need to be applied (1992).

Step 2. Using established modelling techniques (for example Jelliffe, 1998) average annual TP concentrations in runoff are calculated for a range of lot densities. These are plotted as Predicted Pollutant Loading (or concentration) vs Average Lot Size (or lot density). Figure 2 is an example for Oyster Creek, Nambucca Shire.

Step 3. The lot densities which give the water quality objectives for the three levels may then be read from the figure. The overall catchment objective will be that lot density which results in no change to the existing pre-development loading. From the example in Figure 2 this is where the curve levels off at between 10 ha and 15 ha per residence (0.1 and 0.066 residences per hectare).

Step 4. The limiting density for the sub-catchment level may also be determined from the figure, and will be around the point of the curve where the pollutant loading is not significantly different from the background, but is greater than for the overall catchment. From the figure this is around 0.038 mg/L to 0.039 mg/L, and is achieved by an average lot size of approximately 3 hectares. (0.33 residences per hectare).

Step 5. The limiting density for the local level may also be determined from the figure. The density which would achieve an average annual concentration in runoff of 0.05 mg/L is approximately 0.91 residences per hectare or an average lot size of 1.1 lots per hectare.

In summary for the example shown the maximum lot density for rural residential development across the whole catchment is 0.1 res/ha to 0.066 res/ha (ie average lot size of 10 ha to 15 ha), with sub-catchment densities of no more than 0.33 res/ha, distributed in clusters of no greater than the critical minimum lot size required to achieve an average TP concentration of 0.05 mg/L in runoff, which was found to be approximately 0.91 res/ha. This may safely be rounded up to 1 res/ha. The values may be determined using a graph of Avg. Annual Pollutant Concentration Vs Avg Lot Size. The above example is presented in Figure 2.

This distribution pattern would result in the total nutrient loading on the watercourse complying with the overall catchment, while not adversely affecting water quality in any one sub-catchment or within a local reach of the water course. The resulting densities would allow for the practical distribution of development. For the example given (Oyster Creek - Nambucca Shire), the modelling suggests that individually clustered lots should not be smaller than 1 hectare unless additional stormwater management measures are applied, with the overall density of development within the entire catchment no greater than around 0.1 residences per hectare.

8 Conclusion

The method described above acknowledges the environmental characteristics and limitations of individual watercourses at the catchment wide, sub-catchment and local level, and allows development densities to be set which reflect these levels. The method is reasonably simple to set up and is offered as a simple and effective tool for planners to establish planning densities for rural development within sensitive catchments. It is recommended for consideration as a method for deriving planning densities for application in estuary and catchment management plans.

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Figure 1.
Nitrogen Export V Buffer Area

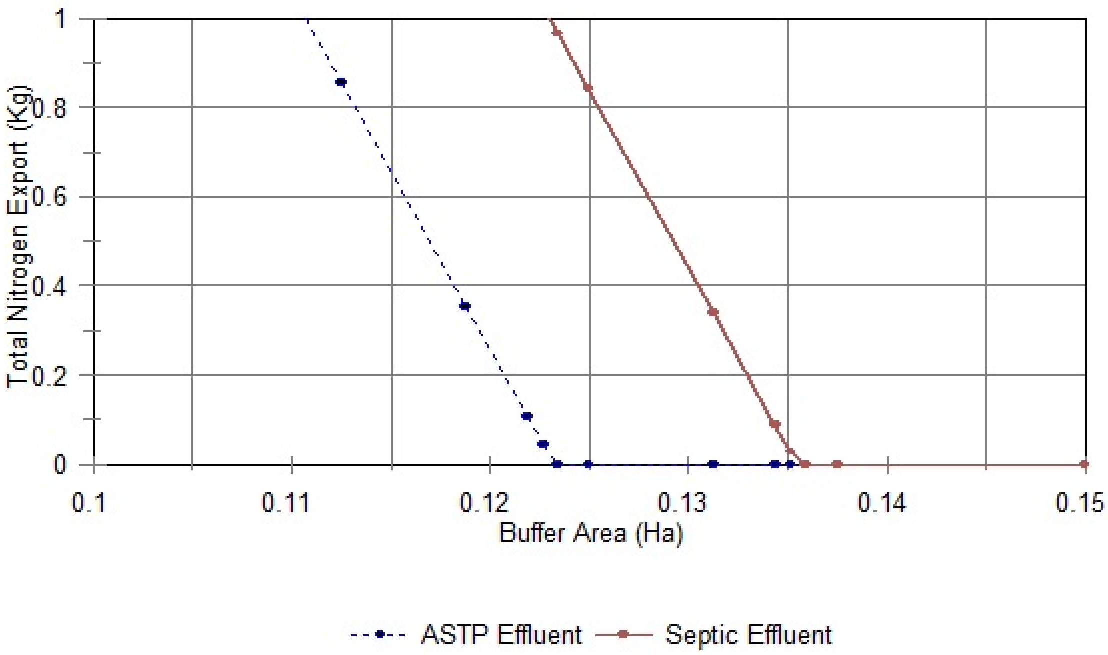

Figure 2.
Avg Lot Size V Avg TP Concentration