Environmental Pollution & Control

Wastewater Treatment – Sewage Sludge

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1. INTRODUCTION

It is estimated that the volume of water used daily in England and Wales (exclusive of water abstracted for cooling purposes) amounts to 5000 x 10^6 gal (23 x 10^6 m^3) or approximately 95 gal (430 l) per capita per day. Domestic use accounts for nearly 1800 x 10^6 gal (8 x 10^6 m^3) of this average daily total. Nearly all of the water used domestically and approximately 1500 x 10^6 gal (6.8 x 10^6 m^3) of the water used by industry each day is discharged to the sewers, yielding a total sewage flow of 3100 x 10^6 gal (14.1 x 10^6 m^3) or about 60 gal (275 l) per capita per day. Nearly 96% of the UK population is connected to sewers leading to wastewater treatment works, while the rest is served by small private treatment works, cesspits or septic tanks. To achieve this degree of wastewater treatment requires some 5000 sewage treatment works serving populations in excess of 10000; these are distributed throughout the ten Water Plc’s in England and Wales.

The sewerage systems which carry the sewage to the site of treatment, or point of discharge, are of two types. Foul sewers carry only domestic and industrial effluent. In areas serviced in this way there are entirely separate systems for the collection of stormwater which is discharged directly to natural water courses. However, in older towns and cities considerable use has been made of combined foul and stormwater systems. The use of combined sewerage systems leads to very significant changes in the flow of sewage during storms. However, even in foul sewers significant changes in the flow occur due to variations in the pattern of domestic and industrial water usage which is essentially diurnal, and at its greatest during the day. Infiltration will also influence the flow in the sewage system. Although a properly laid sewer is watertight when constructed, ground movement and aging may allow water to enter the sewer if it is below the water table. The combined total of average daily flows to a sewage treatment works is called the dry weather flow (DWF). The DWF is an important value in the design and operation of the sewage treatment works and other flows are expressed in terms of it. DWF is defined as the daily rate of flow of sewage (including both domestic and trade waste), together with infiltration, if any, in a sewer in dry weather. This may be measured after a period of 7 consecutive days during which the rainfall has not exceeded 0.25 mm.

The DWF may be calculated from the following formula:

\[ DWF = P(Q + I) + E \]

where,

- \( P \) = population served
- \( Q \) = average domestic water consumption (l d\(^{-1}\))
- \( I \) = rate of infiltration (l d\(^{-1}\))
- \( E \) = volume (in litres) of industrial effluent discharged to sewers in 24 hours

1.1 Criteria for Sewage Treatment

Sewage is a complex mixture of suspended and dissolved materials; both categories constitute organic pollution. The strength of sewage and the quality of sewage effluent are described in terms of their suspended solids (SS) and biochemical oxygen demand (BOD);
these two measures were originally either proposed or devised by the Royal Commission (1898-1915). The SS are determined by weighing after the filtration of a known volume of sample through a standard glassfibre filter paper, the results being expressed in mg l\(^{-1}\). Dissolved pollutants are determined by the BOD they exert when incubated for 5 days at 20°C. Samples require appropriate dilution with oxygen saturated water and suitable replication. The oxygen consumed is determined and the results again expressed in mg l\(^{-1}\).

The two standards for sewage effluent quality proposed by the Royal Commission were for no more than 30 mg l\(^{-1}\) of suspended solids and 20 mg l\(^{-1}\) for BOD, the so called 30: 20 standard. The Royal Commission envisaged that the effluent of this standard would be diluted 8:1 with clean river water having BOD of 2 mg l\(^{-1}\) or less. This standard was considered to be the normal minimum requirement and was not enforced by statute because the character and use of rivers varied so greatly. Currently, most sewage treatment works are required to meet discharge standards set by the Urban Wastewater Treatment Directive.

Sewage treatment now attempts to consistently produce an effluent with a quality superior to its 'Legal Consent' and attempts to achieve an 'Operating Target', frequently half the Legal Consent. In addition considerable importance has been placed upon the concentration of ammonia in the effluent. In the case of a works attempting to nitrify the effluent (see Section 2.4) the ammonia concentration is frequently limiting. Typical Legal Consent and Operating Targets are outlined in Table 1.

It is evident that the Operating Targets included in Table 1 are the same as the Royal Commission 30:20 standard.

**Table 1 Legal Consent and Operating Target values for a typical two stage STW**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Legal Consent (mg l(^{-1}))</th>
<th>Operating Target (mg l(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>SS</td>
<td>50</td>
<td>30</td>
</tr>
<tr>
<td>BOD</td>
<td>35</td>
<td>20</td>
</tr>
<tr>
<td>ammonia</td>
<td>25</td>
<td>12</td>
</tr>
</tbody>
</table>

**Table 2 The Urban Wastewater Treatment Directive (UWWTD)**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>TSS</td>
<td>35 mg l(^{-1})</td>
</tr>
<tr>
<td>BOD</td>
<td>25 mg l(^{-1})</td>
</tr>
<tr>
<td>COD</td>
<td>125 mg l(^{-1})</td>
</tr>
<tr>
<td>N (sensitive areas)</td>
<td>10 (15) mg l(^{-1}) or 80% removal &gt;100000 p.e. (10000 – 100000 p.e.)</td>
</tr>
<tr>
<td>P (sensitive areas)</td>
<td>1 (2) mg l(^{-1}) or 80% removal &gt;100000 p.e. (10000-100000 p.e.)</td>
</tr>
</tbody>
</table>
1.2 Composition of sewage

Domestic sewage contains approximately 1000 mg l \(^{-1}\) of impurities of which about two-thirds are organic. Thus sewage is 99.9% water and 0.1% total solids upon evaporation. When present in sewage approximately 50% of this material is dissolved and 50% suspended (see Figure 1). The main components are: nitrogenous compounds - proteins and urea; carbohydrates - sugars, starches and cellulose; fats - soap, cooking oil and greases. Inorganic components include chloride, metallic salts and road grit where combined sewerage is used. Thus sewage is a dilute, heterogeneous medium which tends to be rich in nitrogen.

2. SEWAGE TREATMENT PROCESSES

Conventional sewage treatment is a three stage process including preliminary treatment, primary sedimentation and secondary (biological) treatment; these are presented schematically in Figure 2. In addition some form of sludge treatment facility is frequently employed, typically anaerobic digestion.

2.1 Preliminary Treatment

These treatment processes are intended to remove the larger floating and suspended materials. They do not make a significant contribution to reducing the polluting load, but render the sewage more amenable to treatment by removing large objects which could form blockages or damage equipment.

Floating or very large suspended objects are frequently removed by bar screens. These consist of parallel rods with spaces between them which vary from 40 to 80 mm, through which the influent raw sewage must pass. Material which accumulates on the screen may be removed manually with a rake at small works, but on larger works some form of automatic raking would be used. The material removed from the screens contains a significant amount of putrescible organic matter which is objectionable in nature and may pose a disposal problem. Typically the material is buried or incinerated.

2.2 Primary Sedimentation

The raw sewage (containing approximately 400 mg l \(-1\) SS and 300 mg l\(-1\) BOD) at a flow rate of 3 DWF or less and with increased homogeneity as a result of the preliminary treatment process enters the first stage of treatment which reduces its polluting load, primary sedimentation, or mechanical treatment. Circular (radial flow) or rectangular (horizontal flow) tanks equipped with mechanical sludge scraping devices are normally used. However, on small works hopper bottom tanks (vertical flow) are preferred; although more expensive to construct these costs are more than offset by savings made as a result of eliminating the requirement for scrapers.
Primary sedimentation removes approximately 55% of the suspended solids and because some of these solids are biodegradable the BOD is typically reduced by 35%. The floating scum is also removed and combined with the sludge. As a result the effluent from the primary has a SS of approximately 150 mg l\(^{-1}\) and a BOD of approximately 200 mg l\(^{-1}\). This may be acceptable for discharge to the sea or some estuaries without further treatment. The solids are concentrated into the primary sludge which is typically removed once a day under the influence of hydrostatic pressure.

Types of sedimentation tank

2.3 Secondary (Biological) Treatment

There are two principal types of biological sewage treatment:

(i) The percolating filter (also referred to as a trickling or biological filter).
(ii) Activated sludge treatment.

Both types of treatment utilize two vessels, a reactor containing the microorganisms which oxidize the BOD, and a secondary sedimentation tank, which resembles the circular radial flow primary sedimentation tank, in which the microorganisms are separated from the final effluent.

Percolating Filter

These units consist of circular or rectangular beds of broken rock, gravel, clinker or slag with a typical size in the range of 50-100 mm. The beds are between 1.5 and 2.0 m deep and of very variable diameter or size depending on the population to be served. The proportion of voids (empty spaces) in the assembled bed is normally in the range 45 to 55% (Figure 4). The settled sewage trickles through interstices of the medium which constitutes a very large surface area on which a microbial film can develop. It is in this gelatinous film containing bacteria, fungi, protozoa and on the upper surface algae that the oxidation of the BOD in the settled sewage takes place.
**Activated Sludge**

In the activated sludge process the majority of biological solids removed in the secondary sedimentation tank are recycled (returned sludge) to the aerator. The feedback of most of the cell yield from the sedimentation tank encourages rapid adsorption of the pollutants in the incoming settled sewage and also serves to stabilize the operation over a wide range of dilution rates and substrate concentrations imposed by the diurnal and other fluctuations in the flow and strength of the sewage. The sludge which is not returned to the aerator unit is known as surplus activated sludge and has to be disposed of.

**Nitrification**

The production of a final effluent with the minimum BOD value is dependent upon the complete nitrification of the effluent, which involves the conversion of the ammonia present to nitrate. This is a two-stage process undertaken by autotrophic bacteria principally from the genera *Nitrosomonas* and *Nitrobacter*. Nitrification occurs in percolating filters and activated sludge plants operated in a suitable manner. The first stage, sometimes referred to as 'nitrosification' involves the oxidation of ammonium ions to nitrite and follows the general formula:

\[
\text{NH}_4^+ + 1.5\text{O}_2 \rightarrow \text{NO}_2^- + 2\text{H}^+ + \text{H}_2\text{O}
\]

_Nitrosomonas_

In the second stage nitrite is oxidized to nitrate:

\[
\text{NO}_2^- + 0.5\text{O}_2 \rightarrow \text{NO}_3^-
\]

_Nitrobacter_

\[
\text{NH}_4^+ + 2\text{O}_2 \rightarrow \text{NO}_3^- + 2\text{H}^+ + \text{H}_2\text{O}
\]

Two important points are evident from this last formula. Firstly, nitrification requires a considerable quantity of oxygen. Secondly, hydrogen ions are formed and hence the pH of the wastewater will fall slightly during nitrification. Nitrification significantly increases the cost of sewage treatment since more air is required. Furthermore, because these autotrophic organisms grow only slowly, longer retention periods are also required resulting in higher capital costs. Nor does nitrification result in the production of an entirely acceptable sewage effluent. In areas where water re-use is practised the concentration of nitrate in river waters causes concern. There exists a limit on the concentration of nitrate in drinking water to avoid the occurrence of methaemoglobinaemia (so called 'blue baby' syndrome). As a consequence denitrification is now practised after nitrification in some activated sludge treatment plants.
Table 3. Contrasting features of the percolating filter and activated sludge processes

<table>
<thead>
<tr>
<th>Percolating filter</th>
<th>Activated sludge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uses larger land area</td>
<td>Uses less land area as a result of higher loading</td>
</tr>
<tr>
<td>Minimal operator attention</td>
<td>Greater operational control is possible</td>
</tr>
<tr>
<td>Fly and odour nuisance</td>
<td>Does not cause nuisance</td>
</tr>
<tr>
<td>Low power requirements</td>
<td>Power required for aeration</td>
</tr>
<tr>
<td>Large capital investment</td>
<td>Lower capital investment</td>
</tr>
<tr>
<td>Robust process</td>
<td>Better quality effluent</td>
</tr>
<tr>
<td></td>
<td>Easier to upgrade to include nutrient removal</td>
</tr>
<tr>
<td></td>
<td>Can fail catastrophically</td>
</tr>
</tbody>
</table>

Secondary Sedimentation

Both types of biological treatment require sedimentation to remove suspended matter from the oxidized effluent. Tanks similar to those normally employed for primary sedimentation are generally employed, although at a higher loading of approximately 40 m³ m⁻² d⁻¹, at 3 DWF. Because of the lighter and more homogenous nature of secondary sludge, simple sludge scrapers are possible and scum removal is not necessary.

2.4 Tertiary Treatment

Secondary treatment will be sufficient to achieve the effluent standards described earlier apart from the bathing beach standard or perhaps the phosphorous limitation. In certain circumstances it may be required to achieve a solids standard better than the 35 mg/l quoted. In this case tertiary treatment, sometimes known as polishing is required. This is basically aimed at reducing the suspended solids more by either simple filtration or settlement.

Some examples are:

Lagoons: Simple lined excavations where effluent is allowed to settle. This also reduces bacteria by providing time for them to die off. Suitable for small sites or where large areas of land are available.

Pebblebed Clarifiers: Small tanks containing a layer of pebbles supported on a mesh submerged near the top of the tank. Particles coalesce as they pass between the pebbles and settle on the top of the pebbles. Smaller than lagoons but intensive in manpower. Can be used up to medium sized works (10000 population)

Reed Beds: Although originally thought to encourage biological action in reality they can only be relied on as a filtration process and work best
when planted on a gravel layer. Suitable for small works.

**Grass Plots:** Simple filtration through grass but large area required and intensive in manpower suitable for small works.

**Sand Filters:** Sand filters can either be large horizontal beds or tall cylinders both containing a simple sand bed with air scour and final effluent back washing system suitable for medium to large sites. The best results are achieved by continuous backwashed systems. Up to 15% of the flow may be used by continuous backwashing which must be returned to the head of the works.

### 2.5 Disinfection

To achieve the removal of bacteria to the level required in the Bathing Water Standard Disinfection is necessary. In the USA chlorine is used for this purpose but this is frowned on in the UK due to the production of unpleasant by-products. Irradiation by UV light is generally preferred. Proprietary systems may be purchased.

Other disinfectants (not usually in the UK) used are: Peracetic Acid and Ozone.
SOME DEFINITIONS

BOD<sub>5</sub> (mg/l): Biochemical Oxygen Demand, a definition of the biodegradability of a wastewater. Test takes 5 days.
- High BOD is bad
- Low BOD is good

COD (mg/l): Chemical Oxygen Demand, a measure of the total oxygen demand:
- For domestic crude sewage: COD = 2 X BOD approx.
- For final effluent: COD = 5 X BOD approx.

SS (mg/l): Suspended Solids, measure of solids likely to be removed by simple settlement

Ammonia (mg/l): Ammonia dissolved in the wastewater

Total Nitrogen: Ammonia + nitrite + nitrate expressed as nitrogen

Nutrients: For most purposes Nitrate and Phosphorous

Nitrate: Very little Nitrate is present in domestic wastewater or surface water. It is created by the transformation of ammonia into Nitrate during the biological stage of wastewater treatment

FINAL EFFLUENT STANDARD

The final effluent standard required will be calculated on the basis of the capacity for a watercourse to purify the effluent discharged. Within the European Union this simplifies to a set of minimum standards summarised below:

<table>
<thead>
<tr>
<th>Normal waters</th>
<th>BOD  = 25mg/l</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>COD  = 125mg/l</td>
</tr>
<tr>
<td></td>
<td>SS  = 35mg/l  (Latest consents have no SS standard)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sensitive Waters</th>
<th>Total Nitrogen = 15 mg/l &lt; 100K P.E.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10 mg/l &gt; 100K P.E.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Phosphorous = 2 mg/l &lt; 100K P.E.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 mg/l &gt; 100K P.E.</td>
</tr>
</tbody>
</table>

A consent can have any combination of the above parameters.

<table>
<thead>
<tr>
<th>Bathing Waters</th>
<th>Faecal Coliforms (Bacteria) &lt;2000 per 100 ml</th>
</tr>
</thead>
</table>

Faecal Coliforms are bacteria that normally live in the human gut and are generally known as E.Coli. Storm discharges are limited to a frequency determined by the EA. Flow to treatment can be reduced by negotiation with the EA.
3 SLUDGE TREATMENT & DISPOSAL

Sewage sludge is produced from the treatment of wastewater and consists of two basic forms; raw primary sludge (basically faecal material); and secondary activated sludge (a living ‘culture’ of organisms that help remove contaminants from wastewater before it is returned to rivers or the sea). In 2009 waste water sludge production in U.K amounted to around 1.2 megatonnes of dry solids of which 77% was recycled to agricultural land, and for EU as a whole there are about 6.5 megatonnes of dry solids produced annually. The sludge production values has significantly increased, possibly by as much as 50%, as the urban waste water treatment directive was implemented over the period up to 2005 and in the next decade, sludge disposal to all the established outlets could become increasingly difficult. The challenges faced had been how to (a) maintain cost effective and secure methods of sludge disposal and (b) engender public confidence in all disposal and recycling options. Of increased importance is the potential of renewable energy from the anaerobic digestion of sewage sludge. Sludge treatment and disposal may account for 40% of the operating costs of a wastewater treatment facility. Prior to treatment the sludges contain between 1 and 7% solids (they are therefore nearly all water) which are usually highly putrescible and offensive. A wide range of treatment processes and disposal options has been used, although, recently, the cost of energy has reduced the numbers currently employed because of economic considerations.

![Sewage sludge routes in the UK, 2008](image)

Most often the sewage sludge is transformed into biosolids using a number of complex treatments such as digestion, lime stabilisation, thickening, dewatering and drying.

![Biosolids products recycled to land](image)
Anaerobic Digestion

During anaerobic digestion the organic matter present in the sewage sludge is biologically converted to a gas typically containing 70% methane and 30% carbon dioxide. The process is undertaken in an airtight reactor usually equipped with a floating gas collector. Sludge may be introduced continuously, but more frequently is added intermittently, and the digester operates on a 'fill and draw' process. The methane produced is generally utilized for maintaining the process temperature, heating and power production by combustion in dual fuel engines which use oil in the absence of methane. Methane production is only significant at elevated temperatures, when 1 m$^3$ of methane at STP is produced for every 3 kg of BOD degraded.

![Figure 7. Digester setup and phases of anaerobic digestion](image)

3.2 Disposal of Sewage Sludge to Land

The practice of disposing sewage sludge to land has several potential benefits. Both dried and liquid sludges are applied to land, the latter from tankers by spraying. Arable land can be ploughed, following the application, which speeds up incorporation of the sludge and can reduce any odour problems. However, when it is applied, even spreading is important to prevent localized ‘hotspots’. Liquid sludges may also be injected directly into the soil giving uniform application and almost complete elimination of odour problems. The application of sludge to land may help to slow down the decline in organic matter in soils under modern farming methods, leading to improvements in water holding capacity, porosity and aggregate stability. The main value of sludge as a fertilizer lies in its nitrogen and phosphorus contents. However, much of the nutrient content may be in organic forms, and thus be unavailable to plants until mineralization occurs. Although from an economic point of view it may be desirable to apply dried sludge to land, significant quantities of available forms of the nutrients may be lost during drying. Liquid digested sludge may contain up to 10% (w/w) of nitrogen but only a fraction of this may be in available forms. For the purpose of calculating the available nitrogen in sludge, it is assumed that 85% of the total nitrogen in liquid digested sludge and 33% of that in dried sludge is available to crops during the growing
season. Since most agricultural soils are deficient in nutrients, fertilizers nearly always have to be added. However, sewage sludge is deficient in potassium, and therefore cannot fulfil complete fertilizer requirements. Furthermore, if all of the sewage sludge produced in the UK were to be applied to agricultural land, it would only provide 4.5% of the country’s fertilizer requirement. Liquid sludges consist mainly of water. Some farmers value sludge solely for its water content which can often help to overcome irrigation problems during dry weather. Sewage sludge generally represents the non-degradable residue left after the treatment of domestic or mixed industrial/domestic wastewater. This means that it contains many of the materials originally present in the wastewater which could be classified as pollutants. The potential hazards from the application of sludge to land are protozoal, viral, bacterial and other pathogens, which are present to the greatest extent in untreated sludges, persistent toxic organic compounds and toxic heavy metals.

The table below indicates the suitability of biosolid (sludge) types to crop groups.

<table>
<thead>
<tr>
<th>CROP GROUP</th>
<th>UNTREATED SLUDGES</th>
<th>CONVENTIONALLY TREATED SLUDGES</th>
<th>ENHANCED TREATED SLUDGES</th>
</tr>
</thead>
<tbody>
<tr>
<td>FRUIT SALADS</td>
<td>✗</td>
<td>✗</td>
<td>✓</td>
</tr>
<tr>
<td>VEGETABLES</td>
<td>✗</td>
<td>(12 month harvest interval applies)</td>
<td>✓</td>
</tr>
<tr>
<td>HORTICULTURE</td>
<td>✗</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>COMBINABLE &amp; ANIMAL FEED CROPS</td>
<td>✗</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>- GRAZED GRASS &amp; FORAGE</td>
<td>✗</td>
<td>✗</td>
<td>✓ (3 week grazing and harvest interval applies)</td>
</tr>
<tr>
<td>- HARVESTED</td>
<td></td>
<td></td>
<td>✓</td>
</tr>
</tbody>
</table>

NOTE: ✗ All applications must comply with the Sludge (Use in Agriculture) Regulations and DEFRA Code of Practice for Agricultural Use of Sewage Sludge. ✗ Applications not allowed (except where stated conditions apply).

The use of biosolids in agriculture is recognised by the UK Government and European Commission as the Best Practicable Environmental Option. The water industry, in partnership with the British Retail Consortium which represents supermarkets and other major retailers, developed a voluntary code of practice in 1999 known as the ‘Safe Sludge Matrix’. This sets out the treatment required to remove harmful pathogens from biosolids, and the correct method of applying biosolids to agricultural land to ensure that public health is protected. The code has been used voluntarily since and is now given legal backing in revised UK regulations.