Sludge management in water treatment plants: literature review

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Abstract: Due to the increased environmental concern; there is a considerable pressure on the water authorities for the safe treatment and disposal of sludge. It is very important to choose a suitable sludge treatment and disposal system, which is both economical and technically feasible. In this article, sludge characteristics, quantities and sources will be outlined. A detailed sludge management and treatment methods will be presented. Sludge reuse, incineration, landfilling and disposal were also considered. The study concluded that sludge management should be considered when designing and operating WTPs, adopting beneficial reuse options of sludge will become very essential and it is necessary to investigate the appropriate options for formulating long term sludge management plans under strict environmental regulations. The study recommended that sludge must be treated and disposed of in a safe and effective manner. Great emphasis is to be enforced to minimise the quantity of generated sludge, more studies should be conducted to develop suitable sludge management plans, when applying sludge reuse in agricultural purposes it is highly recommended to investigate the long term effects of sludge reuse, and finally the environmental impacts of different of sludge disposal methods should be evaluated.

Keywords: sludge; management; treatment plants; environmental; disposal; characteristics; quantities; sources; regulations; reuse; long-term effects.

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1 Introduction

Raw water abstracted from surface water sources (reservoirs and rivers) and groundwater sources may contain a wide variety of contaminants; including microorganisms, inorganic and organic contaminants. These contaminants incorporate dissolved solids, turbidity-causing solids, organic and inorganic material, algae, microscopic organisms, colloids, precipitated solids from the original water and those added in chemical treatment (Anjithan, 2016; Crittenden et al., 2012; USEPA, 2011). Most of the surface Water Treatment Plants – employ the conventional treatment process such as coagulation, flocculation, sedimentation, filtration, aeration and disinfection – produce large quantities of sludge by removing impurities from raw water and from the various water treatment chemicals used for relevant water treatment processes (Anjithan, 2016).

Water treatment processes utilised to produce safe drinking water, generate a wide variety of residual products (consist of the liquid, solid, semisolid, and gaseous phase by-products). These residuals depend on the raw water source, chemicals used for treatment, and types of unit operations used. Due to the increased environmental concern; there is a considerable pressure on the water authorities for the safe treatment and disposal of sludge. It is very important to choose a suitable sludge treatment and disposal system, which is both economical and technically feasible (Anjithan, 2016; Crittenden et al., 2012; Ippolito et al., 2011).

Water treatment plants (WTPs) usually utilise innovations and modern management strategies to enhance treatment, disposal, and prevention/controlling the release of source water treatment sludge into the environment. Adoption of certain innovation and modern management strategies may significantly help WTPs to meet the acceptable limits. Many advantages of innovations and modern management strategies in water treatment include better water quality, less operational expenses, and lower energy consumption (USEPA, 2011). Water treatment sludge management is important in terms of quantities, handling expenses, composition, and the environmental and regulatory requirements that any treatment system must comply with (Crittenden et al., 2012).

2 Characteristics of sludge in WTP

Recognising the physical, chemical, and biological characteristics of the sludge generated from water treatment processes is a necessity to determine the proper management procedures and to design facilities to execute these processes. The volume, properties and characteristics of the sludge rely on the source and type of raw water, production rate of water being treated, contamination level of source water treatment, type of coagulant added and the dosage applied during the water treatment and plant operating conditions (Anjithan, 2016; Crittenden et al., 2012; USEPA, 2011).

Sludge, in particulate of gelatinous form, is formed during the processes of chemical coagulation and softening at drinking water treatment plants. Most of the sludge has common characteristics; including high water content (usually >95% by weight (Anjithan, 2016). One important parameter which influences the sludge characteristics is the WTP system configuration. There are many WTP system configurations; each configuration produces its own characteristic sludge. The expected floc characteristics of different water treatment configuration can be as shown in Table 1 (Dharmappa et al., 1997)

Table 1 Expected floc characteristics for different configurations

Floc	*System configuration*		
	Conventional treatment	*Direct filtration treatment*	*Contact filtration treatment*
Floc volume	High	Medium	Low
Floc density	Low	Medium	High
Macro floc	High	Medium	Low
Micro floc	Low	Medium	High

WTPs sludge may contain a variety of microorganisms, according to: the source and the quality of the source water, the treatment method being utilised, and the period of treatment during the year. Coagulation sludge will include microorganisms, protozoan blisters and oocysts, and infections evacuated during the treatment process. In the case of water treatment (WT) sludge treatment and management, the physical and chemical characteristics are the most important ones (Anjum et al., 2016; Crittenden et al., 2012; Dharmappa et al., 1997; Ippolito et al., 2011; Mowla et al., 2013).

The variations in the physical characteristics among sludge of various compositions are urged to the variation in the physical structure of the sludge. A coagulation sludge is comprised of the suspended material in the source water, coagulants added, and a large amount of the entrapped water. In the coagulation–flocculation process, the suspended solids and the coagulant are united to compose the flocs, after that they settle down and make sludge. The suspended solids contain clay and sediment particles, colour-causing colloids, algae, and other dirt materials. Clays and sediments are solid and have a density of about 2,600 kg/m^3; the alternate materials are agglomerations of coagulants with other ions and water molecules all loosely held together by electrostatic bonds (Crittenden et al., 2012).

Sludge chemical characteristics are generally related to the chemical content of the source water and the type of chemical coagulants. The constituents of sludge are highly complex, and they mainly include water and different species of solids. Typically hydrated alumina oxides and iron oxides are present. Chemical components of WT sludge include aluminium and iron hydrous metal. Alum [$Al_2(SO_4)_3.14H_2O$] is the most common coagulant in use; iron salts $FeCl_3$ and $Fe_2(SO_4)_3$ are also used.

The physio-chemical characteristics of the sludge can be broadly classified into two categories: micro-properties and macro-properties. The micro-properties define the influent conditions of the sludge, and can be treated as suspension characteristics. Whereas, the macro-properties describe the sludge characteristics which are dependent on the micro-properties of the sludge and they directly determine the treatability of the sludge. Establishing appropriate relationships between micro- and macro-properties is needed to aid the design of a thickening and dewatering processes. Once this is achieved, designing of the process could be readily done by selecting a relevant set of macro-properties and using the corresponding relationships with the micro-properties (Dharmappa et al., 1997).

3 Sludge quantities generated by during WT processes

The amount of solid, semisolid, and liquid residuals that exits the conventional water treatment plant can be as much as 3 to 5% of the volume of the water entering the plant. The great part of that volume will be the filter waste wash-water, which regularly contains <10% of the expelled solids in the treatment process within the plant. Typical reported values for the sludge quantities generated by different treatment methods are given in Table 2 (Crittenden et al., 2012).

Table 2 Typical production of sludge in WTP

Sludge type	*Portion of plant flow*	
	Range	*Typical*
Alum coagulation	0.08–0.3%	0.1%
Flotation (at reactor surface)	0.01–0.1%	0.06%
Flotation (at reactor bottom)	0.001–0.04%	
Iron coagulation	0.08–0.3%	0.1%
Lime-softening	0.3–6%	4%

Source: Crittenden et al. (2012)

4 Environmental constraints of sludge in WTP

Sludge disposal is a basic portion of water treatment framework. Sludge disposal techniques are facing difficulties and opportunities at the same time, and persistently still need modifications. Before, treatment plant residuals were frequently released to the close-by streams, put in lagoons for a certain time, or spread on land with the least or no treatment, which resulted in both negative aesthetic and adverse ecological impacts. Aesthetic impacts incorporate the discolouration or rising up the turbidity in accepting water bodies and development of sludge deposition in waterways and occupying large land areas with lagoons (Crittenden et al., 2012; Wei et al., 2018).

Direct release of water treatment sludge to water bodies adversely affects the water quality of downstream and aquatic biota and it is not acceptable in accordance with Environmental Protection Agency (EPA) regulations. According to the environmental regulations, sludge disposal will be a licensable activity in the near future. Large quantities of sludge are disposed of by landfilling also. The openly dumped sludge washed away with rain water affects the surface water quality. Groundwater quality may also be affected due to leaching of sludge in to soil (Anjithan, 2016). The vast majority of sludge, whenever spread on land to any depth, will anticipate or restrain plant growth; however, if well blended with the soil, sludge may have practically no effect on plant growth. Lime sludge may have positive impacts on the soil, whenever utilised in suitable quantities (Crittenden et al., 2012).

5 Regulatory constraints of sludge in WTP

Handling and discharging the sludge generated from WT process have critical concerns in the WT process. Recently, the issue of where and how to discard this sludge has gotten expanded consideration. Stricter water quality standards for drinking water, and for water bodies accepting sludge and groundwater underlying surface waste disposal sites, have made the process of sludge disposal more troublesome. Combined with these stricter regulations, the land available for the final disposal of sludge has been diminished. Sludge release and disposal is a common challenge for any WTP for drinking purposes (Cornwall and Koppers, 1990). In this manner, it is important to identify appropriate methodologies and technologies for sludge management in the WTP that guarantee accomplishing the required ecological and technological results. The choice of an option should depend upon financial as well as regulatory considerations. The type and characteristics of sludge are considered as important criteria to be followed when developing sludge disposal and transfer options. In that capacity, they are currently required to meet standards for best practicable technology (BPT) and the best available technology (BAT) monetarily attainable. Such regulatory constraints, while securing public and environmental health, can seriously restrict the available sludge management options and increase the expenses of its disposal (Anjithan, 2016; Crittenden et al., 2012).

6 Sources of sludge in WTP

The conventional water treatment process is well established, adopted and strong. In the conventional coagulation-filtration treatment process, suspended solids and natural organic matter are expelled from the source water by adding iron and aluminium salts as chemical coagulants, bringing out the formation of WT sludge. In addition to the chemical coagulant added, WT sludge also includes the mineral and other components from the raw water. Sludge of water treatment work remains an inescapable by-product of WT process. The WT sludge is a mixture of liquid and solid and can be treated as a waste. Though it can be considered as a natural resource in some cases, often, it is economically and environmentally an unwanted burden. The quantities of sludge produced from WTPs in our modem society are staggering and are continuously increasing. The sources of this sludge and a brief description of them are presented in

Table 3 (Anjithan, 2016; Crittenden et al., 2012; Dharmappa et al., 1997). Detailed description of sludge sources will be presented in the following subsections.

Table 3 Sources of sludge from WT plants

Source of sludge	*Description*
Alum and iron precipitation	Sludge resulting from the alum and iron precipitation of surface waters containing clay, silt, colloids, and microorganisms with coagulant chemicals and polymers.
Coarse screening	Coarse screening inhibits the passage of debris and fish into the intake structure.
	Coarse sludge accumulated on screens includes: rags, viscous matter, and big sized wooden pieces.
Floatation	Floatation, sometimes referred to as a sludge thickening technique, results in the formation of float sludge. Sludge is collected uniformly in small plants and continuously in large plants.
Pre-sedimentation	Pre sedimentation occurred prior to conventional treatment, and will result in the removal of gross amounts of sludge.
Slow sand filter scrapings	The scraping of the slow sand filters surface, sometimes will result in the accumulation of semisolid materials
Spent sorbents	Solid materials utilised to remove constituents including: hardness, As, F, P, and some organic matters from water by sorption, and have lost their significant adsorptive capacity or they cannot be reactivated again effectively.
Travelling screens	Travelling screens are mainly utilised to inhibit grit, sand, and small gravel from continuing travel into the treatment facility. Retained materials usually include grit, sand, and small gravel.
Water softening	Removal of Ca^{+2} and Mg^{+2} ions from hard water during precipitation softening will result in the formation of lime sludge.

Source: Crittenden et al. (2012)

6.1 Coarse and micro-screening

Screens are used in surface water intakes to prevent the entrance of materials which might damage or clog pumps or other mechanical equipment in the plant. It is utilised to remove sticks, rags, and other large debris from raw water by straining on screens. Fish protection is of great importance when treating water from a river or a lake. The screen may be cleaned manually on a time basis, or automatically. Inclined or vertical flat plate screens are mounted on a framework submerged in flowing waters. Coarse screening is the passage of raw water through coarse screen to remove large particles from 2 to 15 cm in diameter and larger. Coarse screenings are usually disposed in landfills or other waste disposal site. Micro-screens, which come after the coarse-screens, keep out material that can clog pipework at the WT plant. Micro-screening is the passage of water through stainless steel or polyester media for removal of small particles from 0.025–1.5 mm in diameter from raw water by straining on screens. It is used for the removal of filamentous algae. Fine screenings (in the form of slurry) may be discharged to a wastewater network or sent to landfills. Note that the volumes of the collected screenings are quite considerable, and amount about 50 L/1,000 capita/day (Crittenden et al., 2012; Hammer and Hammer, 2008; McGhee, 1991; De Kreuk, 2013).

6.2 Pre-sedimentation

In WTPs, sometimes primary settling is done in the unit of pre-sedimentation tank (PST) in entrance (upstream) of source water to the plant. Water streams may contain high concentrations of suspended sediment; therefore, preliminary treatment processes are employed for the removal of debris and part of the sediment load. When treating the raw water of high turbidity – especially during storm season, flood conditions, high coliform counts and highly polluted rivers – solids loadings including bigger particles will diminish substantially with the use of pre-sedimentation in the WTP. Pre-sedimentation is performed physically without the application of chemical coagulants. Contaminants from source water could be expelled by consecutive treatment methods. The choice and arrangement of various treatment processes are of extraordinary significance for attaining high contaminant removal efficiency. Pre-sedimentation affects water treatment plant operation, and the treated water characteristics depend upon source water quality (Jahanshahi and Taghizadeh, 2018; Reynolds and Richards, 1996; Departments of the Army and the Air Force, 1985). The amount of sludge separated from pre-sedimentation tanks depends upon the quality of the raw water being treated.

6.3 Coagulation sludge

Coagulation sludge is generated by the coagulation and settling of natural turbidity by added coagulant chemicals. Sludge that is formed in the coagulation process is usually collected in the sedimentation tanks or on filters. The characteristics and quality of the collected sludge (either from the sedimentation tanks or from the filters) is a function of the source water quality, type and amount of coagulant added, operation efficiency and design of plant. The coagulation sludge contains microbial, organic, and inorganic contaminates derived from water, and metallic or polymeric coagulants (Crittenden et al., 2012; McGhee, 1991).

The solids content of this sludge averages from 8–10%. For typical WTPs utilising alum for coagulation process, somewhere in the range of 60 and 90% of the total sludge formed will be collected in the sedimentation tanks with the remaining in the filters. The sludge accumulated on the filters is expelled from the filters during the backwashing process and are removed from the waste wash water by plain (gravity) sedimentation. Sludge from the sedimentation tanks can be removed continuously or on a discontinuous manner. If the cleaning method of tanks is performed manually, the time between cleaning intervals will be 3 months or even more. Automatic cleaning equipment is typically intended to work between once per week and once at regular interval of hours or continuously (Crittenden et al., 2012; Hammer and Hammer, 2008; McGhee, 1991).

6.3.1 Estimating quantities of coagulation sludge

Estimating the amount of sludge is unfortunately very complex since it depends on several factors such as; the source water quality and the type of chemical treatment, chemical dosage and the point at which the chemicals are added in the treatment process. Amounts of the sludge produced during the coagulation process were previously presented in Table 2. The quantity of sludge expected to be collected at the WTP is generally estimated to help in the plant design. The suspended solids portion of the sludge may be securely assumed to be equivalent to the suspended solids of the source water. On the chance that the information regarding the total suspended solids (TSS) are not available, it may be roughly calculated based upon the correlation with turbidity. It is worth to note, however, that there is a dramatic change in the TSS/turbidity proportion depending on the organic content of the raw water source. The proportion for most water sources will change somewhere from 1 to 2, with a typical value of about 1.4. For turbidities under 10 nephlometric turbidity unit (NTU) the proportion is ≈1 (Crittenden et al., 2012; Snurer, 2008).

6.3.2 Coagulation reactions

When alum or iron is being utilised as the coagulant agent, the reactions will be as:

$$Al_2\left(SO_4\right)_3 \cdot 14H_2O \rightarrow 2Al(OH)_3\downarrow + 6H^+ + 3SO_4^{2-} + 8H_2O \tag{1}$$

$$FeCl_3 + 3H_2O \rightarrow Fe(OH)_3\downarrow + 3H^+ + 3Cl^- \tag{2}$$

$$Fe_2\left(SO_4\right)_3 \cdot 9H_2O \rightarrow 2Fe(OH)_3\downarrow + 6H^+ + 3SO_4^{2-} + 3H_2O \tag{3}$$

The expected precipitates will be iron hydroxide when utilising iron as the coagulant agent, on the other hand the precipitate will be aluminium hydroxide when using alum as the coagulant. The expected amount of sludge can be estimated from the stoichiometry. To estimate the amount of sludge resulting from iron or alum addition, one can use the values presented in Table 4.

If polymers are used to enhance coagulation process, the amount of polymer utilised is to be added to the total quantity of the generated sludge. Also, if chemicals including activated carbon or activated silica or other emulsifying materials (such as bentonite) are used to aid the coagulation process, they should be taken into account when estimating sludge quantity at sedimentation tanks or filters (Crittenden et al., 2012).

Table 4 Typical values for coagulation sludge quantities

Coagulant	*Unit*	*Range*	*Typical value*
Alum: $Al_2(SO_4)_3 \cdot 14H_2O$	kg dry sludge/kg coagulant	0.2–0.33[a]	0.26
Ferric sulphate: $Fe_2(SO_4)_3$	kg dry sludge/kg coagulant	0.5–0.53[a]	0.53
Ferric chloride: $FeCl_3$	kg dry sludge/kg coagulant	0.6–0.66[a]	0.66
Polymer addition	kg dry sludge/kg coagulant	1	1
Turbidity removal	mg TSS/NTU removed	1.0–2	1.4

Note: [a]Value without bound water.

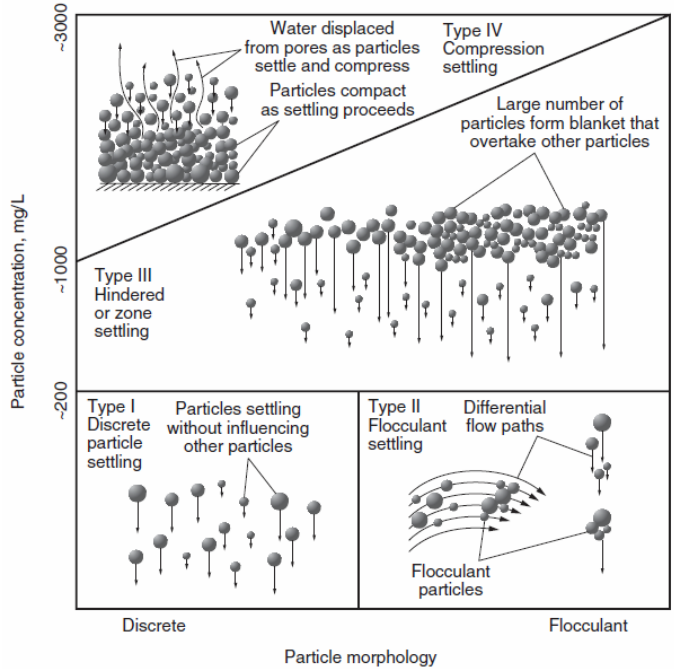
Source: Crittenden et al. (2012)

6.4 Sedimentation sludge

Sedimentation is a treatment method that permits the suspended particle in water (like flocs, sand and clay) to settle out of the suspension under the influence of their own weight. Particles that settle out from the water become sediment and, in water treatment, is named as sludge. Sedimentation can take place naturally in reservoirs or in compact settling installations. In water treatment process, sedimentation is utilised to lower the portion of particles in the suspension prior to coagulation – to reduce the dose of chemical coagulants required – or after coagulation and sometimes even flocculation. At the point when sedimentation is following the coagulation, its intended goal is normally to diminish the solids concentration in water with the purpose that the consequent filtration process can work more successfully. Examples of settling installations are the horizontal flow settling tanks, the tilted plate settlers and the floc blanket installations. There are many strategies for applying sedimentation including: horizontal flow, radial flow, inclined plate, ballasted floc and floc blanket sedimentation (IWA, 2010; TU Delft, 2007). Depending on their concentration and morphology, particles can be classified into four groups, as shown in Figure 1.

- Type I particles are not united and do not interfere with each another when settling. Type I settling occurs generally in grit removal chambers, pre-sedimentation tanks for sand expulsion before coagulation, and settling of sand particles during backwashing of rapid sand filters.
- Type II settling zone comprises of particles that are fit for flocculating. As particles agglomerate and develop in size, they can settle down quicker. Type II settlings are observed when settling happens after iron and alum coagulation and in the majority of conventional sedimentation tanks.
- Type III, or hindered settling happens at concentrations of more than types I and II settling, where a blanket of sludge is formed. The blanket traps particles under it as it settles; thus, a clear interface is found over the formed blanket. Type III settling zones are found in thickeners (sludge disposal) and the lower portions of some sedimentation tanks (e.g., lime-softening sedimentation).
- At concentrations much higher than that found in type III settling, the suspension starts to consolidate gradually. This type of consolidation is referred to as type IV settling or compression settling. For type IV settling zones, the particles may not settle by any means, and water flows or drains out of a mat of particles very slowly. Type IV settling zones are found in dewatering operations, and once they are dewatered, the suspension may become a paste or cake (Crittenden et al., 2012).

Figure 1 Types of settling



Source: Crittenden et al. (2012)

6.4.1 Sedimentation sludge quantity estimation

6.4.1.1 Type I settling (Crittenden et al., 2012)

Any particle in the inlet zone with a settling velocity (v_s) ≥ the overflow rate (v_c) will be removed regardless of its starting position. Depending upon the position of particle at the inlet of the sedimentation tank, the removal may also take place once the settling velocity is less than the overflow rate. The % of particles removal will be:

$$\%\text{ of removed particles} = (v_s \div v_c) \times 100\%, \qquad (v_s < v_c) \tag{4}$$

6.4.1.2 Type II settling (Davis, 2010)

There is no adequate mathematical relationship that describes type II settling. Settling columns tests conducted at laboratories can help to model the behaviour of flocculants settling. A settling column is filled with the water sample to be tested. The water sample containing solids is left and allowed to settle. Samples are taken from the suspension at different depths and at specified time periods. The concentration of suspended solids is then calculated for each sample and the percentage of solids removed is obtained from:

$$R(\%) = \left(1 - \frac{C_t}{C_0}\right) \times 100 \tag{5}$$

where

$R\%$ percent solids removal at certain depth and time (%)

C_t concentration at time, t, and certain depth (mg/L)

C_0 concentration at the beginning of the test (mg/L).

6.4.1.3 Types III and IV sedimentation (Crittenden et al., 2012; Davis, 2010)

When water contains high concentration of particles (more than 1,000 mg/L), both type III settling (occurs in lime-softening sedimentation) and type IV settling will happen alongside with discrete and flocculants settling. The solids flux in a sedimentation basin or solids thickener describing types III and IV settling is shown in Figure 2. It includes the downward particles movement from plain settling and the downward movement of particles due to water flow towards the underdrain, and is given by the expression:

$$J_T = J_s + J_u = (v_s + v_u) \times C \qquad (6)$$

where

J_T total solids flux toward the bottom of the basin, kg/m^2 · h

J_s solids flux due to particle settling, kg/m^2 · h

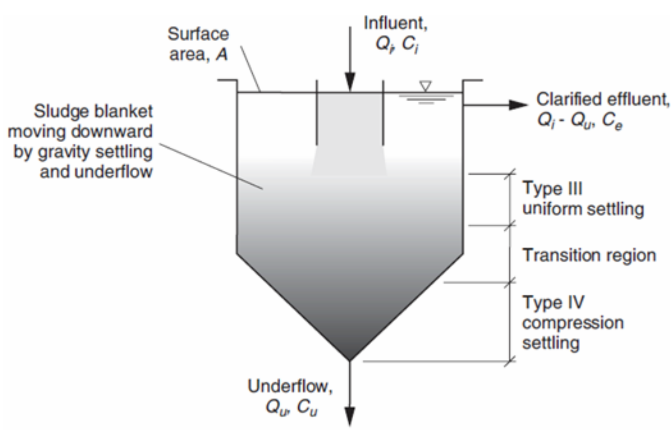
J_u solids flux due to fluid flow from the underflow, kg/m^2 · h

v_s settling velocity for particle concentration m/h

v_u bulk downward fluid velocity, m/h

C suspended solids concentration, kg/m^3.

Figure 2 The solids flux in a sedimentation basin



Source: Crittenden et al. (2012)

6.5 Dissolved air floatation

The presence of low density particles in water sources, for example: algae will result in problems during the sedimentation process. This is mainly due to their low density. An alternative to sedimentation process will be used, dissolved air floatation (DAF) which is considered as an effective separation technique to deal with such type of solids. This technique has been utilised successfully for the treatment of waters containing algae, waters having low turbidity, as well as highly coloured waters. In FAD, floc particles are allowed to move up to the water surface and finally form a solids layer named as float. The formed flocs have been produced when waters being treated have low settling velocity. The layer of floating materials is collected at the effluent of the tank, and then is expelled into a collection channel named a trough. The removal process of the collected floats can be either performed by a mechanical skimming apparatus or by solids overflow into the collection channel (Crittenden et al., 2012; Zabel, 1985, 1992).

Floatation can produce water of better quality than sedimentation, so, the solids portion of the produced sludge by floatation is higher than the solids portion of the sludge produced by sedimentation. Of the flotation advantages, one can list the following: it can be performed at high surface loadings (hence leading to the construction of small and shallow WTPs), can be initially operated with a stable water quality being obtained within a short period of time; 45 min (Zabel, 1985, 1992).

6.6 Filter scarping

The treatment process that incorporates the removal of solids particles from water by the passage of water that includes contaminating particles through a porous medium is termed as filtration. For the case of granular infiltration, the porous material is usually composed of a granular material, for example; sand. Rapid filtration, is the most commonly filtration method utilised in the water treatment train. Rapid filtration is usually used to describe a filtration rate of 50–100 times higher than that of the older filtration method or commonly known as slow sand filtration (Crittenden et al., 2012).

Amid the filtration process, water moves downward and percolating through the filter medium, hence solid particles are collected on the bed of the filter. The process of filtration continues typically for a period ranging from 1 to 4 days. To ensure effective infiltration, the water flow is to be maintained at a rate ranging from 0.1 to 0.3 m/hr. This flow will provide stability of nutrients and oxygen supply for the micro-organisms, and provides sufficient time for the water treatment process. Following half a month to a few of months of filter operation; the number of micro-organisms increases excessively and begins to fill in the filter pores. In the event that flow rates are very small, the filter must be decanted and the upper sand layer (20–30 mm) is scratched off, washed, left to fry in the sun, and put aside as a means of storage. After a few scrapings times, the washed and dried sand is added back to the filter, together with fresh sand, so that to compensate the lost sand when filter backwashing takes place. The sand can be scratched for a few filtration cycles, yet in the end it must be totally replaced. This procedure is usually known as re-sanding (Crittenden et al., 2012; Pizzi, 2011; Bruni and Spuhler, 2011).

6.7 Precipitation (softening) sludge

Softening process by using chemical precipitation utilises lime (CaO) and soda ash (Na_2CO_3). The aim of this softening process is to expel calcium and magnesium ions from the source water. Moreover, treatment by lime will add indistinguishable advantages of bactericidal activity, evacuation of iron and help in the removal of turbidity from surface water sources. The chemical precipitation process that aims to remove calcium carbonate and magnesium hydroxide from water is known as lime-soda softening and will formulate a precipitate named lime sludge. Lime sludge might be basically a chemically pure sludge or it may contain suspended solids from the source water if turbidity removal is joined with softening. Similar sludge will be obtained when magnesium carbonate softening process takes place (Crittenden et al., 2012; Hammer and Hammer, 2008).

6.7.1 Estimating quantities of lime (softening) sludge

The typically adopted amounts of the sludge resulting from the water softening process are presented in Table 2. The quantity of sludge that may be produced from a certain softening process can be obtained based upon the chemical treatment used and the quality of the water being treated. The obtained amounts of sludge can be used for design purposes. The composition of sludge mainly contains the calcium carbonate being precipitated, magnesium hydroxide, turbidity or colloidal solids that have been settled during the softening process. Any insoluble materials already exist in the water treatment chemicals will also be precipitated (lime grit is an example of such materials). Turbidity can be correlated to suspended solids, and hence the expected contribution of suspended solids to the sludge quantity can be also estimated (Crittenden et al., 2012).

The quantities of calcium carbonate and magnesium hydroxide being precipitated can be calculated from the anticipated calcium and magnesium removals. The total amount of lime sludge can be calculated from:

$$M_{total} = \left[\left(2.0\text{Ca}^{2+} + 2.58\text{Mg}^{2+}\right) + \text{TSS} + \text{X}\right]\left(10^{-3}\ \text{kg/g}\right). \quad (7)$$

where

M_{total} total amount of produced sludge, kg/m^3

Ca^{2+} calcium removed, g/m^3 as $CaCO_3$

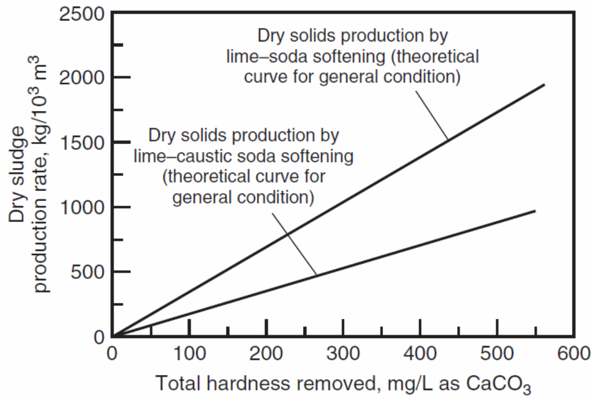
Mg^{2+} magnesium removed, g/m^3 as $CaCO_3$

TSS total suspended solids concentration, g/m^3

X coagulant aids used to improve the precipitation, g/m^3.

It can now be recognised that, to remove 1.0 mg of calcium (expressed as $CaCO_3$) will result in the formation of 2.0 mg sludge of $CaCO_3$. By the same convention, to remove 1.0 mg of magnesium (expressed as $CaCO_3$) one can expect the formation of 2.58 mg of sludge [$CaCO_3$ + $Mg(OH)_2$]. The amount of sludge produced as a function of the total hardness removed can be estimated graphically as shown in Figure 3.

Figure 3 Sludge production rate vs. hardness removed



Source: Crittenden et al. (2012)

Table 5 Spent sorbents solids management methods

Sorbent	*Reuse or disposal method*
GAC	Spent GAC can only be reactivated in WT applications once the quantities used are >150,000 kg/yr. If the used quantity is <150,000 kg/yr, the spent amount is transferred to a central reactivation facility. The reactivated GAC can be applied in industrial wastewater treatment plants, and cannot be utilised for the purpose of drinking water treatment. If the quantity of the available reactivated GAC > the required amount, the extra quantity is transferred to a sanitary landfill for disposal.
PAC	The coagulation sludge will contain PAC. This type of spent sorbent solids cannot be reactivated again, therefore, it is disposed of with sludge.
Ion exchange resins, mixed bed resins	Once the operational life of resins has been finished, the optimum option for their disposal is transfer to a sanitary solid waste or hazardous waste landfill. Other option is to transfer them to a suitable processing facility. Based upon the resins used, certain types of them can be eradicated via pyrolysis or incineration.
AA	If sorbents lose a great of their ability to adsorb and become unable to be reactivated efficiently, they have to be transferred to a sanitary municipal or hazardous waste landfills or hazardous waste processing facilities. The final destination of such spent depends on the composition of the sorbed and local laws.
GFO, GFH	If sorbents become unable to be reactivated efficiently, they have to be transferred to a sanitary municipal or hazardous waste landfills or hazardous waste processing facilities. The final destination of such spent depends on the composition of the sorbed and local laws.

Source: Crittenden et al. (2012)

6.8 Spent sorbents solids

The spent sorbent solids may include the following constituents: granular activated carbon (GAC), powdered activated carbon (PAC), ion exchange resins, blended bed resins, activated alumina (AA), granular ferric oxide (GFO), and granular ferric hydroxide (GFH). Except the activated carbon, the majority of the solid sorbents including AA and GFH are utilised one time only. Likewise the granular activated carbon, recovery of these sorbents is only of economic benefit for large treatment units. The most widely recognised reuse and disposal process for the spent solid sorbents are shown in Table 5. On the off chance that the spent solid sorbent can successfully pass the toxicity characteristic leaching procedure (TCLP) test, ordinary landfilling in a sanitary landfill is the most financially savvy strategy for disposal. If it is not the case, the solid sorbents must be discarded of in a hazardous waste disposal site (Crittenden et al., 2012).

7 Need of sludge management in WTP

The method that describe the water treatment solids disposal and reuse infrastructures, their operation, design and planning of are usually referred to as sludge management. Technically, the main aim of sludge management is to reduce its amounts; especially that to be disposed of. Sludge has to be handled, transferred and finally disposed in conformity with the guidelines put by the responsible agencies. Reduction of the water content of the sludge and increasing the solids content is also an important objective of the sludge management process (Anjithan, 2016; Crittenden et al., 2012).

Sludge management will have a significant effect on the design and the activity of numerous WTPs. For the already operating WTPs, solids management systems may inhibit the whole plant capacity if its design and operation conditions were not appropriate. As often as possible, sludge is temporarily put aside before sending for treatment, reuse, as well as transfer for disposal. Sludge expulsion and management must be controlled and performed according to the designed sludge management system to ensure a reasonable water quality.

Historically, WTP sludge used to be discharged into the nearest water courses or sewer systems with little or no treatment. Now, this sludge cannot be disposed of in sanitary sewers as this would have many adverse effects. Moreover, due to stringent effluent discharge standards, it can’t be disposed of into the natural water bodies. Recently, the sludge is usually dumped into a lagoon system located at and around the plants (Anjithan, 2016; Dharmappa et al., 1997; USEPA, 2011).

In general, the expense of transporting and final disposal of sludge compromises the largest portion of sludge management expenses, therefore, the most feasible option in sludge management is to minimise its quantity being finally disposed. Different options incorporate reducing the environmental effects and complying disposal regulations established by responsible agencies. Hence, it is worth to investigate appropriate choices for developing sustainable sludge management strategies under strict environmental standards (Ahmad et al., 2016; Crittenden et al., 2012).

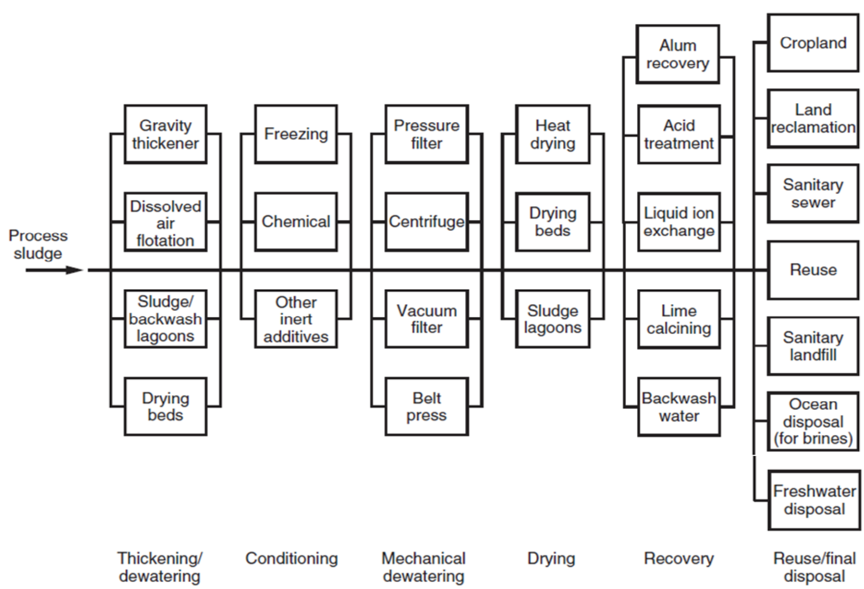
8 Sludge treatment and management methods

The essential step in water treatment sludge processing is the decline in its moisture content. Being this step is not achieved, it would be troublesome and extensively unfeasible to deal with and treat the sludge. The techniques and expenses for dealing with treatment, transfer and final disposal of sludge are affected by the quantity and properties of the sludge. Therefore, development of a complete sludge process treatment train for a certain type of sludge needs a good knowledge of the suitable and available techniques for processing that type of sludge. The amount and properties of the sludge are influenced by the source water quality and the chemical reagents utilised in the treatment process. Despite still being little to be done for changing the quality of the source water, it is still possible in some occasions to alter the water treatment technique. This alteration will be in the favour of reducing the amount of the produced sludge. The decrease in the sludge amount will result in reducing the plant operational costs (Anjithan, 2016; Crittenden et al., 2012). In order to achieve economic management of the sludge, it is important to reduce the quantity of sludge by increasing the solids concentration. This can be achieved by an appropriate treatment method. The sludge treatment and disposal system can be broadly classified into the following categories:

- thickening
- conditioning (chemical, physical)
- dewatering (non-mechanical, mechanical)
- solids minimisation
- solids recovery
- final disposal/landfilling.

A general process chart demonstrating the different methods and techniques used in in sludge management and the order in which they may be arranged and grouped to formulate a comprehensive treatment system is outlined in Figure 4.

Figure 4 Unit operations and processes for management of WTP sludge



Source: Crittenden et al. (2012)

To formulate an integral sludge management system, it is required to utilise one-unit process or more of the steps shown in Figure 4; for example, thickening/dewatering and conditioning. Any sludge management system must also contain a unit process from the final reuse and/or disposal step (Anjithan, 2016; Crittenden et al., 2012; Dharmappa et al., 1997). The following subsections will present the main unit operations and processes utilised for sludge management.

8.1 Collection processes

By sludge collection processes, we consider the methods utilised to collect or gather the sludge expelled from the water in the treatment plants. During the water treatment, sludge is expelled by a variety of methods. Screens existing at the WTPs inlet capture the large segments of debris (normally >1 in) from the water to be treated. Grit basins collect the coarsest, heaviest substances from the source water preceding the process of pre-sedimentation. Pre-sedimentation tanks collect the heavier particles that do not need coagulation and flocculation for solids separation. Sedimentation tanks encourage settling by gravity for solids particles to the bottom of a water column where the collected solids are then evacuated. There are many techniques can be utilised in the sedimentation process, such as chain and flight, suction, and circular collector units. In the conventional treatment plant, filtration is commonly the last step used for suspended solids removal from water. Solids are expelled by a bed of granular media (sand, anthracite and/or garnet) by the means of straining, impingement, gravitational settling, or adsorption. Backwash procedures are adopted in filter reactivation, and solids can also be expelled during this process (USEPA, 1996).

8.2 Thickening

Thickening is a well-established technique, utilised to minimise the sludge volume and to enhance its dewatering characteristics via sludge densification at the bottom of thickener. The main goal of thickening is to maximise solids portion of the sludge by settling and expelling a part of the water by decanting. Thickening will produce sludge with a solids concentration <10%. Such a sludge is still pumpable by conventional means and has most of the characteristics of liquid. Sludge thickening process can take many trains, however, the final result is the removal of a portion of the influent water and to increase the solids concentration resource recovery. Having higher solids content in the subsequent treatment phases will benefit by lowering capital and operating expenses of the treatment process. The main process utilised for coagulation or softening sludge is the sludge compaction. Coagulation sludge can be thickened by gravity, and will result in solids content of 2–10%. Sludge formed due to lime-softening, can be thickened and result in 2–30% solids (AWWA, 1981; Westerhoff and Cline, 1980; Dharmappa et al., 1997; USEPA, 2011).

Although thickening can lower the costs for sludge transfer, it is indicated in literature that most WTPs dedicate less efforts to reduce sludge quantities. Thickening happens firstly by gravity settling and is enhanced by the compression applied on sludge (Anjithan, 2016).

8.3 Conditioning

Conditioning is a process joint into many sludge handling systems to enhance the adequacy of the dewatering process. Conditioning of WTP sludge is commonly performed by either chemical or physical conditioning (USEPA, 1996).

8.3.1 Chemical conditioning

Chemical conditioning of sludge can be attained by a reasonable utilisation of organic polyelectrolytes, inorganic chemicals, and acidification. This process is incorporated in the majority of mechanical thickening or dewatering processes. It involves the application of ferric chloride, lime, or polymer. Chemical conditioner type and dose vary greatly depending on the source water quality, coagulants used, pretreatment, required solids concentration, and thickening/dewatering technique being applied.

Polymers with different specifications are currently obtainable for use in the dewatering processes. Anionic polymers (hydrolysed polyacrylamides) have proved to be very efficient conditioning agents for coagulating sludge before dewatering by gravity of suction.

Ferric chloride, lime or fly ash is perhaps appropriate for specific sludge conditioning process. The utilisation of chemicals, independently or in combination, should be assessed for a specific type of sludge. Chemical providers are required to provide the chemical's rating adopted by National Sanitation Foundation (NSF[1]) if the by-product water of the process is planned to be returned to the treatment plant stream. Another effective conditioning technique, especially with the recovery of alum is the acidification of sludge. The sludge that is being acidified must be neutralised before its final disposal (Anjithan, 2016; USEPA, 1996).

8.3.2 Physical conditioning

To optimise the effectiveness of thickening/dewatering, many physical conditioning processes can be utilised. These processes include:

- Pre-coat or non-reactive added substances: some dewatering systems, mainly vacuum filtration and pressure filters, utilise a pre-coat added substance in the process, commonly diatomaceous earth.
- Freeze-thaw conditioning: this process can be complemented by an open-air process in chilly climates or through mechanical equipment.
- Thermal conditioning at high temperatures (175°C to 205°C) and high pressure (1.72 to 2.75 MPa): This process is very efficient when the organic content in the sludge is at high portions (USEPA, 1996; Cornwall and Koppers, 1990).

8.4 Non-mechanical dewatering

After the collection and thickening steps, the sludge can be additionally concentrated or dewatered by disposal in conjunction with sewage sludge or by mechanical or non-mechanical dewatering techniques. This step is performed for extra volume lowering and more solids content. Dewatering of sludge is a very important process in sludge disposal, as well as it is essential for the efficient decrease of the overall processing expenses. Examples of non-mechanical dewatering techniques are; lagooning, drying on sand beds, natural or artificial freezing and thawing (Anjithan, 2016; USEPA, 2011; Wei et al., 2018).

8.4.1 Lagooning

WTPs can gather and keep treatment sludge in settling ponds, tanks, or lagoons to isolate solids from water. What's more, lagoons and ponds can also be used as long-term waste disposal that need cyclic emptying, cleaning, and maintenance. The utilisation of lagoons, ponds, and settling basins is considered as a non-mechanical dewatering process, this is due to the fact that the isolation of solids happens only by physical processes. Lagooning is the cheapest but may be the least efficient method for alum sludge, it usually results in 5% solids. Utilisation of this technique relies upon the availability of land, rates of evaporation, and groundwater pollution concerns. Lagoons can also work as a flow balance, solids isolator, sludge thickener, and sludge storage zone. Lagoons generally provide adequate surface area and volume for treatment. They are usually equipped with under drain channels and decant facilities for sludge water expelling (Anjithan, 2016; USEPA, 2011).

Lagoons design guidelines and rules can vary according to every specific plant circumstances, according to the liquid being received. In most cases, a minimum of two lagoons are needed. Liquid can be discharged by an under drain channel or through an overflow. The lagoon may be operated in a fill-and-draw mode or in a continuous pattern. Recovered water can be reused again and back-flow to the treatment plant. Sludge may be expelled by earth-moving device after it has been drained. Sludge can be withdrawn without draining by means of hydraulic equipment. It should be noted that once the alum sludge is settled; it is not well pumpable even when it is wet (Anjithan, 2016; AWWA, 1981).

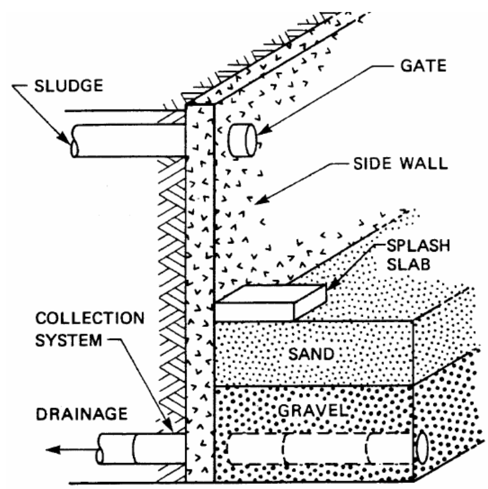
8.4.2 Sand drying beds

The sand drying beds are historically the first method of dewatering the sludge from various sources and have been widely used in many countries. The sand drying bed is an improvement over the sludge lagoon, that provides an economical method of producing a dry sludge cake, and have the added advantage of requiring little mechanical equipment, little operator skill or attention, and are less sensitive to influent solids concentration. In spite of these advantages, this type of sludge dewatering has been yielding ground to mechanical processes for a variety of reasons, mainly due to the requirement of large area of land and high capital costs. Thus any study aimed at reducing the land area requirement by sand drying beds will be useful. By drying, a more sludge concentration will be obtained, which results in almost solid material with 30–60% solids concentration (Dharmappa et al., 1997). Sand drying beds are usually utilised to dewater the sludge of coagulation process, and it may be used – to a less extent – to dewater the sludge produced from lime softening process. Utilisation of sand drying beds is an effective method to dewater a sludge mixture resulted from both the coagulation and softening processes (Anjithan, 2016).

One of the most important factors affecting the sand drying beds is precipitation. In rainy seasons and cold regions, one may expect a bad dewatering efficiency of the sludge. On the occasion of unavailability of suitable mechanical equipment, the sludge from drying beds can be manually removed after being dewatered. The manual removal of dewatered sludge is unfeasible due to the difficulty of sludge removal in some cases and the large labour effort required (Anjithan, 2016). The entrance of sludge in the sand pores, especially at the first time of sludge application, is an obstacle that renders the sand layer to be replaced frequently. Sludge entrance to the sand can be prevented by raising the rate of gravity drainage and improving the evaporation; this can be accomplished by polymer conditioning. The prevention of cake crust formation can also be another advantage (AWWA, 1981).

The sand drying bed is composed of a sand layer (15–30 cm) of size up to 0.5 mm, which is being placed above graded gravel and drainage pipes, as shown in Figure 5. Sludge is layered in 12 to 24 in layers and left to drain water. The beds can be covered or uncovered (Anjithan, 2016; Faber, 1969). Design and operation parameters of the sand drying beds are: sludge application depth, polymer type, polymer dose, media depth, media size, number of applications, application frequency, and mixing conditions (Dharmappa et al., 1997).

Figure 5 Cross section in sand drying bed



Source: USEPA (1996)

8.4.3 *Freezing and thawing*

Freezing and thawing process usually includes two 45 minutes freezing cycles and one 45 minutes thawing cycle. Sludge is put on the bed in repetitive layers to enhance the freezing. Due to the cycles of freezing and then thawing, the sludge become more compacted, more granular, and easy to dewater. WTPs utilise this process to dewater alum sludge that has a gelatinous nature. This gelatinous nature makes it hard to dewater in the lack of the freezing step. Changing the properties of sludge and forming small granular particles that settle easily can be achieved by the freezing and thawing technique. At the end of the process, the volume of the sludge can be lowered to 1/6 of the original volume. It has been recognised in literature that freezing and thawing has no specific advantage for the sludge produced during lime-softening. The capital and running expenses of freezing and thawing are generally high. When the land is available, coupled with the cold climate conditions, natural freezing is economic to dewater coagulation sludge. A storage facility of adequate volume to keep the sludge accumulated in the non-freezing periods is needed (Anjithan, 2016; USEPA, 2011).

8.5 Mechanical dewatering

Mechanical dewatering has offered itself a part solution to the problem of WTP sludge disposal. It is essential to lower the sludge volume prior to any treatment or disposal option. It is worth to mention that, direct mechanical dewatering of sludge with no pretreatment cannot accomplish the perfect dewatering result (Dharmappa et al., 1997; Wei et al., 2018).

The mechanical dewatering processes, while advantageous in some respects, have some inherent disadvantages, such as, high maintenance costs, energy requirements, need for greater operator skills and attention, and lastly low cake solids concentration. Thus drying process would normally follow the mechanical dewatering in most of the cases. Dewatering results in a sludge with a solids concentration between 10–30% and this sludge generally behaves as a semi-solid material (Dharmappa et al., 1997).

Common mechanical dewatering technologies that are utilised to dewater WTP sludge are centrifugation, vacuum filtration, and pressure filtration. Belt filtration and dual cell gravity solids concentrators have been installed to a lesser degree. Pellet flocculation is moderately new and is utilised less regularly to dewater sludge. Pre-conditioning is usually needed in almost all mechanical dewatering systems (Anjithan, 2016; USEPA, 2011). The performance of the dewatering process is measured by the kilograms of dry solids filtered per hour per square metre of the filter area, and also by the percent dry solids in the filter cake (Reynolds and Richards, 1996).

8.5.1 Centrifugation

Centrifugal separators utilise centrifugal force to remove suspended solids from water. The force applied to the sludge relies upon the rotational speed of the centrifuge. The efficiency of the separation process is a function of the applied force and the time of the centrifuging. The operational obstacles and power expenses get higher as the centrifuges become more industrialised and larger in size. Centrifuges perform better in the case of the application of a conditioning agent, thus they are always operated with the application of a polymer to the sludge before dewatering (USEPA, 2011).

The concentration of solids put in the centrifuge usually ranges from 2–6%, however a successful dewatering process of alum sludge being fed to the centrifuge with a concentration of 0.4–1.0% has been reported (Westerhoff and Cline, 1980). The predicted cake dryness is influenced by the centrifugal force, feed rate, polymer dosage rate, source water quality, density and size of floc and retention time. The expelled water may be recycled again to the plant or discarded in a suitable manner (Anjithan, 2016).

8.5.2 Vacuum filtration

A negative (suction) pressure is applied in this system, thus promoting the percolation of water into the filter bed, and hence the drying process is speeded up. The mostly used type in the mechanical dewatering systems is the rotary vacuum filter. This process utilises a rotating drum with a cloth or a stretched medium along the surface as shown in

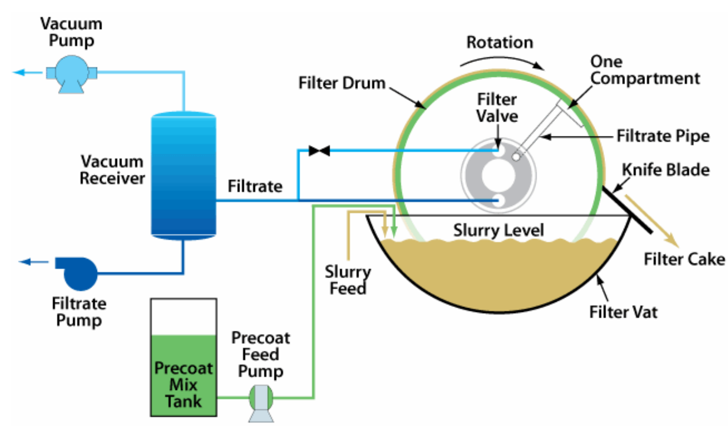
Figure 6. The media used in the filter may be a moving cloth or a pre-coated filter drum. The choice of a suitable filter media is a key factor in determining the efficiency of the process. The pressure in the tank where sludge is placed for dewatering is negative (vacuum), therefore the drum will be also under vacuum.

The pre-coated filter drum revolves gently (5–12 rpm), the permeability of the deposited cake and the grade of pre-coat medium affecting the drum revolving rate. The average pre-coat layer of 5–7.5 cm is applied and its peeling is allowed in a very small increments. The time required for the pre-coating a vacuum filter is about 50–60 minutes. Three main phases are usually encountered in the vacuum filtration process, they are: cake forming, cake drying, and cake discharging.

When studying the vacuum filter performance, it is important to investigate the distribution of floc size. The sludge cake will be formed at the external surface of the medium, it will be scraped later on, and finally it will be disposed of (Anjithan, 2016; USEPA, 2011; Reynolds and Richards, 1996).

There is a limit for the success of the vacuum filtration when utilised for sludge resulting from the coagulation process. If the source water has a turbidity ranging from 4 to 10 NTU, the alum sludge dewatering will be a hard task. Vacuum filters registered success when they are utilised for dewatering the sludge resulting from lime softening process. Dewatering of lime sludge by vacuum filter will produce cake solids of final concentrations ranging from 45–65% SS, and the produced filtrate is of acceptable quality (Anjithan, 2016).

Figure 6 Rotary vacuum drum type filter (see online version for colours)



Source: Komline-Sanderson (2018)

8.5.3 Pressure filtration

In pressure filtration technique, a high pressure is applied to a solid/liquid suspension and obliges the water out while keeping solids. The pressure filter is mainly composed of many porous filter plates including depressions, kept vertically in a supporting frame. The face of every plate is coated with a suitable filter cloth enabling water seep while keeping the solids. The plates may contain a common feed hole or many holes for the sludge entrance. When the pressure is applied mechanically or hydraulically, the sludge is pumped into the filter through the feed holes to the chambers located between the plates.

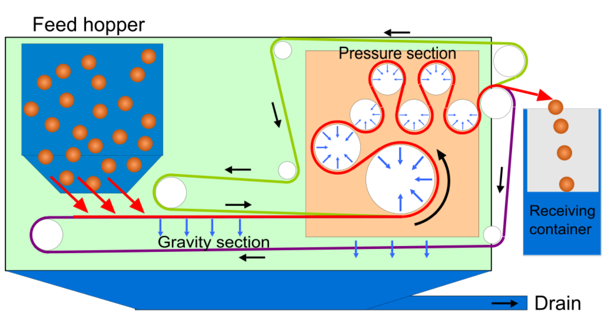
The liquid then passes through the filter medium, leaving the solids in the area between the plates. With continuous pumping, sludge cakes are formed and ultimately fill the chamber. The process will continue to the point when the pressure drop across the filter equals the pumping pressure, at this stage the unit is shut down. After the filtration process, the plates are isolated and the dewatered solids fall directly to a discharge conveyance. When the filter is out of service, it can be cleaned manually and returned again to operation (Anjithan, 2016; USEPA, 2011).

8.5.4 Belt filtration

Belt filter utilises pressure to oblige water out of the sludge through the porous belt while keeping the solids on the belt. It is composed of two infinite filtration fabric belts kept in tight contact with each other by parallel rollers. The belt located below is made of coarse mesh fabric media and usually composed of twisted metal, plastic, or mixed fibres, while that located above is solid (Anjithan, 2016; USEPA, 2011).

Figure 7 shows a schematic diagram design of a belt filter. Sludge to be treated is put in the feed hopper and drained in the free drainage zone. The remaining solids/water are sandwiched between the two porous belts and travelled over/under a series of various diameter rollers. The different rollers produce low and high pressure on the belts, resulting in extra water squeezing from the solids. The extended belt travel will result in a drier filter cake. Belt filtration is suitable for softening sludge, due to its granular structure which can bear high pressure. Plants using this process reported a lime filter cake of solids content of 50–60% (Campbell, 2018; USEPA, 2011).

Figure 7 Schematic diagram of the belt filter (see online version for colours)



Source: Campbell (2018)

8.5.5 Pellet flocculation

Pellet flocculation is a technique that has been advanced in Japan, where a few plants utilised it. It is a specific kind of flocculation through which the macroscopic energy exerted from outside the system obliges the liquid out of a solid, which gradually turns into compact. The system is flocculated by addition of a synthetic organic matter or a second liquid, then mechanical or macroscopic energy is applied from outside the system. The pellet flocs are compact and have various preferable characteristics not exist in ordinary flocs; they can settle rapidly and are effectively isolated and decanted from water (Lin and Green, 1987; Yusa et al., 1975).

In the case that the pressure distribution surrounding the floc is equal, the pressure will be the same within the liquid, and the floc will not be removed. However, if the pressure distribution is uneven, and the solids cohere to each other strongly so they resist the applied pressure, the liquid is exuded at points where the external forces are weak; then the floc will be compact. Two methods are accomplished for the formation of floc: rolling the floc along a plane or bended surface, and to impose the collision of flocs with each other or with a plane or the bended surface (Yusa et al., 1975).

The system is mainly composed of a gently rotating horizontal drum and a three parts divided reactor. The first part of the reactor receives the conditioned sludge, where the rotating action enhances the formation of sludge pellets. The liquid is then drained off in the nest part. The sludge is compacted and then dehydrated by the effects of both piling up and rotation in the third part. The pellet flocculation technique is a continuous dewatering operation, and the low rotating speed of the pellet flocculation results in a lower operational and maintenance expenses (Lin and Green, 1987).

8.6 Thermal drying

This technique is not widely utilised due to its high cost; which is estimated to be more than the savings that could be achieved from the reduced volumes of sludge. Water treatment plants generally utilise this method to achieve solids-water separation and to overcome the problems of pathogens control, odour problems, and storage problems. Thermal drying technology includes direct fired systems (rotary kiln, fluidised bed, low temperature desorption), indirect fired systems (heated coils), and infrared radiation (USEPA, 2011).

8.7 Solids minimisation

As the population grows up, stricter potable water standards and regulations will be imposed; hence, more WT sludge generation is expected to be produced and will continue to increase. On the hierarchy of waste management sludge minimisation is at the top of the pyramid, followed by selecting beneficial sludge reuse options. This will become essential since environmental and economic pressures have limited sludge disposal options (Ippolito et al., 2011). The amount of the generated sludge can be reduced by removing water and hence reducing the sludge volume, minimising the solids content of the sludge or combination of both. Techniques used to minimise the produced sludge include: reducing the amount of applied chemical dosages (alum or lime), water direct filtration, filter wash water recycling, substitution of coagulant and softening material, and chemical recovery (AWWA, 1981; Westerhoff and Cline, 1980).

8.8 Chemical recovery of sludge

Chemical recovery of sludge is actually attainable for the recovery of alum, iron, and magnesium carbonate and for the re-calcination of softening sludge. For each situation; the treated water quality, side stream discharge, and gases emitted should be considered. Chemical recovery from WTP sludge can give the advantages of the recoverable chemicals themselves, reduce the quantity of the produced sludge, reduce the expenses of disposing of sludge, and/or improve the sludge treatment process (Anjithan, 2016).

8.8.1 Alum recovery

Aluminium and iron solubility diagrams outline that these species will reach their smallest solubility at pH value from 6 to 8. Since this range pf pH is the common running condition for almost all WTPs, the majority of the insoluble coagulants utilised are predicted to present in the precipitated sludge, hence it can be recovered. From the solubility diagrams of the previously mentioned metals, it can be recognised that the solubility will be increased in acidic environments, i.e., when the pH is below 6 (Tchobanoglus et al., 2003; USEPA, 2011). Acid extraction is the most common concept utilised for the recovery of alum, during which alum is converted to a soluble form then is decanted and finally recycled. When adding sulphuric acid to the thickened sludge; aluminium hydroxide will rapidly react with the sulphuric acid, resulting in the formation of aluminium sulphate (alum) solution. At a pH value of 3, it has been reported that the rate of alum recovery ranges from 60–80% (USEPA, 2011; Fulton, 1976).

8.8.2 Re-calcining (lime recovery)

Re-calcination of lime is an old technique practiced at water treatment plants. The technique incorporates the softening sludge combustion at high temperature reaching about 1,010°C. This technique is indicated in the following chemical reaction (AWWA, 1981):

$$CaCO_3 \xrightarrow{\text{heat}(1,700-2,000°F)} CaO + CO_2 \quad (8)$$

The technique incorporates sludge thickening from original solids concentration of 3–10% to finally reach a solids concentration of 18–30%. Re-calcination is also successful in recovering higher amounts of lime than amounts that has been utilised in softening process, while lowering the weight of sludge to reach 20% of the original value. Simultaneously, the emitted carbon dioxide during the re-calcining can also be utilised for the of re-carbonation process (Westerhoff and Cline, 1980).

The lime that has been recovered can be utilised to adjust the pH of the soil, or it can be reused at the water treatment plants. It is worth to mention that light metal hydroxides including $Mg(OH)_2$, $Fe(OH)_2$, $Fe(OH)_3$ and $Al(OH)_3$ are unfortunate compounds in the re-calcining process of lime. Additionally, the high expenses of fresh lime alongside that of the energy required renders the re-calcining process excessively costly, making it hard to embrace (Anjithan, 2016).

8.8.3 Magnesium recovery

On the occasion of utilising magnesium carbonate ($MgCO_3.3H_2O$) as a coagulant in water treatment, the pH reaches about 11 and magnesium hydroxide ($Mg(OH)_2$) is precipitated. The formed precipitate is then carbonated to alter $Mg(OH)_2$ to a soluble form as magnesium bicarbonate $Mg(HCO_3)_2$, then a thickener is utilised to isolate $Mg(HCO_3)_2$. The solid part is sent for disposal, while the magnesium existed in the water filtrate is recycled back to the flocculation tank for reuse. The release of carbon dioxide during re-calcination encourages the use of magnesium carbonate as a coagulant in conjunction with the re-calcination of lime (Anjithan, 2016).

8.9 Sludge recycling options

Sludge is considered as a simple type of waste as appeared, it is an inexpensive by-product of water treatment process and that can be utilised to obtain an extra revenue source. Once the sludge treatment process is completed, it can also be bought by farmers and applied as a fertiliser as well as soil conditioner. Sludge with a plenty of phosphorus and nitrogen is an ideal means for the recovery of nutrients. These nutrients can also be obtained from the returned liquid sludge and combusted sludge ash. Due to the depletion phosphorus mine, its restoration from water treatment sludge has become more charming option. Sludge and sludge ash can likely be utilised as a crude material when manufacturing the construction products, for example; cement, mine filler and building bricks. The fundamental advantage in this regard is the capability to lower the disposal expenses while displaying an environmental friend concept for sludge management to the general society (Anjithan, 2016).

Reuse of WT sludge is a sustainable end point solution and it is a favoured option to disposal. Depending on the properties and strength of the produced water treatment sludge, more than eleven reuse options were globally specified and are categorised into three main groups. A short detailing of each will be presented in the next sections.

8.9.1 Use WT sludge in wastewater treatment process

WT solids, specifically alum, have been utilised to improve the wastewater treatment process performance. Such utilisation aims to raise the plant efficiency, to improve sludge conditioning and to promote the phosphorous removal when treating wastewater. Sludge can be utilised in wastewater treatment process as follows:

- recovery and reuse of coagulants
- enhancing the coagulation process itself
- absorbing pollutants and metals
- combined conditioning and dewatering with sewage sludge
- constructed wetland substrate (Anjithan, 2016; Lai and Liu, 2004).

8.9.2 Use water treatment sludge as building and construction materials

Even though the water treatment sludge has been preliminary investigated and utilised as building and construction materials, its use is still admitted. Efforts made so far for using water treatment sludge into the construction are as follows:

- brick manufacturing
- hollow block manufacturing
- geotechnical and pavement applications
- manufacture of cement and cementious materials (Anjithan, 2016).

8.9.3 Use water treatment sludge in land application

Next to the solids separation process from water and the recovery of the usable portion of them, sludge can basically be managed by land application or it is transported to landfills for disposal. Land application of WT sludge is referred to the process of the managed utilisation of the solids or their spreading on the upper layer of the soil. The benefits can be gained from sludge land application are the stabilisation, the degradation and immobilisation of the solids components. The crops being implanted, the soil chemistry and sludge characteristics; affect the utilisation of sludge onto the soil. It was reported that, sludge resulting from the lime softening can be the most eminent sludge for land application. This type of sludge is suitable as a substitute for agricultural limestone. Right now, land application of water treatment sludge is getting more considerations, since it is considered as a suitable option other than disposal. It is worth to mention that sludge land application is presumably relied on the physical, chemical and biological characteristics of soils. In normal operating conditions, soil will imbibe the applied sludge without unfavourable impacts on its quality and with the possibility of improving its quality (Basta, 2000; Elliott and Dempsey, 1991; Roy and Couillard, 1998; USEPA, 2011).

When compared with landfilling, land application is more advantageous despite requiring a large area of land; this is due to the lower expenses and no need for regulatory declarations. Throughout the years, the aims of land applications are typically to: dispose water treatment sludge, enhance or improve specific soil qualities and be utilised as a growing environment for plants (Anjithan, 2016).

Land application may have some limitations depending on the characteristics of the sludge. Land application may conclude the increase of metals' content in soil and probably contaminate the groundwater. In the case of coagulation sludge application, the adsorption of phosphorus from the soil to the applied sludge will occur, resulting in possible harmful impacts on the soil and the planted crop. Regarding the disposal of water treatment sludge, probable toxicity to the nearby environment is of a major interest for both public community and the environmental agencies. Thus, when utilised in land applications, soil conditions, plant growth and nutrient uptake, and anionic species should be closely monitored (Anjithan, 2016; Ippolito et al., 2011; USEPA, 2011).

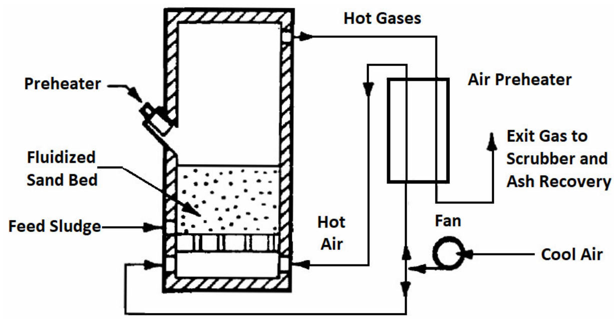
8.10 Incineration

Incineration of water treatment sludge includes the dry combustion of solids to form non-reactive ash that is usually disposed of in landfills. The amount of fuel required relies on the fuel heat content and the solids moisture content. Two types of incinerators are used for this purpose; the multiple heart type and the fluidised bed incinerators.

The multiple heart incinerator consists of a heart type furnace, in which the dewatered sludge is fed to the first heart at the top. In the incinerator, sludge moves downward by the raking action of the rabble arms. In the upper heart, the water content is vaporised and the sludge is dried at a temperature ranging from 480°C to 650°C. In the middle heart, the sludge is ignited and burned at a temperature of 650°C to 815°C, while in the lower heart, the slow burning material is burnt and the ash undergoes cooling at a temperature of 315°C. The ash that is produced leaves from the bottom of the incinerator. The efficiency of the multiple heart furnaces incinerator is about 55%.

The fluidised bed incinerator consists of a combustion reactor containing a bed of sand above a grid as shown in Figure 8. To start the incineration, a preheater is ignited and the fluidising air is passed upward through the bed to suspend the sand. Once the sand temperature reached about 760°C to 815°C, the sludge feed to the incinerator began. The water is vaporised, and sludge solids are burned in the fluidised sand bed. The ash created is carried from the reactor by the exit combustion gases and is subsequently removed by a cyclone or a scrubber (Reynolds and Richards, 1996).

Figure 8 Fluidised bed incinerator



Source: Reynolds and Richards (1996)

8.11 Final disposal/landfilling

Sanitary landfilling, requiring a dewatered sludge of 20–40% solids content, is considered as the most acceptable method for sludge disposal. Landfills for sludge disposal can be mono-fills (containing one type of waste) or municipal sanitary landfills (containing various types of waste). Disposal expenses are estimated according to the mass of the sludge being presented for disposal, and it will also vary according to the distance from the treatment plant and the landfill (Dharmappa et al., 1997; USEPA, 2011). Several alternatives are available for the disposal of WTP sludge. The selection of any available option should be done with respect to economic and regulatory considerations. Sludge type and characteristics are of great importance, and should be considered when the disposal alternatives are being developed (Anjithan, 2016).

8.12 Comparison between sludge treatment and management methods

In the previous sections, the different techniques and methods used for sludge management and treatment were covered. The selection and adoption of a certain technology for sludge treatment and management within a water treatment plant is dependent on many factors including: cost of reuse versus disposal, equipment, energy needs, land area, equipment, operation and maintenance cost, scale, type of sludge, environmental considerations, local regulations and standards, required degree of treatment, final destination of sludge and other factors. The final selection of a certain technology should take these factors in consideration. Table 6 outlines a comparison between the requirements of sludge treatment and management methods.

Table 6 Comparison between the requirements of sludge treatment and management methods

Treatment method	*Cost*	*Energy needs*	*Land area*	*Advanced equipment*	*Solids content*	*Technique*	*Skilled personnel*	*Scale/applicability*	*Need chemicals*
Thickening	Inexpensive, low operation cost	Low	Thickener or lagoon area is required (according to site conditions)	Not required	Typical: 2–10% Softening sludge: 15–30%	Settling and expelling water by decanting	Not required	Sludge pre-treatment, coagulation and lime softening sludge	Not required
Conditioning	High cost (chemicals, pressure and energy)	High, for thermal conditioning	-	Required	19–40%	Chemical, physical conditioning	Required	Required for all mechanical dewatering systems	Required for chemical conditioning
Lagooning	The cheapest and least efficient	Not required	Large surface area is required	Not required	5%	Physical, non-mechanical process	Not required	-	Not required
Sand drying beds	High capital cost	Not required	Large land area is required	Not required	30–60%	Physical, non-mechanical process.	Required (to some extent)	Coagulation and lime softening sludge treatment	Polymers are sometimes required
Centrifugation	Low cost	High power expenses for industrialised and larger centrifuges	Not required	-	Lime softening: 55–70% Coagulation sludge: 12–20%	Utilisation of centrifugal force to remove solids from water	Not required (easy to operate)	Alum sludge treatment	Polymers are used as conditioning agents
Freezing and thawing	High capital and running cost for artificial technique	High for artificial technique	Large land area is required for natural technique	Required for artificial technique	Up to 25%	Natural or artificial freezing and thawing cycles	Required (to some extent)	Coagulation (gelatinous consistency) sludge treatment	Chemicals are required for freezing
Vacuum filtration	-	High to produce the negative pressure	-	Required	45–65%	Negative pressure by rotary vacuum filter promotes water percolation into the filter bed	Required	Lime softening and coagulation sludge treatment	Not required
Pressure filtration	High maintenance cost	Energy is required for pressure application	Not required	-	30–35%	Positive pressure is applied mechanically or hydraulically to pump the sludge through filter holes	-	Limited applicability for lime softening sludge	Addition of lime, polymer or fly ash
Belt filtration	Low capital cost	-	Small space is required		Up to 20%	Utilisation of pressure to oblige water out of the sludge through the porous belt while keeping solids on the belt	-	coagulation sludge treatment	Not Required

Source: Anjithan (2016), AWWA (1981), Cornwall and Koppers (1990), Crittenden et al. (2012), Dharmappa et al. (1997), Lin and Green (1987), USEPA (1996, 2011), Westerhoff and Cline (1980) and Campbell (2018)

9 Conclusions

- Sludge management is a very important aspect that should be taken into account when designing and operating WTPs.
- As the world's population grows up, more WT sludge generation is expected to be produced and will continue to increase, therefore, adopting beneficial reuse options of sludge will become essential since environmental and economic pressures have limited sludge disposal options.
- Recognising the different characteristics of the sludge is a key element in selecting and designing the most suitable sludge management, treatment and disposal options.
- It is necessary to investigate the appropriate options for formulating long term sludge management plans under strict environmental regulations.
- Sludge management and disposal is a part and parcel of any water treatment system, and still face problems, gain opportunities and need improvements.
- Agricultural sludge application is an economical solution. However, this solution is acceptable only when the content of valuable substances is high and if the concentrations of hazardous substances are as low as possible.
- Sludge examination and testing should be continuous during the sludge management; to ensure a minimum level of adverse impacts associated to its reuse and disposal options.
- In WTP design, it is important to take into account the optimisation of treatment unit operations and processes as well as the sludge disposal and management.

10 Recommendations

- The sludge accumulated in water treatment process must be treated and disposed of in a safe and effective manner.
- Great emphasis is to be enforced to minimise the quantity of the produced sludge and to maximise its solids content.
- To achieve an effective disposal practice it is important to have data on the sludge generation process, quantities, properties, composition, disposal options and the legal requirements that are applicable of the plant.
- It is still required to conduct more studies to develop suitable sludge management plans for long term development under restrict environmental regulations.
- New water treatment plants should include provisions for sludge treatment, however, sludge should be characterised and well defined prior to constructing a treatment plant.
- In the case of sludge reuse in land applications (agricultural purposes), it is highly recommended to investigate the long term effects of sludge reuse.

- The environmental impacts of different of sludge disposal methods should be evaluated.
- Capacity building of WTPs' operators, municipalities' staff, governmental officials, and the public, must be utilised to overcome the obstacles hindering the widespread of WT sludge reuse and recovery.

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References

Ahmad, T., Ahmad, K. and Alam, M. (2016) 'Characterization of water treatment plant's sludge and its safe disposal options', *Procedia Environmental Sciences*, Vol. 35, pp.950–955.

Anjithan, K. (2016) *Management Practices of Water Treatment Sludge in Sri Lanka and Re-use Potential of Sludge Material*, Master, University of Moratuwa.

Anjum, M., Al-Makishah, N.H. and Barakat, M. (2016) 'Wastewater sludge stabilization using pre-treatment methods', *Process Safety and Environmental Protection*, Vol. 102, pp.615–632.

AWWA (1981) 'Lime softening sludge treatment and disposal', *Journal (American Water Works Association)*, Vol. 73, No. 11, pp.600–608.

Basta, N.T. (2000) 'Examples and case studies of beneficial reuse of municipal by-products', *Land Application of Agricultural, Industrial, and Municipal By-products*, pp.481–504, Soil Science Society of America Inc, Madison, USA.

Bruni, M.A. and Spuhler, D. (2011) *Slow Sand Filtration* [online] http://archive.sswm.info/category/implementation-tools/water-purification/hardware/semi-centralised-drinking-water-treatmen-2 (accessed 8 November 2018).

Campbell, P. (2018) *Horizontal Belt Filters Market 2018-2023: Analysed by Business Growth, Development Factors, Applications, and Future Prospects* [online] https://altertimes.com/horizontal-belt-filters-market-2018-2023-analysed-by-business-growth-development-factors-applications-and-future-prospects/ (accessed 30 October 2018).

Cornwall, D.A. and Koppers, H.M. (1990) *Slib, Schlamm, Sludge*, American Water Research Association, USA.

Crittenden, J.C., Trussell, R.R., Hand, D.W., Howe, K.J. and Tchobanoglous, G. (2012) *MWH's Water Treatment: Principles and Design*, John Wiley & Sons Inc., Hoboken, New Jersey.

Davis, M.L. (2010) *Water and Wastewater Engineering*, McGraw-Hill, New York.

De Kreuk, M. (2013) *CTB3365x – Introduction to Water Treatment*, TUDelft, Netherlands.

Departments of the Army and the Air Force (1985) *Water Supply, Water Treatment*, Departments of the Army and the Air Force, Washington, USA.

Dharmappa, H., Hasia, A. and Hagare, P. (1997) 'Water treatment plant residuals management', *Water Science and Technology*, Vol. 35, No. 8, pp.45–56.

Elliott, H.A. and Dempsey, B.A. (1991) 'Agronomic effects of land application of water treatment sludges', *Journal – American Water Works Association*, Vol. 83, No. 4, pp.126–131.

Faber, H.A. (1969) 'Disposal of wastes from water treatment plants – Part 1', *Journal – American Water Works Association*, Vol. 61, No. 10, pp.541–566.

Fulton, G. (1976) 'Water plant waste treatment: state of the art, Part II', *Public Works*, February, Vol. 107, No. 2, pp.57–60, 96.

Hammer, M. and Hammer, M. (2008) *Water and Wastewater Technology*, Pearson Prentice Hall, Inc., Upper Saddle River, New Jersey 07458.

Ippolito, J., Barbarick, K. and Elliott, H. (2011) 'Drinking water treatment residuals: a review of recent uses', *Journal of Environmental Quality*, Vol. 40, No. 1, pp.1–12.

IWA (2010) *Sedimentation & Flotation*, AWWA, McGraw-Hill, International Water Association [online] https://www.iwapublishing.com/news/sedimentation-processes (accessed 7 November 2018).

Jahanshahi, M. and Taghizadeh, M.M. (2018) 'Pre-sedimentation tank effects on water treatment unit operation', *EQA-International Journal of Environmental Quality*, Vol. 28, pp.35–42.

Komline-Sanderson (2018) *Rotary Drum Vacuum Filters*, New Jersey, 07977, USA [online] http://www.komline.com/products/rotary_drum_vacuum_filter.html (accessed 16 November 2018).

Lai, J. and Liu, J. (2004) 'Co-conditioning and dewatering of alum sludge and waste activated sludge', *Water Science and Technology*, Vol. 50, No. 9, pp.41–48.

Lin, S.D. and Green, C.D. (1987) *Wastes from Water Treatment Plants: Literature Review, Results of an Illinois Survey, and Effects of Alum Sludge Application to Cropland*, Illinois State Water Survey.

McGhee, T. (1991) *Water Supply and Sewarage*, McGraw Hill, Inc., Singapore.

Mowla, D., Tran, H. and Allen, D.G. (2013) 'A review of the properties of biosludge and its relevance to enhanced dewatering processes', *Biomass and Bioenergy*, Vol. 58, pp.365–378.

Pizzi, N.G. (2011) *Water Treatment Operator Handbook*, American Water Works Association, USA.

Reynolds, T.D. and Richards, P. (1996) *Unit Operations and Processes in Environmental Engineering*, Cengage Learning US, USA.

Roy, M. and Couillard, D. (1998) 'Metal leaching following sludge application to a deciduous forest soil', *Water Research*, Vol. 32, No. 5, pp.1642–1652.

Snurer, H. (2008) *Sludge Production from Chemical Precipitation*, Department of Chemical Engineering, Lund Institute of Technology.

Tchobanoglus, G., Burton, F. and Stensel, H.D. (2003) 'Wastewater engineering: treatment and reuse', *American Water Works Association Journal*, Vol. 95, No. 5, p.201.

TU Delft (2007) *Water Treatment – Sedimentation*, TU Delft.

USEPA (1996) *Technology Transfer Handbook – Management of Water Treatment Plant Residuals*, Office of Research and Development, United States Environmental Protection Agency.

USEPA (2011) *Drinking Water Treatment Plant Residuals Management: Summary of Residuals Generation, Treatment, and Disposal at Large Community Water Systems*, Drinking Water Industry Report.

Wei, H., Gao, B., Ren, J., Li, A. and Yang, H. (2018) 'Coagulation/flocculation in dewatering of sludge: a review', *Water Research*, Vol. 143, pp.608–631.

Westerhoff, G.P. and Cline, G.C. (1980) 'Planned processing beats back water-plant sludge disposal problems', *Water and Sewage Works*, Vol. 127, No. 10, pp.32–59.

Yusa, M., Suzuki, H. and Tanaka, S. (1975) 'Separating liquids from solids by pellet flocculation', *Journal – American Water Works Association*, Vol. 67, No. 7, pp.397–402.

Zabel, T. (1985) 'The advantages of dissolved - air flotation for water treatment', *Journal – American Water Works Association*, Vol. 77, pp.42–46.

Zabel, T.F. (1992) 'Flotation in water treatment', *Innovations in Flotation Technology*, Springer, Marlow, UK.

Notes

1 NSF ensures that dangerous toxins are not leached.