ANAEROBIC DIGESTION: RECOVERING MESOPHILIC DIGESTER FROM FAILURE DUE TO TOXICITY

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ABSTRACT

The operation of Anaerobic Digesters (AD) for stabilisation and reduction of organic material is an established process in many Wastewater Treatment Plants (WWTP). One of the challenges faced by large WWTP serving both industrial and domestic sources is the vulnerability to toxicity. The Mangere WWTP is the largest WWTP in Auckland, producing 300 tonnes per day of biosolids and utilising gas from the digestion process to meet up to 60% of the power demand. In October and November 2012, the plant experienced poor digestion. The first sign of failure was a drop in the gas production from 5,500 to 3,500 m^3/day and in the pH, from 7.2 to 6.7. The alkalinity decreased dramatically from 2,700 to 50 mg/L $CaCO_3$ while the volatile acids increased from 10 to 3,800 mg/L. Several steps were taken to recover the digesters from failure. This included reducing the load to the digesters to a minimum of 0.6 kgVS/m^3, modifying the solids stream configuration, and dosing sodium bicarbonate to increase alkalinity. By proactive management of the incident, the digesters were brought back from failure within two weeks. This paper investigates the steps during the recovery phase and some of the investigations undertaken.

KEYWORDS

Anaerobic digesters; Failure; Recovery; Methanogens; Acetogens; Monitoring

1 INTRODUCTION

The Mangere Wastewater Treatment Plant is the largest advanced nutrient removal plant in New Zealand, serving the greater Auckland urban area with a population equivalent of ~ 1,100,000. The plant treats industrial and domestic waste, the industrial waste contribution on a Biological Organic Demand (BOD) basis is about 25% of the load. The plant was first commissioned in 1960 and has had a series of upgrades. The last major was completed in 2003. The plant has two important biological processes: the Anaerobic Digesters (AD) and the Biological Nitrogen Removal systems (BNR). Biological systems are susceptible to variations in influent characteristics. In October 2012, the AD process showed signs of failure which resulted in a series of steps being taken to ensure continuity of service and maintaining compliance. As part of the measures, a major reconfiguration of the solids stream had to be undertaken on a temporary basis, as well as changes in the energy supply and an increase of the monitoring requirement. This paper investigates the steps during the recovery phase and some of the investigations undertaken.

2 TYPICAL OPERATION

As part of the Mangere WWTP consent, biosolids must have been digested prior to disposal. It is also a way to reduce the obnoxious volatile and organic material into by-product that is innocuous, less odorous and potentially inert. Furthermore, it reduces the volume of sludge to be dewatered and disposed. The biogas produced at the Mangere WWTP is extracted, cleaned and used through on site generators. Four gas engines with a maximum output rating of 1.7 MW are capable of running on both biogas and natural gas. The biogas is used to produce half the energy needed at the plant. The Mangere WWTP produces 300 tonnes of solids per day so any impact on the solids stream is critical.

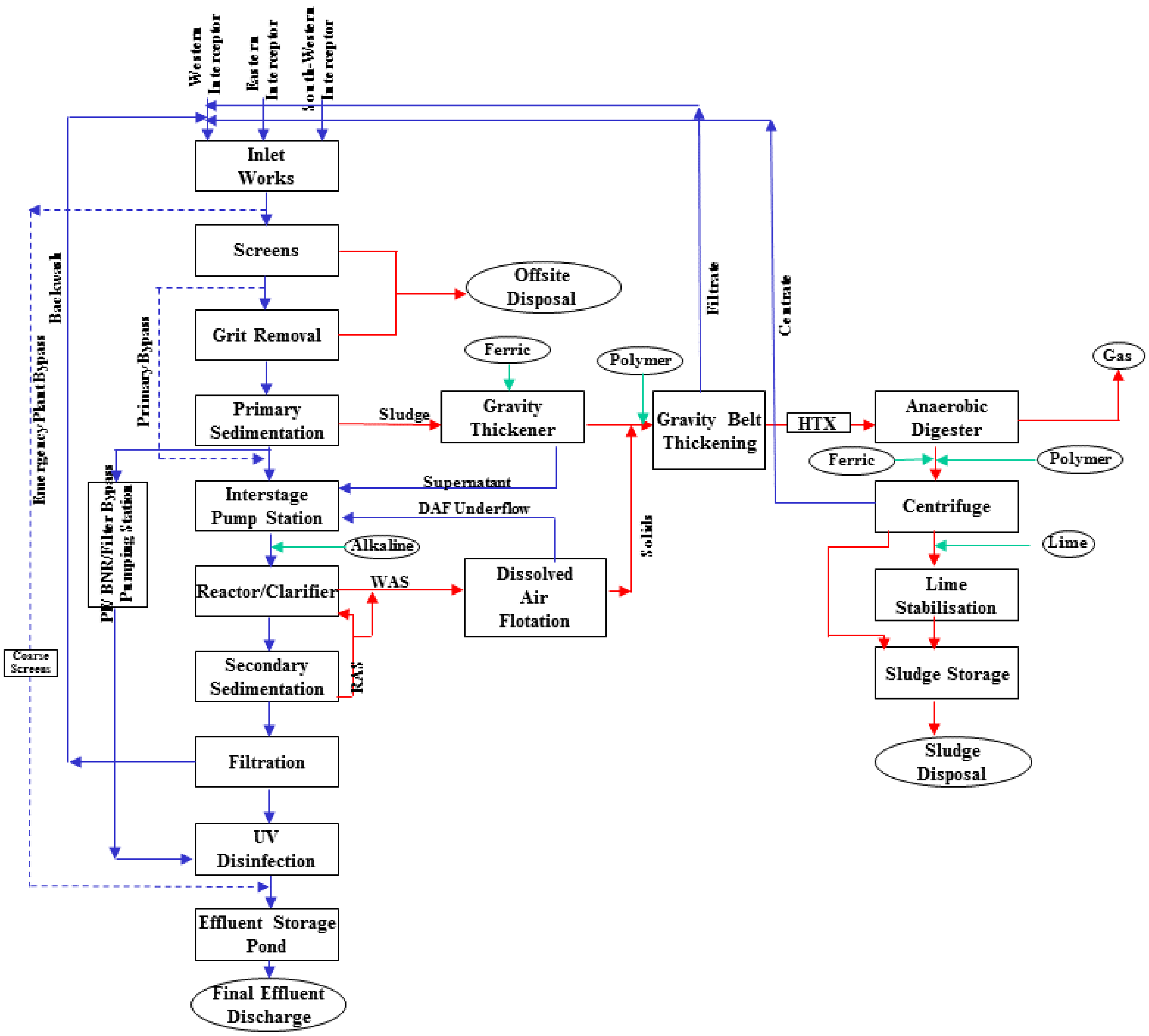
2.1 DESCRIPTION OF SOLIDS STREAM PROCESS

At the Mangere WWTP, the incoming sludge to the ADs is a blend of primary and secondary sludge (Figure 1). The Primary Sedimentation Tanks (PSTs) produce dilute primary sludge. It is thickened in the Gravity Thickener from 0.5% to 3% dry solids. The Reactor/Clarifiers (RCs) produce Wasted Activated Sludge (WAS) that is thickened in the Dissolved Air Flotation units (DAFs) to 3% dry solids. The primary and secondary sludges are blended together and thickened through Gravity Belt Thickeners (GBTs). The purpose of the GBTs is to produce a thickened sludge with approximately 6% dry solids, prior to anaerobic digestion. The thickening processes are adjusted and controlled to meet both pumping capacity and minimum sludge retention time required in the ADs.

Typically, the primary to secondary ratio is close to 50:50. However during the summer period or due to maintenance checks and overhauls, this ratio can be altered and shift to a 40:60 ratio. This impacts greatly on the Volatile Solids Reduction (VSR), which is generally over 50% but can drop below 45% with the changes in the influent Volatile Solids (VS) content and variations in the ratio. The secondary sludge has also less calorific value, hence gas production decreases in summer compared to winter.

Every summer, one digester is overhauled while the production of sludge is at its lowest. It means that each digester is overhauled every seven years. While a digester is offline for maintenance, the loading of solids to the other digesters is increased to meet capacity.

Figure 1: Mangere WTP process stream diagram



2.2 MONITORING

A comprehensive sampling and analysis programme is undertaken on various unit processes at the plant. A list of the monitored parameters from the lab analysis with the sampling frequency is presented in Table 1. The organic loading to the digesters is measured on a daily basis and this has been crucial in preventing an organic overload to the digesters.

Table 1: List of parameters that are monitored on the digesters

Parameters	Frequency	Range
Load (kg VS/m3)	Daily	1.9-2.8
pH	Every second day	7.2-7.4
Alkalinity (mg/L $CaCO_3$)	Every second day	3962-4866
Acetic acid (mg/L)	Every second day	0-33
Propionic acid (mg/L)	Every second day	0-16
Total volatile acids (mg/L)	Every second day	0-55
VA/Alkalinity ratio	Every second day	0.01-0.004
Propionic acid/Acetic acid ratio	Every second day	0.4-0.5
Hydraulic Retention Time (days)	Daily	17-25
Total solids (% dry weight)	Every second day	2.6-3.2
Volatile solids destruction ratio	Every second day	43.1-59.7
Gas produced (m^3/day)	Daily	6178-8498
m^3gas produced/kg VS load	Daily	1972-4542
Temperature (°C)	Daily	37.08-37.52
Digested sludge VS (%)	Daily	69.3-74.3

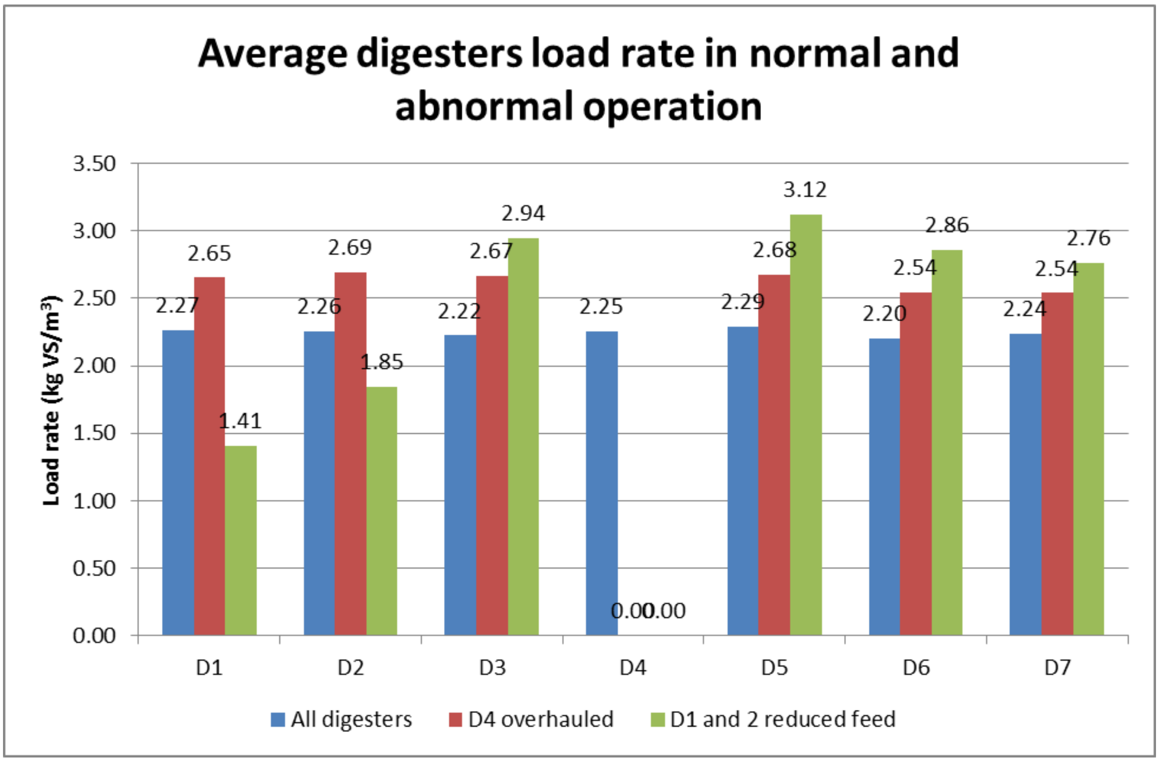
2.3 DIGESTION PROCESS OPERATION

The plant consists of seven ADs operated at a mesophilic temperature range of 37 °C. The effective volume of each AD is ~ 6770 m^3. The seven digesters have floating roofs, operated as constant volume tanks. Mixing is done through dedicated mixing pumps, run on a continuous basis. The ADs operate in parallel and are loaded sequentially through two incoming lines: line A and line B. The loading sequence is time-based: Digester 1 is filled for 20 minutes, then Digester 2, etc until Digester 7 has been fed. Then, the sequence restarts with Digester 1. The loading time is adjustable, and the inlet flow can be set to a constant flow. Digester unloading occurs in continuous manner, by overflowing two weirs in the digester wall. The withdrawn sludge is then gravity fed to the digested sludge sump. The mixing of the sludge is carried out by a mixing system, which includes a pump and six mixing nozzles. Digested sludge is drawn from the digester by the mixing pump and returned at high velocity via mixing nozzles to achieve a highly mixed digester inventory. Bio-gas is collected in the floating roof gas dome through a low pressure pipeline. Finally, heating is controlled through a series of heat exchangers (H/E), and also through individual H/E on the recirculation line, to compensate for heat loss from the digester.

3 CHRONOLOGY OF EVENT

From the 17^{th} of October 2012, there was an elevation in the volatile acids in Digester 1 and Digester 2. This was just prior to the Labour weekend, which is a public holiday in New Zealand. At that time, the plant was operated on a six digester mode due to planned maintenance on Digester 4. The trend of the organic loadings to the digesters is presented in Figure 2. On average, with a seven digester operation, the loading rate is 2.24 kg VS/m^3, increasing to 2.63 kg VS/m^3 when on a six digester operation. Other parameters such as pH, gas flow, and alkalinity changed suddenly in both digesters, and the feed was reduced to protect them. This increased the loading rate to the remaining 4 digesters, by about 15 to 30%.

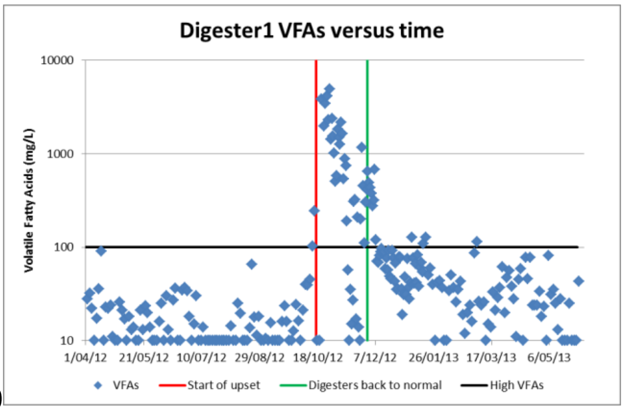
Figure 2: Average load rate for each digester in normal operation and during D4 overhaul and abnormal operation



Digester 1 trends are presented in Figure 3. The volatile acid trends show variability, ranging between 10 to 100 mg/L on the routine sampling. Note that the results are elevated in October and a significant upward trend is observable from mid-October onwards. The average volatile acids measured since the October period, is higher than the pre-October period. The pH decreased on the 19th of October from the normal operating range of 6.8-7.4, and dropped down to 6. The trend in gas flow shows a significant decrease from 17th of October, showing signs of recovery in early November. It is back within range from the end of November. The trend on alkalinity shows variability and decreases during the month of October and is higher than the average when compared pre and post October 2012.

Figure 3: Digester 1 VFAs (a), pH (b), gas flow (c) and alkalinity (d). The black lines represent the high and low range values

(a)



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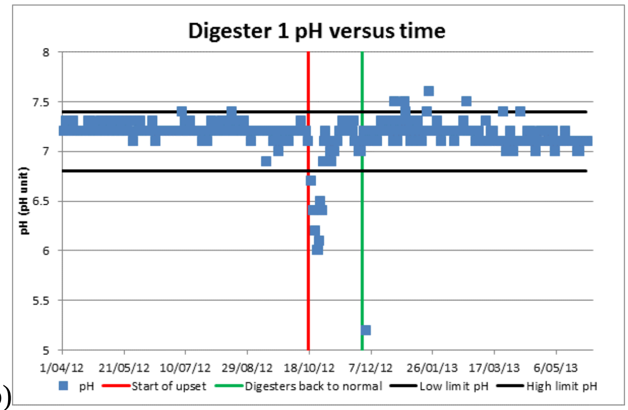
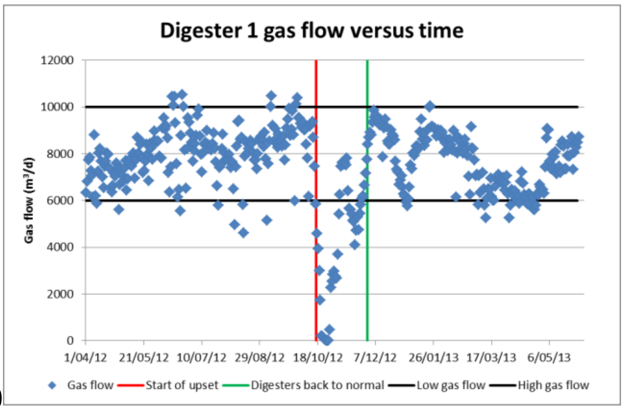
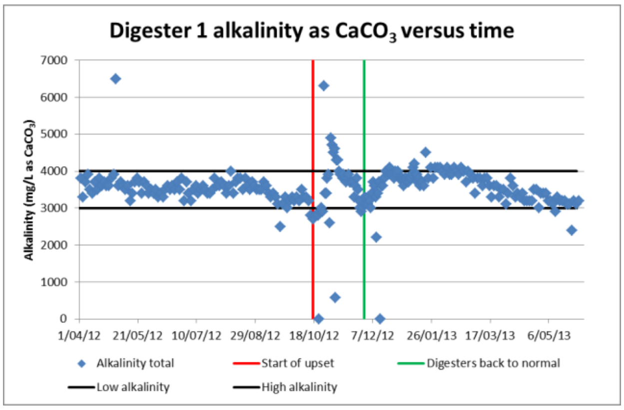


(c) 

(d) 

4 RECOVERY PHASE

4.1 LABORATORY MONITORING

Sampling and analysis frequency of certain variables of interest was increased to twice daily. Testing of pH was done every 6 hours. Amongst these variables, there are environmental parameters that can be controlled, if closely monitored and operated. A manual for operation has been produced by EPA and can help with identifying operational problems through a troubleshooting guide (Zickefoose and Hayes, 1976). A description of the environmental parameters is detailed in Table 2.

Table 2: Description of the environmental parameters that influence AD process

Parameter	Influence
Temperature	Affect viscosity and homogeneity of sludge. Affect growth kinetics of bacteria. Mesophilic digesters operate at 35-40 °C.
Retention time	Affect efficiency of digestion process. If too short, may result in a biomass washout.
Mixing	Affect diffusion of substrate within the digester.
pH	Affect growth of acetogens and methanogens. Ideal pH is neutral (within 6.8 to 7.2). VFAs production decreases pH.
Alkalinity	Provide natural buffer and neutralise VFAs.
Nutrient load	Provide substrate to microorganisms. A good rule of thumb is that loading should be maintained within 10% of the existing VS in the reactor.
Toxicity	Inhibit growth or activity of different group of bacteria.

4.2 PLANT CONTROL STEPS

Reduction in influent feed to the AD's was undertaken as a control step. Initially, feed was completely stopped on Digester 1 and reduced on Digester 2. Because the incoming flow is continuous, the load on the remaining operational digesters was higher than normal, as mentioned previously. Reducing the sludge withdrawal in the primary and secondary treatment processes was used to minimise the load to the digesters.

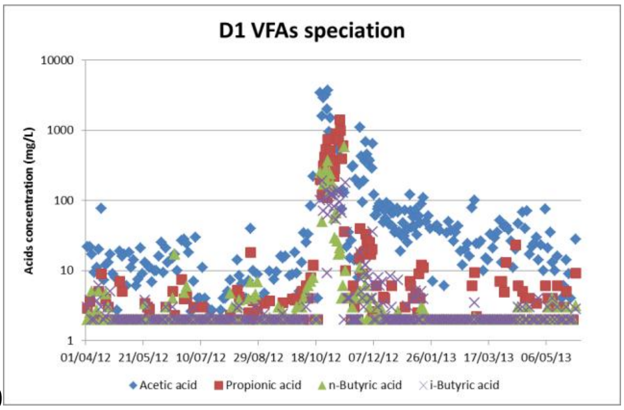
Steps were taken to adjust the alkalinity and raise the pH back to the neutral range. The dosing of sodium bicarbonate commenced on Wednesday 24th and continued over the week-end to bring the alkalinity back in range. The chemical was delivered in 25 kgs bags and dosing had to be done manually and progressively. It is not good practice to add lots of chemical at once, especially with the relative toxicity of sodium. It was then decided to set the dose rate to 1 t/day, except on two occasions when it was increased to 4 and 3 t/day.

Correction of the pH was undertaken with caustic dosing on Sunday 28th October. The calculated amount of caustic to add was 1,000 L to raise the pH by 0.1 unit. The feed was stopped on all digesters at that time, as VFAs were increasing on Digesters 3 and 7.

By Monday 29th October, the pH and alkalinity had returned back within the acceptable operational range in Digesters 1 and 2. In total, 15 tonnes of sodium bicarbonate were dosed mainly to Digester 1, then 2 and 7. The VFAs were still in very high concentration and continuous dosing of caustic had to be undertaken to maintain the neutral range. The gas production of Digester 1 and 2 was close to nil at this stage, due to the inhibition of the VFAs on the methane producers.

At the same time, the VFAs were still increasing on Digesters 3, 6 and 7, decreasing the pH. The acid speciation from Digester 1 in Figure 4 clearly shows the increase in acetic, propionic, and butyric acids, meaning that the methanogens were first inhibited, and then the acetogens were not able to convert the amount of VFAs from the substrate into acetic acids, until the load was decreased.

Figure 4: Digester 1 VFAs speciation during normal and abnormal operation. (a) is the concentration in time, (b) is the concentration per acid dissociation

(a)


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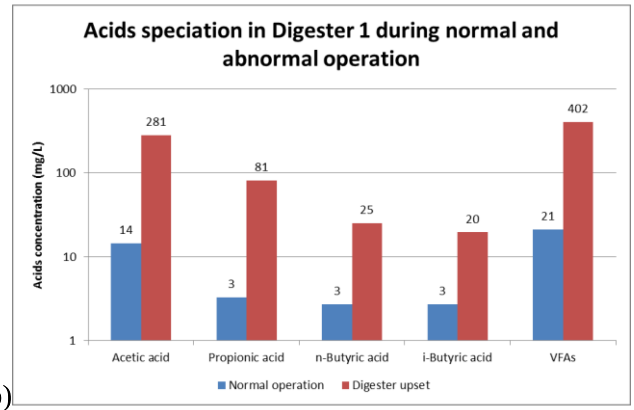
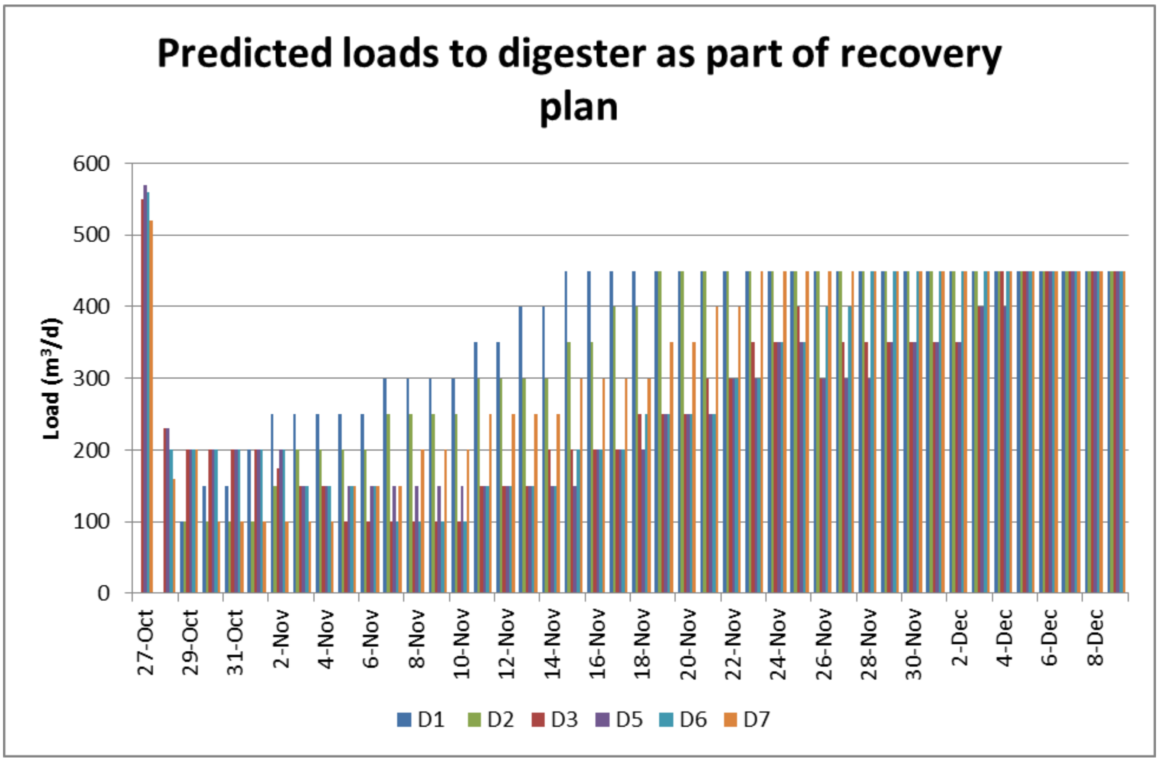


The incoming load to the digesters was reduced by bypassing thickened sludge directly to the dewatering facility. This was done by installing a temporary overland 100mm diameter transfer pipeline 150m long between the blended sludge feed tank and the dewatering facility. It was decided to bypass blended sludge and not secondary sludge only to keep the usual primary to secondary ratio, in order not to further upset the digesters.

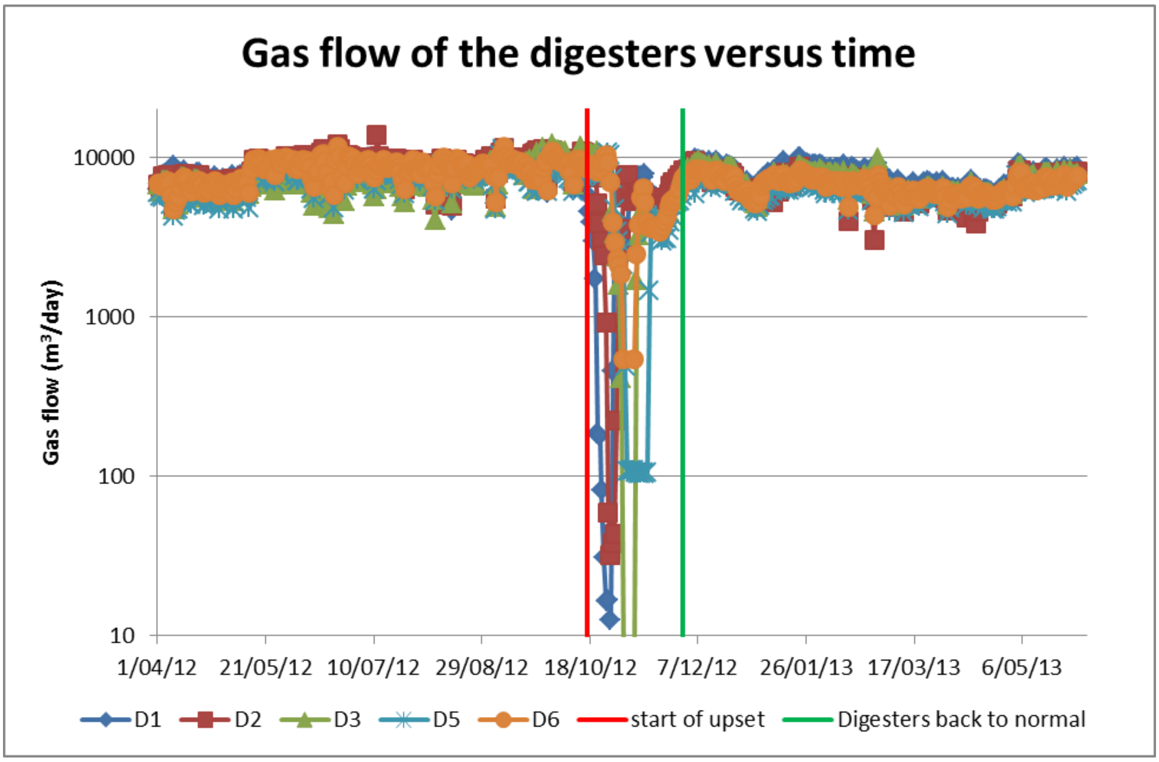
Finally, the feed loads for all digesters were adjusted from predictions that were made from the most recent laboratory results (Figure 5). The key element was to make sure that the acetates were converted back to methane and the VFAs such as propionic and butyric were converted to acetic acids. A minimum load of 0.6 kg VS/m^3 was initially set while the pH was kept in the neutral range to prevent the inhibition of the methanogens. If the results from the laboratory were within the normal range, an increase of 10% of the load, as per good practice, was implemented.

Figure 5: Predicted load rate to digesters during recovery period



With the feeding rates adjusted daily, and the pH and alkalinity back in range, Digester 1 was back within operating levels and started producing gas within two weeks. Even though the VFAs were as high as 2300 mg/L, by maintaining the pH at 7, the gas produced increased from nil to 2300 m^3/d, versus 7500 m^3/d in normal time. All digesters eventually went through the same phase as Digester 1. This is clearly observed in Figure 6: the gas flow shows a range of 9,000m^3/day and decreases during the incident.

Figure 6: Digester gas flow during digester upset



In order to speed the recovery of the remaining digesters, and reduce the concentration of volatile acids, Digester 3 was seeded with Digester 1 sludge.

5 DISCUSSION

The anaerobic digestion is a complex process that involves a diverse group of microorganisms. These groups are working beside each other in a symbiotic relationship. It is crucial to keep the balance between the acetogens and methanogens, in order to keep the process of decomposition going (S.K.Khanal, 2008). Methanogens are extremely vulnerable to environmental conditions and slow growing, which reduces their chance to compete in presence of fast growing competitor feeding on the same substrate (Novaes, 1986).
It is common knowledge that volatile acids concentration is one of the most important parameters to monitor for the prevention of a digester upset. The sign of high concentration of volatile acids happens before any other signs (gas production, pH). This was the case during the Mangere WWTP upset: the first sign of high volatile acids happened on the 15^{th} of October. Even though the gas production started to decrease, it was still within an acceptable range (from 7,500 to 5,800 m^3/day). It is noted that pH started to decrease on the 19^{th} (from 7.2 to 6.7). Gas quality also showed a change with an increase in CO_2 from the 19^{th} of October (from 33 to 36%) and a reduction in methane content.
In the literature, different studies have analysed the cause of toxicity of volatile acids towards methanogens. The work of McCarty and McKinney (1961) has enhanced the high toxicity of hydrogen ion that increases when pH drops. A solution to counteract this toxicity is either to dilute the substrate or increase the pH by adding buffering materials such as lime.
From the results showed in Figure 3, we clearly observe that with a pH below 6.5, the gas production is close to nil, independent of the volatile acids concentration. Furthermore, the VFAs were as high as 5,200 mg/L in Digester 3 on the 8^{th} of November, but pH was corrected and brought back to 6.5, and the load reduced to 0.6 kg VS/m^3. On this day, the digester started producing gas again at a rate of 1,700 m^3/day.
This result may only demonstrate that there is eventual acclimation of the methane producers with regards to their inhibiters and so even at very high concentration of VFAs, methanogens are able to convert acids to methane. It clearly proves that for a quick recovery, one of the key actions is to bring the alkalinity and pH back within range, and reduce loading to the affected digesters to a minimum. When possible, dilution of the high concentration of VFAs by seeding with fresh sludge should be considered. This was successfully completed in the recovery process: VFAs decreased from 5,000 to 1,500 mg/L in Digester 3 within a day. A similar case study have been described by Dague et al. (1970) and provided similar outcomes.

High VFAs events have to be investigated as early as possible to make sure that all eventual causes are investigated. It usually involves increasing sampling and testing of the raw sewage, and all upstream processes. The possible causes of high VFAs are either operation of external parameters (organic overload, hydraulic overload, mixing adjustment, temperature control, etc) or toxicity. Toxicity may be caused by internal or external components. A non-exhaustive list of toxic components found in the literature is detailed in Table 3 below.

Table 3: List of toxic components towards microorganisms from Anaerobic Digesters

Component
Hydrogen ion
Sodium ion
Heavy metals
Ammonia
Sulphate
Long Chain Fatty Acids (LCFA)

For example, aluminium sulphate used as flocculant is toxic towards methanogens and acetogens (Cabirol et al. 2003). Also, ammonia is naturally produced within a digester and impact methanogen bacteria negatively (Benabdallah El Hadj et al. 2009). External components such as heavy metals or LCFA are also commonly known to be toxic. Heavy metals are toxic depending on the metal species and their dissolved concentration as shown by Mueller and Steiner (1992) and Lawrence and McCarty (1965). LCFA are a very good substrate and represent a high calorific value for anaerobic digesters, but are toxic, depending on their concentration and acclimatisation of the microorganisms. Palatsi et al. (2009) have studied the impact of LCFA on methanogens through slaughterhouse wastes and have shown that depending on the concentration, the inhibition is reversible and the microorganisms are able to recover and utilise the substrate after a lag phase. It is also stated that the best strategy to recover from LCFA inhibition is to dilute the reactor to increase the biomass to LCFA ratio. A control of LCFA substrates and particularly C18:1 should be thoroughly monitored as described by Yoochatchaval et al. (2011). Jiang et al. (2012) have developed a simple and reliable gas chromatographic method to quantify LCFA.

If the balance between acetogens and methanogens is altered, the VFAs accumulate, resulting in an abrupt drop in pH. Low pH inhibits the methanogens from decomposing acids, and the digester turns sour. A rancid butter smell is released from the reactor.

In conclusion, a good balance between acid producers and methanogens is a key factor in the AD process. Various variables are good indicators of the health of the reactor, and need to be monitored closely. Overall, a digester process failure has a significant impact on the operational cost of a wastewater treatment plant. First, it decreases the gas production which is an important source of energy. In the Mangere WWTP case, power generation was impacted as well as heat loop, and external natural gas had to be supplied in order to meet demand. Secondly, the amount of chemical needed to re-establish the balance between the acid producers and methanogens can be very high and expensive. Also, the changes on the solids stream will impact on the performance of the downstream processes. In the case of the Mangere WWTP, the capture in the dewatering facility and upstream processes decreased dramatically, resulting in recirculation of solids through the plant. This impacted on the influent organic loads, thus decreased the capacity of liquid and solid processes. Backing up solids upstream is effective for a short term period but cannot be sustained for more than a few days. If solids are backed-up for a long time, performance is highly affected and may result in higher consumption of coagulant, hence increasing treatment costs. Finally, the costs to dispose the undigested dewatered sludge had to be added to the final costs of recovery operation.

6 CONCLUSIONS

In conclusion we can draw the following points for best operations of an AD unit process in a plant which treats variable wastewater streams:

1. Monitoring of volatile acids, gas production, gas quality, pH and alkalinity on a daily basis is vital.
2. In the event of a change in any of the above parameters, there is a need to trigger sampling of influent to the AD's as well as the influent to the plant to investigate further for inhibitory substances.
3. Recovering the biomass through pH and alkalinity correction.
4. Adjust/decrease the loading rate or dilute the substrate to increase the biomass to substrate ratio.
5. Seed with healthy biomass to re-establish the ratio between acetogens and methanogens.
6. Use of online monitoring tools for real time triggers will be useful for plant operation.

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