Sludge characterization at Kadahokwa water treatment plant, Rwanda

A. Uwimana, I. Nhapi, U. G. Wali, Z. Hoko and J. Kashaigili

ABSTRACT

A study was carried out to characterize the sludge produced at Kadahokwa Water Treatment Plant (KWTP) in Butare to assess the effectiveness of the sludge treatment and potential impacts of sludge disposal on the environment. Parameters analyzed were chromium, nickel, cadmium, lead, copper, zinc, iron, manganese, aluminium, total nitrogen, total phosphorus, potassium and cation exchange capacity (CEC). The results showed that 450 ± 244.5 tons (dry weight) of sludge are produced annually. The concentrations of heavy metals in the sludge were below the standard limits for land application set by different countries. The high concentrations of nickel (42.3 ± 2.5 ppm), chromium (29.9 ± 6.2 ppm), cadmium (1.1 ± 0.3 ppm) and lead (31.6 ± 3.7 ppm) in the dried sludge posed a pollution risk for the wetland. The CEC was 28.4–33.3 cmol (+)/kg and pH was 6.50–7.45. It was concluded that the KWTP sludge is a poor source of total carbon, a moderate source of nutrients (NPK), and an important source of micronutrients, making it generally suitable for reuse for crop production. The CEC showed that the sludge could improve soil nutrient and water holding capacity. The higher concentration of aluminium (280 ppm) in the sludge creates an opportunity for recycling.

Key words | environmental pollution, sludge disposal, sludge management, sludge quality, water treatment sludge

A. Uwimana
I. Nhapi
U. G. Wali
Faculty of Applied Sciences,
National University of Rwanda,
P.O. Box 117,
Butare,
Rwanda

Z. Hoko (corresponding author)
Civil Engineering Department,
University of Zimbabwe,
P.O. Box MP 167, Mount Pleasant,
Harare,
Zimbabwe
E-mail: *z_hoko@yahoo.com*;
hoko@eng.uz.ac.zw

J. Kashaigili
Faculty of Forestry and Nature Conservation,
Sokoine University of Agriculture,
Box 3003,
Morogoro,
Tanzania

INTRODUCTION

Water purification processes produce wastes in the form of sludges, which are often hazardous to the public health and the environment. In conventional water treatment, the sludge is generally from sedimentation and filtration processes. It is estimated that some 5 to 10% of the water fed into the treatment plant is wasted as sludge. The sludge composition is mainly determined by the geology, hydrology of the river basin, human activities in catchments and chemicals used in purification process. Consequently sludge produced from water purification processes may contain high residual concentrations of the chemicals used. The sludges contain such metals as aluminium or iron which are constituents of coagulants commonly used. Other chemical constituents of concern include nitrates, arsenic, mercury, fluoride and synthetic organic compounds (Gregory 2006). The heavy metal content of the sludge compels the correct disposal in order to reduce negative impacts on the environment (Hoppen *et al.* 2005).

Sludge production is an unavoidable consequence of water purification processes and creates problems for disposal. According to the type of the sludge, different operations are involved in treatment, reuse and disposal of the sludge. These include thickening, stabilization, conditioning, dewatering, incineration, land application and land filling (Pinarli & Kaymal 1994; Metcalf & Eddy Inc. 2003; Rouf & Hossain 2003). According to APHA/AWWA/WEF (2005), waste minimization methods include source reduction (cleaner production), recycling and reclamation. Source reduction can be achieved through pollution reduction in the raw water, which will result in reduced chemical requirements as well as use of less toxic chemicals. Waste treatment reduces volume, mobility, and toxicity of

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hazardous wastes. According to Snyman (2006), water treatment sludge is predominantly inorganic, displaying physical and chemical characteristics similar to those of fine structured soil while the wastewater sludge comprises relatively much of organic matter. In some cases natural water can contain elevated concentrations of trace elements such as arsenic, copper, lead and zinc which may be incorporated into sludge during potable water treatment (Gregory 2006). Aquatic life is also a significant source of numerous constituents of natural waters (Gregory 2006). The treatment required is therefore dependent on the characteristics of the sludge. Treatment of sludge contaminated with high concentrations of heavy metals or toxic chemicals will be more difficult and the potential for re-use will be limited due to the presence of heavy metals (Snyman 2006). Sludge from water treatment plants was traditionally disposed of to landfill but there is a growing interest in applying this waste to land as an alternative disposal option (Snyman 2006). In South Africa water treatment sludge was added to top soils at different rates to investigate its effect on soil quality (Snyman 2006), the findings of this study suggested that water treatment sludge can be applied to the soil at rate of at least 15% volume of the soil, to increase soil respiration without having a detrimental effect on microbial indicators of soil quality. According to Hughes & Titshall (2005), land application of water treatment residue is becoming the preferred method of disposal when applied at optimum rates.

Traditionally, sludge from water treatment plants was directly discharged to a watercourse (Elliott *et al.* 1990; Joukoski *et al.* 2005) or disposed of to landfill (Snyman 2006). In developing countries, discharge of water treatment plant (WTP) sludge in watercourse continues to be practiced until now and remains the main disposal practices. Major challenges in the proper treatment and disposal of sludge, often requiring mechanized and sophisticated approaches, are to some extent linked to the heavy investment associated with this, which are often beyond the reach of many developing countries. In developed world disposal alternatives include application in a land unit, surface impoundment, and waste pile or mixed with sewage (Texas Commission on Environmental Quality 2005).

A study was carried out in Dublin to identify the characteristics of dewatered alum sludge for phosphorus adsorption using potassium dihydrogenophosphate (KH_2PO_4) as model phosphorus source. The results showed that alum sludge is suitable for use as adsorbent for removal of phosphate from wastewater (Sötemann *et al.* 2006). The Recycling of Aluminium (REAL) process was tested as alternative for water treatment sludge management in Sweden (Snyman 2006). The potassium aluminium sulphate obtained is comparable to standard aluminium sulfate which can be used as coagulant in water treatment works. WTP sludge was also used as a clay substitute in the production of quality bricks (Rouf & Hossain 2003), in the construction of Portland cement concrete floors (Joukoski *et al.* 2005), and in the production of novel lightweight bricks produced by sintering mixes of dried water treatment sludge and rice husk (Chiang *et al.* 2009). It is becoming common for water treatment sludge to be used as a soil ameliorant in preference to dumping it in municipal landfill sites (WSAA 1997). This was confirmed by Hughes & Titshall (2005) who stressed that land application of WTP sludge is becoming the preferred method of disposal when applied at optimum rates. WTP sludge may be co-applied with biosolids on cropland (Ippolito *et al.* 1999). According to Park *et al.* (2009) technology that can reuse a larger amount of WTP sludge would be beneficial to the environment.

In Rwanda, water treatment utilities face a problem of treating water with a high solids content resulting from land degradation by erosion against a background of increasing demand. As a result of the high solids content a wide range of chemicals at high doses are required in the treatment processes for the water to meet acceptable quality. The increase in demand for drinking water implies an increase in sludge production from water treatment plants. Rwanda Public Utility for Production, Transmission and Distribution of Electricity and Water (ELECTROGAZ) currently owns and operates 13 water treatment plants countrywide (ELECTROGAZ 2004). In Butare the sludge produced at Kadahokwa water treatment plant, one of the plants operated by ELECTROGAZ is treated by drying beds. The dried sludge is removed from the bed and disposed off in wetland nearby the plant while the supernatant is discharged to the river. The impurities in the dried sludge and supernatant water are likely to change the natural properties of the wetland and adversely affect the environment and communities living downstream.

This study was carried out at Kadahokwa WTP during a period of four months (July to October 2008). The objectives of this study were to characterize the sludge and to determine selected physico-chemical parameters throughout the plant (raw water, between settling tanks and filters, sludge line from settling tanks, sludge line from filters, sludge line from sludge dewatering beds, treated water, and supernatant from sludge dewatered bed). Heavy metals such as nickel, cadmium, lead and chromium, plant micronutrients such as zinc, copper, iron, manganese, plant major nutrients such as nitrogen, phosphorus, potassium and cation exchange capacity were considered.

DESCRIPTION OF THE STUDY AREA

The Kadahokwa WTP is the main water supply source for the town of Butare, in Huye District, in the Southern Province of Rwanda. Figure 1 shows the location of Kadahokwa WTP in Butare town of Rwanda.

According to the national census commission report, Rwanda's population was 8.1 million at the time of a census carried out in August 2002. The 2007 estimated population of Rwanda was 9,907,509. The population density is 397 persons/km^2, making Rwanda one of the most densely populated countries in Africa. According to AQUASTAT (2005), the average population density of Africa is 29 persons/km^2. According to ELECTROGAZ (2004), the average water production of about 43 litres per person per day would just meet basic demand in Rwanda. In small cities, production is at a drastically low level of 14 litres per person per day. As reported by ELECTROGAZ (2004), the water production figures in 2002 showed that the specific water production in Butare town was 30 litres per capita per day. This does not meet the national estimated specific water demand.

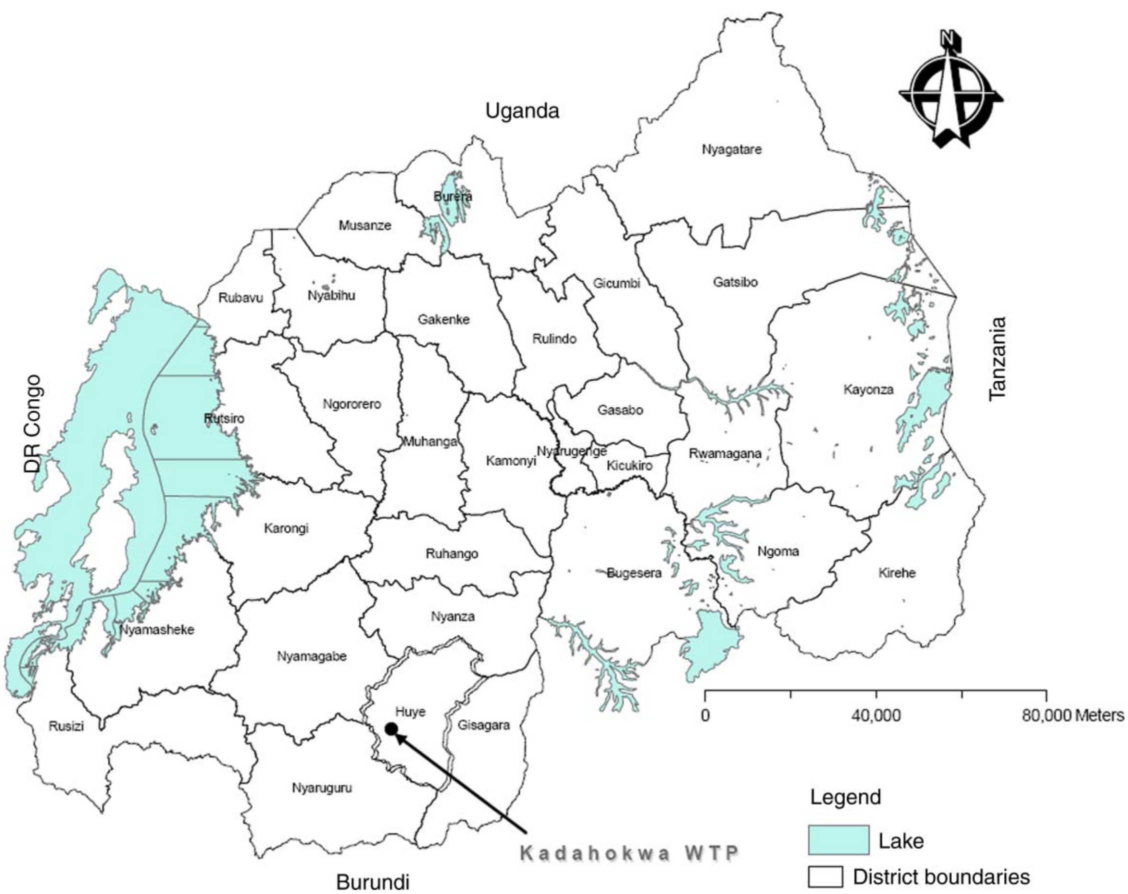

Figure 1 | Location of Kadahokwa WTP in Butare in the Huye District, Southern Province of Rwanda.

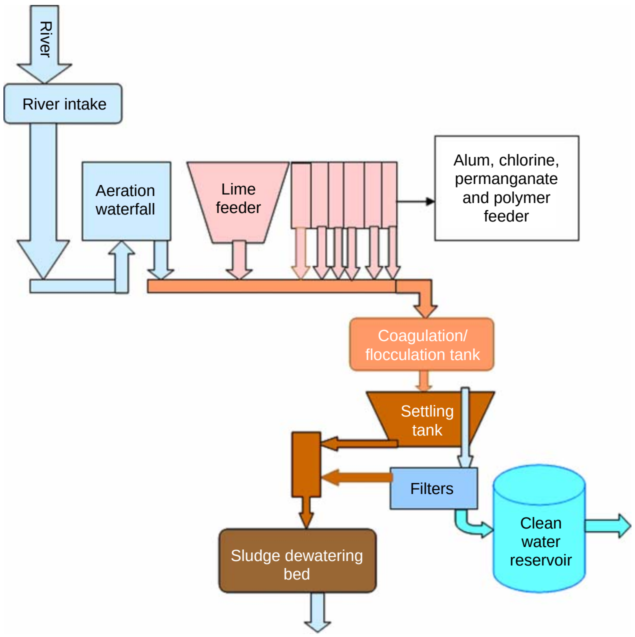

Figure 2 | Kadahokwa WTP water flow scheme.

The mean annual rainfall in the district is 1,400 mm/year (ELECTROGAZ 2004). The catchment is affected by inappropriate land practices and the water intake is facing a serious siltation problem. The raw water is highly loaded with dissolved and suspended particles resulting from erosion due to poor soil management and the hilly nature of the terrain, coupled with the high rainfall intensity. The annual mean turbidity recorded from September 2006 to October 2007 at the Kadahokwa intake was 105.5 ± 92.6 Nephelometric Turbidity Unit (NTU).

As shown in Figure 2, Kadahokwa water treatment plant comprises of the following main units; pre-treatment (screening and grit removal and aeration), coagulation and flocculation, sedimentation, filtration, disinfection, storage, pumping and sludge dewatering units. From the intake raw water is transported by gravity to the plant. At the inlet of the plant, before chemicals are added, raw water is aerated using a cascade waterfall system. The chemicals used are alum, calcium hypochlorite, potassium permanganate and a polymer (activated silica). Mixing is performed by baffles and mechanized agitators. In the sedimentation tanks the heavy flocs are allowed to settle. The remaining impurities are detained in rapid sand filters after which the treated water is stored in reservoirs. The sludge from the sedimentation tanks and filters is conveyed to the sludge drying beds where water is filtered through a porous media and the remaining solids are allowed to dry. After the dewatering process, the sludge is disposed into the wetland and the supernatant effluent is discharged into a river.

MATERIALS AND METHODS

Study design

Location of sampling sites

The samples were taken at different points of the Kadahokwa WTP shown in Figure 3. The sampling sites were: inlet for raw water (RW), between settling tanks and filters (WS), sludge line from settling tanks (SST), sludge line from filters (SF), sludge line from sludge dewatering beds (SDB), treated water (TW), supernatant from sludge dewatered bed (ESDB). The points were considered because they give the whole picture of the performance of the plant and characteristics of the wastes discharged in environment. The reason for choosing these sampling points is that:

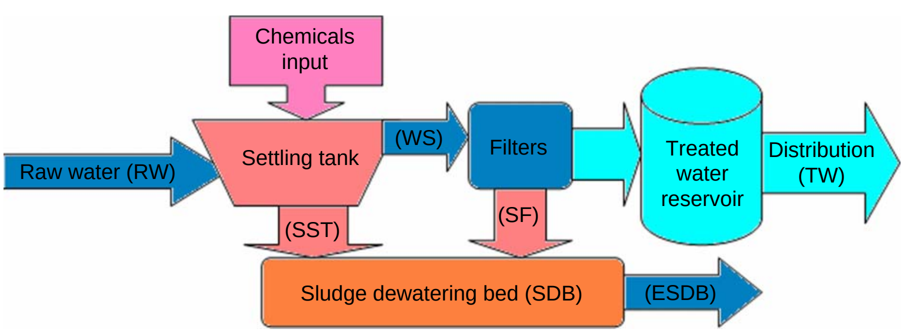

Figure 3 | Sampling sites at Kadahokwa water treatment plant.

- the raw water (RW) samples could give an indication of the quality of water obtainable before treatment and the potential chemical composition of the dried sludge;
- samples collected between sedimentation tank and filters (WS) indicates the performance of the coagulation/flocculation processes;
- samples collected after the backwashing filters (SF) indicate the performance of the filtration system;
- the treated water (TW) gives an indication of the performance of the operations and processes in the plant and drinking water quality distributed to the consumers;
- the dried sludge (SDB) and supernatant from sludge dewatered bed (ESDB) give the quality of the wastes discharged into the environment.

Selection of study parameters

Initially, a survey on raw water and treated water characteristics was carried out using data from Kadahokwa WTP laboratory database. The data is obtained from routine analysis in order to monitor water quality and optimise the chemical processes. The parameters of concern were: aluminium, chloride, chlorine, chromium, cobalt, conductivity, copper, cyanide, dissolved oxygen, fluoride, iron, manganese, nickel, nitrates, nitrites, pH, phosphates, potassium, residual turbidity, silicon, silver, sulphates, sulphide, and zinc.

Method and frequency of sampling

Samples were taken during a period of four months from July to October 2007, with a sampling frequency of once in three weeks amounting to 5 times. In general, all the samples taken were in liquid form except slurry samples taken from sedimentation tank and solid samples taken from sludge dewatering tank. The liquids samples for total metal analysis were taken in plastic bottles and preserved using nitric acid while those for total nitrogen analysis were preserved at 4°C and for total phosphorus at −10°C according to Kruis (2005). The SST (slurry) and the SDB (solids) were collected in plastic bags. The dried sludge was sieved through a 250 μm mesh sieve after drying at 40°C in the oven until the sample attained constant weight. Only the data for raw water, treated water, dried sludge and effluent from the drying bed were prioritized in interpretation because they give the whole picture of the study.

Laboratory analysis

Water treatment chemicals

Water treatment chemicals were identified using containers' labels and information given by Electrogaz Authorities.

Sludge production

To study the sludge production, a settleability test (Jar test followed by settling in an Imhoff cone) was carried out to assess the sludge volume removed from water by coagulation/flocculation processes. The principle of the method consists of two minutes rapid mixing followed by a five minutes slow mixing. The sludge is allowed to settle for 30 minutes and sludge volume is measured (APHA/AWWA/WEF 2005). The sludge total solids were determined by weighing the dried material after having evaporated the sample to dryness in a drying oven operating at 105°C. The volatile solids contents were determined by burning the residue from total solids at 550°C to constant weight. The remaining solids represent the fixed solids while the weight lost on ignition is the volatile solids (APHA/AWWA/WEF 2005).

Total metals, total nitrogen, total phosphorus and cation exchange capacity

The samples for total metal determination were digested using nitric acid and analyzed using spectrophotometric methods by the Atomic Absorption Spectrometer; Perkin Elmer type (APHA/AWWA/WEF 2005). Samples for total nitrogen determination were digested using persulfate and analyzed using cadmium reduction method (colorimetric methods) (APHA/AWWA/WEF 2005). Samples for total phosphorus were also digested using persulphate and analyzed using phosphovanadate molbdate methods (colorimetric methods) (APHA/AWWA/WEF 2005). The cation exchangeable was extracted using ammonium acetate. The cationic exchange capacity was determined using atomic adsorption spectrometer method. This consists of determining the relative proportion of sodium, potassium, calcium and magnesium cations (Okalebo *et al.* 2002).

RESULTS AND DISCUSSIONS

Historical data of the parameters regularly monitored at Kadahokwa WTP

The results for raw and treated water regularly monitored at the plant are presented in Figure 4.

From Figure 4, some chemical concentrations in raw water were reduced in treated water. But others were not, while for some parameters the concentrations in treated water were higher than in raw water. Levels were higher in treated water for the following parameters: nitrates, phosphates, sulphates, silicon, fluoride, cyanides, zinc and chromium. After a statistical analysis of *t*-Test, the concentration increase from raw water to treated water was only significant for sulphates; silicon, fluoride and aluminium. The source of the extra load was the treatment chemicals used. The increase in silicon is due to use of activated silica as a coagulant aid while the increase in sulphates and aluminium was linked to the coagulant used which is aluminium sulphate. The Electrogaz long-term average results of treated water, in comparison to the WHO's Drinking Water Quality Guidelines are shown in Figure 5. This showed that aluminium concentration (0.35 ± 0.01 mg/L, $n = 5$) exceeded the WHO safety guidelines (0.2 mg/L) most of the time. According to House & Reed (2004), if more than 0.3 mg/L aluminium is present after treatment, there is possibility of a fault in the coagulation or sedimentation stages.

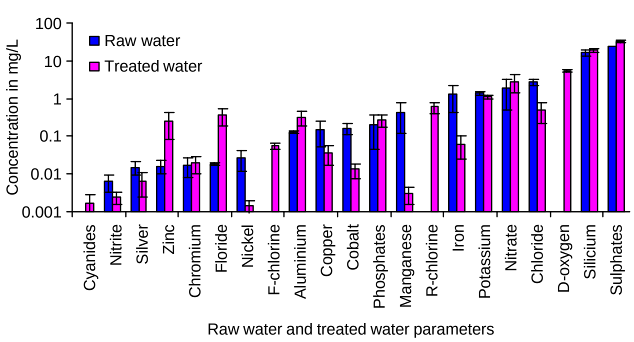

Figure 4 | Historical data of raw and treated water parameters regularly monitored at Kadahokwa WTP July to October 2007 (mean ± StDev, $n = 5$).

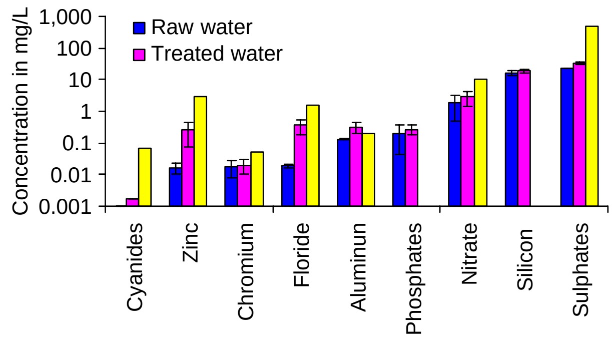

Figure 5 | Historical data of raw and treated water parameters regularly monitored at Kadahokwa WTP for the period July to October 2007 (mean ± StDev, $n = 5$). and related WHO toxicity limits (House & Reed 2004; LENNTECH 2006).

Water treatment chemicals and chemical dosages

The chemicals used in the water treatment plant are commercial aluminium sulphate ($Al(SO_4)_3 \cdot 14–18\ H_2O$) as a coagulant, a polymer (activated silica) used as a coagulant aid, calcium hypochlorite ($Ca(OCl)_2$) as disinfectant and lime (CaO) as pH corrector and hardness remover. The range of dosages at the Kadahokwa WTP and recommended dosages for the chemicals for the period July to October 2007 are presented in Table 1.

The alum dosage of 12–20 mg/L was within recommended dosage range of 10–100 mg/L. The residual chlorine of 0.7 ± 0 mg/L observed is within the health-based recommended limit of the WHO guideline value of 0.2–1.0 mg/L for residual chlorine. The lime was able to maintain a pH range of 6.50–7.45 in various streams of the plant (the pH boundaries for alum coagulation performance are 5.5–7.5).

Sludge production

Samples from sedimentation tank from July to October 2007 were settled using an Imhoff cone. This enabled the

Table 1 | Chemical dosages at Kadahokwa WTP (July–October 2007) and recommended dosages

Chemicals	Dosages (mg/L)	Recommended dosages (mg/L) (House & Reed 2004)	Remarks
Alum	12–20	10–100	Acceptable
Residual chlorine	0.7 ± 0	0.2–1.0	Acceptable
Polymer	0.1 ± 0	0.1	Acceptable

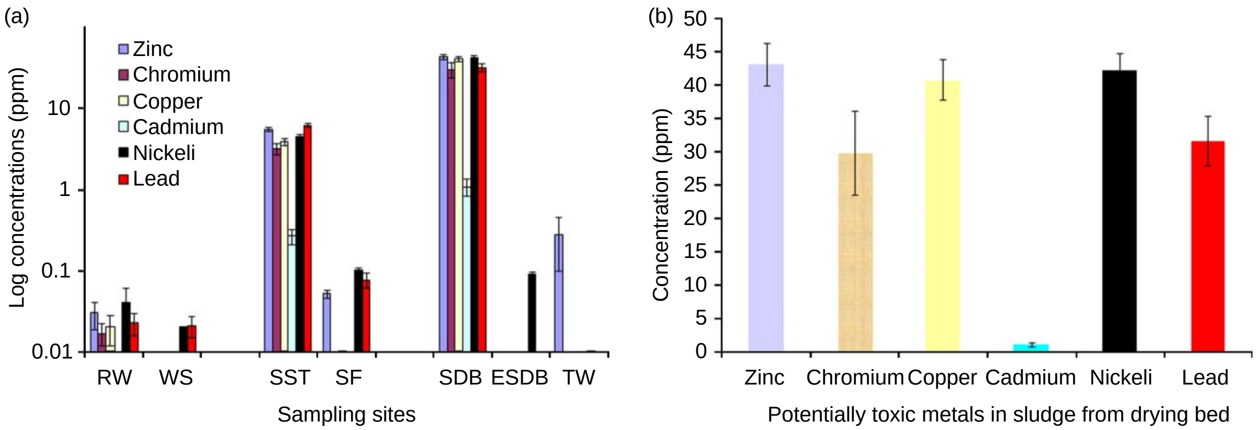

Figure 6 | Toxic metals in various streams of Kadahokwa WTP for the period of July to October 2007 (mean ± StDev, $n = 5$). (a) results for liquid samples in mg/L (b) Results of the solid samples in mg/kg.

determination of the sludge volume removed from water by coagulation/flocculation processes. An estimated volume of 6,717 ± 3,650 m^3 (450 ± 244.5 tons on a weight basis) is annually produced at Kadahokwa WTP. The dry matter was 6.7 ± 1.3 g/100 ml of the sludge from the sedimentation tank. The volatile solids were 16.1 ± 0.006%, weight of the total solids (dry matter) of the sludge produced in sedimentation tank. This confirmed that the plant sludge is less organic than mineral. Water treatment sludge contains impurities (including chemicals of health significance such as heavy metals) removed by water treatment processes. As the dried sludge is removed from the bed and disposed in wetland closer to the plant, the impurities accumulated in the sludge risk flowing back into the environment. To avoid this, a feasible long-term solution is to recycle the sludge and use it for beneficial purposes.

Toxic metals

The results of toxic metals in raw water (RW), supernatant water in sedimentation tank (SW), sludge in bottom of the sedimentation tank (SST), back washing sludge from the filters (SF), the effluent from sludge dewatering bed (ESDB), treated water (TW) and the dried sludge from sludge dewatering bed (SDB) are presented in Figure 6.

The results show that coagulation/flocculation together with sedimentation were performing the removal of cadmium, chromium and copper. These heavy metals settle with the flocs and their concentrations were reduced below the detection limit whereas lead, nickel and zinc remained in water after sedimentation. Lead was removed by filtration, but nickel and zinc were not.

The heavy metals concentrations in raw water were compared with the limits in natural water sources suggested by the World Health Organization, only nickel and cadmium were exceeding the limits as shown in Figure 7. The source of heavy metals in raw water could be the natural geology of the catchment. The nickel and cadmium concentrations were 0.035 ± 0.02 mg/L and 0.0018 ± 0.001 mg/L respectively. The normal concentration found in freshwater is less than 0.002 mg/L for nickel and 0.001 mg/L for cadmium (WHO 1993). This suggests the need for monitoring these elements in water resources of the Kadahokwa WTP.

With the exception of nickel and cadmium which exceeded the natural water limits, all other potential toxic metals concentrations in effluent from sludge dewatering bed (ESDB) were lower than their concentrations in raw water as it is shown in Figure 6. The same trend also was observed in the case of other parameters like turbidity, iron,

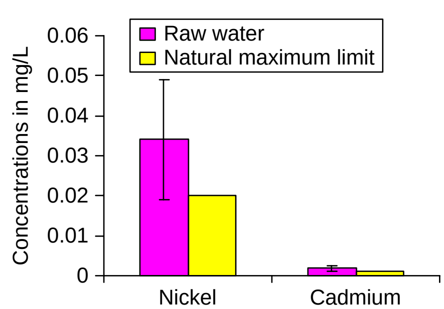

Figure 7 | Nickel and cadmium concentrations in raw water at Kadahokwa in comparison with limits for natural water.

Table 2 | Comparison of the PTM concentrations (ppm) in Kadahokwa sludge with limits from various countries (Synman 2006)

Kadahokwa sludge and related limits	Zinc	Chromium	Copper	Cadmium	Nickel	Lead
Kadahokwa SDB	43.15 ± 3.1	29.9 ± 6.2	40.85 ± 2.9	1.1 ± 0.26	42.3 ± 2.46	31.65 ± 3.6
EU limits	4,000	None	1,750	40	400	1,200
USA limits	7,500	None	4,300	83	420	840
China limits	500–1,000	600–1,000	250–500	5–20	100–200	300–1,000
South Africa limits						
Class A	<2,800	<1,200	<1,500	<40	<420	<300
Class B	2,800–7,500	1,200–3,000	1,500–4,300	40–85	420	300–840
Class C	>7,500	>3,000	>4,300	>85	>420	>840

and manganese. For effective water purification and management of the Kadahokwa water treatment operations and processes, it is recommended that supernatant from the sludge drying beds be recycled directly into the sedimentation tank.

From Figure 6, the levels of toxic metals in dried sludge (SDB) were compared with the toxicity threshold level for land application set in different countries as shown in Table 2. The zinc concentrations (43.15 ± 3.1 ppm), chromium (29.9 ± 6.2 ppm), copper (40.85 ± 2.9 ppm), cadmium (1.1 ± 0.26 ppm), nickel (42.3 ± 2.46 ppm) and lead (31.65 ± 3.6 ppm) were below the toxicity threshold level for land application. In respect of pollutant classes according to the South Africa system, Kadahokwa water treatment sludge was classified in pollutant Class A. According to Snyman (2006), sludge that complies with pollutants Class A may be used in agricultural practices without carrying out soil analyses as long as agronomic application rates (up to a maximum load of 10 tons/ha/month) are not exceeded. Results from this study indicated that the Kadahokwa water treatment sludge is within permissible levels to be applied to agricultural land. This shows that there is a possibility of recycling these water treatment residues for crop production.

Nitrogen, phosphorus and potassium

After having realised the suitable characteristics of the Kadahokwa sludge for land application, the next step was to check the nutrient value of the sludge. The origin of nitrogen and phosphorus was attributed to the organic matter in the raw water as these parameters are constituents of organic matter. Potassium originates from earthen cluster (soil). Figure 8 shows the concentrations of major nutrients

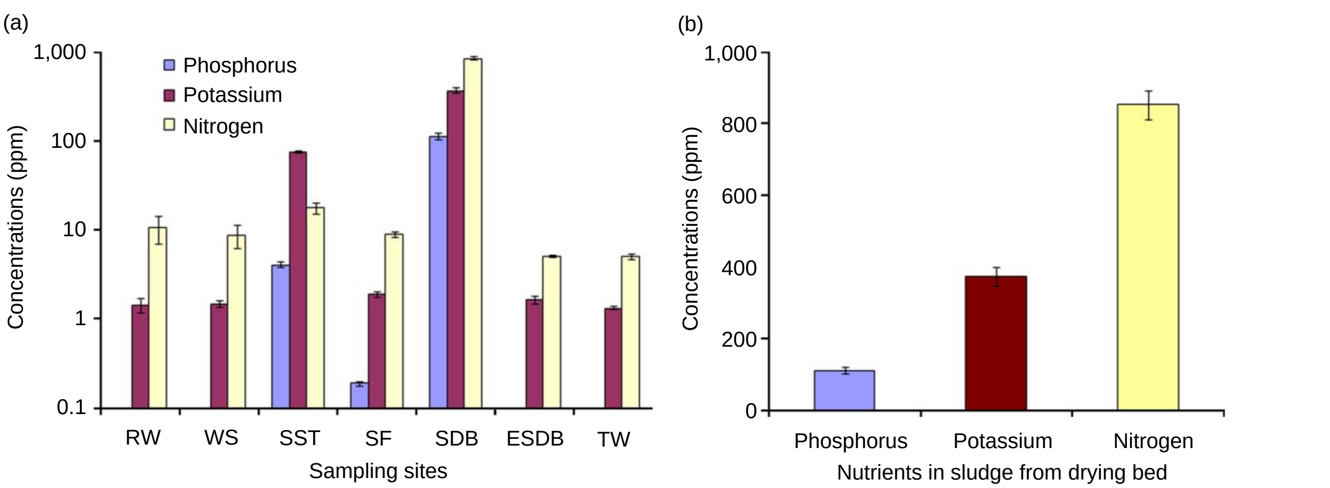

Figure 8 | Nutrients in various streams of Kadahokwa WTP for the period of July to October 2007 (mean ± StDev, $n = 5$). (a) The liquid samples results in mg/L (b) solid sample results in ppm.

(nitrogen, phosphorus and potassium) in raw water (RW), supernatant water in sedimentation tank (SW), sludge in bottom of the sedimentation tank (SST), back washing sludge from the filters (SF), the effluent from sludge dewatering bed (ESDB), treated water (TW) and the dried sludge from sludge dewatering bed (SDB).

The results showed that phosphorus is strongly removed by water treatment processes whereas nitrogen and potassium remained in treated water and in effluent from sludge dewatering beds (Figure 8). This is due to the solubility of nitrogen compounds which is higher than for phosphorus compounds. The use of lime in water treatment leads to the formation of tricalcium phosphate, a water insoluble compound. Plant phosphorus availability can be reduced when sludge is applied on soil (WSAA 1997; Ippolito *et al.* 1999), as a result of additional sorption sites for phosphorus provided by WTP sludge (Erdincler & Seyhan 2006). Studies by Agyin-Birikorang *et al.* (2007) have shown that the application of aluminium rich water treatment residues can reduce solubility of phosphorous on areas where application of manure or fertilizers is common. They showed that mobility of P was reduced by at least 50% and that the P remained stable during the 7.5 years of the study and that this was independent of the soil pH. As a result transportation of phosphorous by rainfall runoff to the water courses was very reduced. Experiments by Eliott *et al.* (2002) where leachate P was monitored by greenhouse columns where bahiagrass (*Paspalum notatum* Flugge) was grown it was demonstrated that in the absence of WTP sludges, 21% of triple superphosphate (TSP) was leached while the leaching was reduced to less than 1% of applied TSP when WTP sludges were applied. Parks *et al.* (2009) suggest that the addition of fertilizer and organic matter such as: biosolids, compost and wood fiber is necessary to improve the nutrients in WTP sludge, when the sludge is reused as plant based soil and soil amendment material. Water treatment sludge can retain phosphorus of the soil for a long time and looses it progressively, thus controlling phosphorus eutrophication from agricultural activities.

Iron and manganese

Iron had the higher concentration: 5.03 mg/L in raw water, 92.64 mg/L in the sludge from filters, 5,647.3 mg/L in the sludge from sedimentation tanks and 45,007 mg/kg in the sludge from the sludge dewatering bed. The manganese in raw water was 0.36 mg/L, 424 mg/L in sludge from sedimentation tank and 1759 mg/kg in the sludge from dewatering bed. The concentrations of iron and manganese were the highest of all the parameters analyzed. This is related to the fact that these elements are more abundant in earthen cluster than the potentially toxic elements analyzed. Table 3 compares the concentrations of metal micronutrients with the concentrations required for normal plant growth.

Table 3 | Comparison of the measured micronutrient concentrations in SDB with the required concentrations ranges for normal plant growth (Indian Agricultural Resources/Soil Management 2007)

Micronutrients	Measured concentration in ppm (parts per million)	Required concentration in ppm for normal plant growth
Iron	$(45 \pm 8.5) \times 10^3$	0.5 to 5.0
Manganese	$(1.7 \pm 0.34) \times 10^3$	0.1 to 0.5
Zinc	43.15 ± 3.17	0.02 to 0.2
Copper	29.9 ± 2.99	0.001 to 0.05

The range of micronutrient concentrations required for normal plant growth (0.5 to 5.0 ppm for iron, 0.1 to 0.5 ppm for manganese, 0.02 to 0.2 for zinc and 0.001 to 0.05 for copper) were more than 10 times lower than the micronutrients in the sludge dewatering bed. Kadahokwa WTP sludge is an important source of micronutrients (iron, manganese, zinc and copper), essential for the plant growth.

Aluminium

The aluminium concentration in the sludge from sedimentation tank was found to be about 280 mg/L. The Recycling of Aluminium (REAL) process was tested in Sweden (Snyman 2006). Recovering and reusing the alum both at the drinking and sewage treatment plants were found effective to reduce both raw material and disposal costs as shown in Table 4. Therefore, by extrapolation, it is clear that alum recovery from Kadahokwa water treatment sludge is feasible and could reduce both operational and environmental costs.

Cation exchange capacity, pH, metals plant uptake and toxicity

The cation exchange capacity in Kadahokwa Sludge was varying from 28.4 to 33.3 cmol (+)/kg. This showed that it

Table 4 | Alum recovering from alum water treatment sludge (City of Durham 1986)

Different aspects of sludge recovering	Performance
Alum recovery	75%
Dry weight solids reduction	35–40%
Acid demand	0.67 tons acid/ton alum dissolved
Recovered alum concentration	2–3%
Cost of recovered alum	\$50–\$70/ton
Alum cost in that period	\$112/ton

can improve the nutrient and water holding capacity of the soil. Several studies have supported the fact that WTP sludge can improved soil quality of tillage considerably, and that water retention capacity and soil pH resulted in an improvement in crop growth (Parks *et al.* 2009). A figure above 10 cmol(+)/kg is preferred for plant production. Soils with high levels of swelling (clay) and organic matter can have a cation exchange capacity (CEC) of 30 cmol(+)/kg or more. Therefore CEC is a useful indicator of soil fertility because it shows the soil's ability to supply three important plant nutrients (calcium, magnesium, potassium) and sodium (Camberato 2001).

The pH value in the sludge and other streams of Kadahokwa WTP was in the range of 6.50–7.45. This is within the recommended range of the WHO guidelines for treatability (5.5–7.5) using aluminium sulphate as coagulant, and for water acceptability to consumers (6–8). The solubility and toxicity of metals such as aluminium (Al), iron (Fe), manganese (Mn) and zinc (Zn) is affected by pH. Consequently, from a pH more than 5 to 6, Al, Fe, Mn and Zn mobility, plant uptake and plant toxicity are reduced (Schubert 1992; Dekker *et al.* 2006; Wang *et al.* 2006). This was confirmed by Heil & Barbarick (1989) and Elliott *et al.* (1990) who suggested that most metals in water treatment sludge occur predominantly in weakly mobile non-bioavailable forms that cannot decrease plant growth. This corroborates with WSAA (1997) findings: WTP sludge was found to possess no serious detrimental properties and in particular no soluble aluminium. Skene *et al.* (2007) claim that no evidence was found that aluminium toxicity would be a problem if WTP sludge is used as growth media. On the contrary, a number of beneficial properties were found such as low bulk density, high infiltration rate, available nitrogen, a neutral to alkaline pH, and modest calcium carbonate equivalence. The beneficial physical and chemical properties of the WTP sludge make it a good plant growth medium. Ippolito *et al.* (1999) observed a linear relationship between increasing WTP sludge application rate and crop yield. However, yields declined at higher sludge application rates (15–25 ppm) as compared to low application rates (5–10 ppm).

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The results on water treatment chemicals, study dosages and final sludge production and the physico-chemical parameters throughout the plant allowed drawing the following conclusions:

1. Water treatment chemicals used at Kadahokwa WTP are chemicals recommended for water purification. The chemicals dosages are in the recommended dosage range but aluminium in treated water exceeded the acceptable drinking water standards. Sulphates, fluoride, and silicon showed also a significant concentration increase from raw water to treated water. Nickel and cadmium in raw water exceed the normal level found in natural water sources.
2. The estimated annual sludge production was 450 ± 244.5 tons on a dry weight basis.
3. In terms of alternative uses or disposal of the sludge, the results showed the following:
   - Kadahokwa water treatment sludge is an important source of micronutrients (iron, manganese, zinc and copper), essential elements for plants growth.
   - Cation exchange capacity showed that Kadahokwa water treatment sludge can improve nutrients and water holding capacity of the soil.
   - Kadahokwa water treatment sludge is a poor source of total carbon, and moderate source of total nitrogen, total phosphorus and potassium.
   - Kadahokwa water treatment sludge is an important source of aluminium
   - The pH value in the sludge and all streams of Kadahokwa WTP was in the range of 6.50–7.45.

In this range metal mobility, plant uptake and plant toxicity are reduced when WTP sludge is applied to the soil.

Recommendations

From above conclusions, the following recommendations are made:

1. The effluent from the sludge drying beds should be recycled directly into the sedimentation tank. This recycling could contribute to the reduction of water treatment costs as water and chemical wastages are reduced.
2. Kadahokwa sludge should be applied to land as soil conditioner especially for the soil having a low CEC (around 10) and as micronutrients source. The major nutrients (N, P, K and carbon) have to be supplied by other important sources like commercial fertilizers manure and or sewage effluent or sludge. This is an economic and environmental friendly way because it should supply some nutrients to the crops and control the phosphorus eutrophication of the receiving water body. The aluminium recycling of the sludge coming from sedimentation tank is suggested as it can recover more than half of alum cost. It is therefore recommended that the Kadahokwa WTP sludge from sedimentation tank be studied closely to check the feasibility of the internal recycling.

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REFERENCES

Agyin-Birikorang, S., O'Connor, G. A., Jacobs, L. W., Konstantinos, C., Makris, K. C. & Brinton, S. R. 2007 Long-term phosphorus immobilization by a drinking water treatment residual. *J. Environ. Qual.* **36**, 316–323.

APHA (American Public Health Association)/AWWA/WEF 2005 *Standard Methods for the Examination of Water and Wastewater*, 21st edition, Centennial Edition, Washington, DC, USA.

AQUASTAT 2005 AQUASTAT-FAO's Information System on Water and Agriculture, www.fao.org/nr/water/aquastat (Accessed 12 February 2009).

Camberato, J. J. 2001 *Cation Exchange Capacity-Every thing you want to know and much more, Clemson University, Crop and soil Environmental Science*. South Carolina Turfgrass Foundation News. Bulletin E-2781, December 2001, USA.

Chiang, K. Y., Chou, P. H., Hua, C. R., Chien, K. L. & Cheeseman, C. 2009 Lightweight bricks manufactured from water treatment sludge and rice husks. *J. Hazard. Mater.* **171**(1–3), 76–82. (15 November 2009).

City of Durham 1986 *Pollution Prevention Challenge Grant/Project Summary*. Pollution Prevention Pays Program. N.C. Department of Natural Resources and Community Development, Division of Environmental Management. December 1985. Available http://www.p2pays.org/ref/32/31709.pdf Accessed 12 August 2008.

Dekker, J., MacKenzie, H. & Chandler, K. 2006 The effect of soil pH on *Setaria viridis* and *Abutilon theophrasti* seeding growth and tissue nutrients. *Agric. J.* **1**(1), 1–4.

ELECTROGAZ 2004 *ELECTROGAZ/Request for Budget Support 2005–2007*. Lahmeyer International.

Elliot, H. A., Dempsey, B. A. & Maille, P. J. 1990 Content and fractionation of heavy metals in water treatment sludges. *Environ. Qual.* **19**, 330–334.

Elliott, H. A., O'Connor, G. A., Lu, P. & Brinton, S. 2002 Influence of water treatment residuals on phosphorus solubility and leaching. *J. Environ. Qual.* **31**, 1362–1369.

Erdincler, A. & Seyhan, L. D. 2006 Agricultural use of municipal wastewater sludges: phosphorus availability of biological excess phosphorus removal sludges. *Water Sci. Technol.* **54**(5), 131–138.

Gregory, J. 2006 *Particles in Water, Properties and Process*. Taylor & Francis Group CRC Press, New York, USA.

Heil, D. M. & Barbarick, K. A. 1989 Water treatment sludge influence on the growth of sorghum-sudangrass. *Environ. Qual.* **18**, 292–298.

Hoppen, C., Portella, K. F., Joukoski, A. *et al.* 2005 Disposal of centrifuged sludge from water treatment plant (WTP) in concrete matrix: an alternative method for environmental protection. *Cerâmica* **51**(318), 85–95.

House, S. J. & Reed, R. A. 2004 *Emergency Water Sources: Guidelines for Selection and Treatment*, 3rd edition. Water Engineering and Development Centre (WEDC), Loughborough.

Hughes, J. C. & Titshall, L. W. 2005 Characterization of some South African water treatment residues and implications for land application. *Water SA* **31**(3), 299–307.

Indian Agricultural Ressources/Soil Management 2007 *Micronutrients in Soil*. www.indiaagronet.com. (Accessed 18 Feb 2008).

Ippolito, J. A., Barbarick, K. A. & Redente, E. F. 1999 Co-application effects of water treatment residuals and biosolids on two range grasses. *Environ. Qual.* **28**, 1644–1650.

Joukoski, A., Portella, K. F., Hoppen, C. & Andreoli, C. V. 2005 Disposal of centrifuged sludge from water treatment plant (wtp) in concrete mixtures. *Met. Mater. Process.* **17**(3/4), 389–400.

Kruis, F. 2005 *Environmental Chemistry Selected Analytical Methods*. Unesco-IHE Lecture Notes LNO168/05/1. Unpublished.

LENNTECH 2006 *WHO's Drinking Water Standards/1993*. United States Office of Water EPA-816-F-00-006.

Metcalf & Eddy Inc 2003 *Wastewater Engineering, Treatment and Reuse*, 4th edition. Mc Graw Hill, New York, USA.

Okalebo, J. R., Gathua, K. W. & Woomer, P. L. 2002 *Laboratory Methods of Soil and Plant Analysis: A Working Manual*, 2nd edition. Department of Soil Science, Moi University, Chepkoilel Campus, Eldoret, Kenya.

Park, S. G., Yahata, H., Saeki, K., Kurosawa, K. & Kim, Y. J. 2009 Physical properties of water treatment residue and their effects on plant growth as a substitute soil. *J. Fac. Agric. Kyushu Univ.* **54**(2), 481–487.

Pinarli, V. & Kaymal, G. 1994 *An Innovative Sludge Disposal Option-Reuse of Sludge by Incorporating in Construction Materials*. Ondokuz Mayis University, Department of environmental engineering, Samsun 55139, Turquie.

Rouf, Md. A. & Hossain, Md. D. 2003 *Effects of Using Arsenic-Iron Sludge in Brick Making*. Bangladesh University of Engineering and Technology, Department of Civil Engineering, MIST, Dhaka, Bangladesh, pp. 193–208.

Schubert, T. S. 1992 Manganese Toxicity of Plants in Florida. Fla. Dept. Agric. & Consumer Services. Division of Plant Industry, Plant Pathology Circular No. 353, May and June 1992.

Skene, T. M., Oades, J. M. & Kilmore, G. 2007 Water treatment sludge: a potential plant growth medium. *Soil Use Manage.* **11**(1), 29–33.

Snyman, H. G. (ed.) 2006 Sustainable management of residues from water and waste treatment. *Water Sci. Technol.* **54**(5),IWA Publishing, London, 250 pp.

Sötemann, S. W., Rensburg van, P., Ristow, N. E., Wentzel, M. C., Loewenthal, R. E. & Ekama, G. A. 2006 *Agricultural Use of Wastewater Sludge and Land Disposal*. Research Group, Department of Civil Engineering, University of Cape Town, Rondebosch, 7701, Cape Town, South Africa.

Texas Commission on Environmental Quality 2005 Chapter 312–Sludge Use, Disposal, and Transportation/Subchapter F: Disposal of water treatment sludge, 312.121–312.123. Effective from October 20, 2005.

Wang, A. S., Angle, J. S., Chaney, R. L., Delorme, T. A. & Reeves, R. D. 2006 Soil pH effects on uptake of Cd and Zn by *Thlaspi caerulescens*. *Plant Soil* **281**, 325–337.

WHO 1993 *Guidelines for Drinking Water Quality*. Vol. 1: *Recommendations*. 2nd edn, WHO, Geneva.

WSAA 1997 *Water Treatment Sludge: Potential for Use as a Soil Ameliorant*. Report No WSAA 106. May 1997.