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Chapter 14

WATER QUALITY MONITORING OF YELLOW JACKET RIVER, MAZOWE, ZIMBABWE: A REVIEW

***G. Nyamadzawo**[*1]**, F. Mapanda**[2]**, M. Wuta**[2]**, J. Nyamangara**[3]**, P. Nyamugafata**[2]** and Z. Jiri**[4]*

[1]Department of Environmental Science,
Bindura University of Science Education,
Bindura, Zimbabwe
[2]Department of Soil Science and Agricultural Engineering,
University of Zimbabwe, Mount Pleasant, Harare, Zimbabwe.
[3]ICRISAT Matopos, Bulawayo, Zimbabwe
[4]Department of Biological Sciences,
Bindura University of Science Education,
Bindura, Zimbabwe

ABSTRACT

Disposal of wastes from sulphate mining operations has been a perennial problem to the environment in many countries, because these wastes usually continue to produce acid mine drainage (AMD) for a long time after the wastes have been generated. The impacts of AMD include reduction in the quality of water. This review is a synthesis of all the research work that has been done at Iron Duke Mine (IDM) that extracts pyrite minerals in Zimbabwe and a major source of AMD for the Yellow Jacket River, which is a mere 100 m stretch from the mining operations. The data used in this review was collected over a 15 year period (1994-2010). During this period the mine has rehabilitated the pyrite waste rock dump, upgraded the of loading methods and the transformation of the mining operations to include ore processing operation. The objective of the review was to assess the chemical progresses that have come about through the rehabilitation of the pyrite waste rock dump, upgrading of equipment and the establishment of the onsite processing plant on the water quality of the Yellow Jacket River.

[*] Author for Correspondence: Department of Environmental Science, Bindura University of Science Education, Box 1020 Bindura, Zimbabwe; E-Mail: gnyama@yahoo.com

1. INTRODUCTION

Iron pyrite is an important raw material for the fertilizer industry in Zimbabwe and for export to countries like Zambia, where it is used in the making sulphuric acid for copper processing. Iron Duke Mine is the biggest supplier of iron pyrite used in the manufacturing of compound fertilisers in Zimbabwe and for exports. The mine has a production capacity of about 106 7500 tonnes per month at full capacity (William and Smith, 1994).

The extraction of iron pyrite has caused some environmental problems worldwide particularly the acidification of water bodies by acid mine drainage (AMD) resulting from the oxidation of the pyrite in waste rock and worldwide an estimated 19,300 km of rivers and streams have been affected by AMD. Areas of verified pyrite deposits in Zimbabwe include Shurugwi, Gwanda, Mazowe, Kadoma, Bulilimamangwe, Shamva and Hwange (HRC, 2009). One of the most studied mines causing AMD and affecting surface water in Zimbabwe is Iron Duke Mine which is located in Mazowe (Figure 1). Acid mine drainage from the mine has severely polluted the nearby Yellow Jacket river (The Farmer, 1998; William and Smith, 2000; Ravengai et al., 2005).

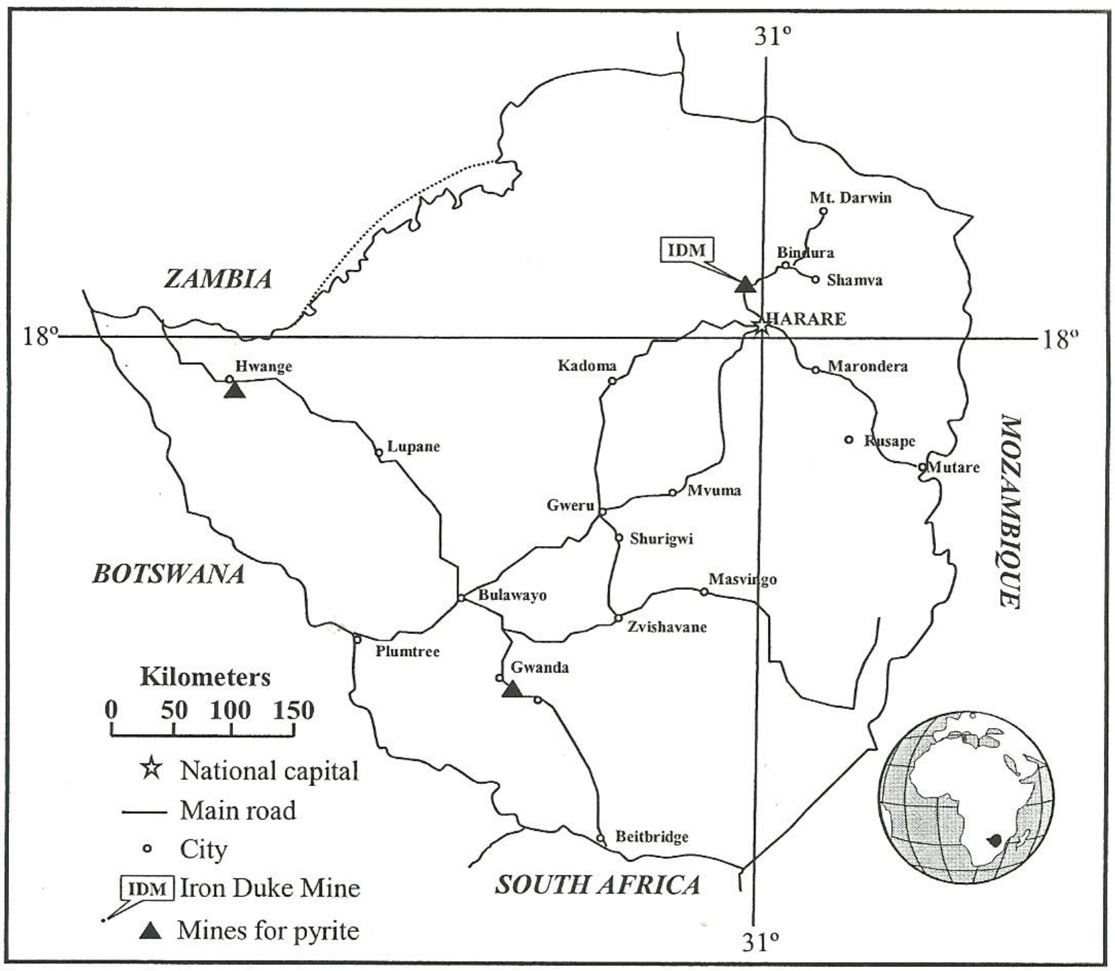

Figure 1. Location of pyrite mines in Zimbabwe including the Iron Duke Mine in Mazowe.

Acid Mine drainage at IDM has resulted in very low water pH (<2), high electrical conductivity, high concentrations of iron and sulphates, and traces of metals such as nickel, lead, and metalloids such as arsenic (William and Smith, 1994). Oxidation of waste pyrite rock from the waste rock dump generates AMD with pH as low as 0.52 and sulphate concentration of up to >2000 mg L^1 (Nyamadzawo et al. 2007). Acid mine drainage has also resulted in a significant decline in ground water pH (2.1-4.5) and water pH in Yellow Jacket River to < 3 ate the seepage point (commonly referred to as point E), (Williams and Smith, 1999; Gratwick, 2001; Ravengai et al., 2005; Nyamadzawo et al. 20007; Mapanda et al. 2007). The identified sources of AMD at IDM are the underground mining tailings, waste rock dumps, the processing plant and the evaporation ponds.

Pollution of Yellow-Jacket River is of concern because, besides affecting aquatic fauna, the river supplies irrigation water to the surrounding farms and it ultimately flows into Boroma Estate Dam that supplies Glendale Municipality and some commercial farms with potable water (Mapanda, 2007). There have been reports of fish deaths along the yellow Jacket River and these deaths have been linked to deteriorating water quality (The Farmer magazine, 1998; Williams and Smith, 2000).

The objective of this review was to synthesis the data from previous research to establish whether there has been progress in reducing AMD in the Yellow Jacket River. The review also assessed the progress made by rehabilitation of the pyrite waste rock dump, the establishment of the onsite processing plant and the establishment of temporal waste water holding ponds on the water quality of Yellow Jacket River.

2. Materials and Methods

The materials examined during this review included published articles, journal articles and book chapters, unpublished materials, academic materials, student thesis, conference proceedings, the World Wide Web and consultancy reports e.g. Environ Green report. Table 1 is a summary of some of the monitoring studies that were carried out at IDM.

Table 1. Some of the studies on the impact of mining activities at IDM on selected surface water parameters in the Yellow Jacket River.

Year	pH	EC ($mScm^{-1}$)	As	Fe	Cu	Cd	Cr	Ni	Zn	$SO4^{2-}$
93/94 [a]	0.52		72	132909	20.087	3.7	18	24	55	355425
09/2001 [b]	2			7485						.7167
99/00 [c]	3	3.2								1500
99/00 [d]	5	1.5	6	0.9				0.6		300
09/2010 [e]		10260		65.4						1357

All metals/ions concentrations are in mg l^{-1}.

[a] William 2001; [b] Ravenganai et al. 2005 ; [c] Mapanda et al. 2007; [d] Nyamadzawo et al. 2007 and [e] Mchongwe, 2010.

2.1. Study Site

Iron Duke mine is located about 50 km north of Harare, at 31° 03' E and 17° 26' S (Figure 1). It is located along a range of hills called the iron mask range which runs from north east to the south west of the country (Ferguson and Wilson, 1933; William and Smith, 2000). The mine is located in a gorge cut through the iron mask range by the Yellow Jacket River. Pyrite occurs at a depth of 100 m and a mixture of quartz and iron oxides commonly known as ironstone overlies the pyrite. The mean annual rainfall of the area is 1000 mm $year^{-1}$ and the mean temperature varies between 16°C and 21°C as measured at Mazowe satellite and weather station.

2.2. Sources of AMD at IDM

(i) Waste Rock Dump

The waste rock dump at IDM which developed over seventy years covers approximately 5000 m^2 of land. The waste rock was generated because of old mining techniques where pyrite was mined and the ore content was later tested. If the sulphur (S) contents was <20% the ore was regarded as low grade and the rock was disposed off at the dump Only ore with 20-40% S were regarded as high grade ores and was sold to ready local markets or exported to countries like Zambia where they were used to make sulphuric acid for copper processing. However, with time the mine changed methods of assessing ore content, currently they drill cores to assess ore content and this has reduced the generation of waste rocks.

The dump is located on a hill slope and at a distance of about 500 m to the north of the dump is the Yellow Jacket River. This river supplies drinking and irrigation water to Glendale town and farming communities downstream. Previous research has reported contamination of river water with AMD from the dump. This waste rock dump was rehabilitated in 1998 in to reduce the amount of AMD entering the river. The rehabilitation of waste rock material at Iron Duke Mine, involved leveling the dump to reduce the angle of the slope, making a deep trench upslope, to divert water from getting into contact with waste rock (Environ Green, 1998). A soil cover was applied at the surface and compacted to reduce water infiltration into the rock waste dump (Swanson et al., 1997). Lime was applied on the soil to prevent acidification of the topsoil layer through capillarity and to inhibit the activities of *Ferroxidants* and an acid tolerant cover of vetiver grass (*Vetiveria zizanioides L*) and *Katambora Rhodes* grass (Chloris gayana) was planted to reduce erosion (Eviron Green, 1998). At the bottom of the dump a trench was dug lined with a geo-membrane, a synthetic material which is water impermeable (Daniel, 1993). This trench collected water from the dump and direct it into the sump (temporary pond) before it was pumped into evaporation ponds, thereby reducing acidity getting into the Yellow Jacket River directly from the waste rock dump. However, the 5000 m^2 ground area covered by the waste rock dump was not lined with a geo-membrane; hence the rehabilitation exercise could not totally eliminate movement of AMD into groundwater through deep drainage.

Several studies have evaluated AMD from the waste rock dump among themWilliams and Smith (2000) who reported that the waste rock dump generated AMD with pH as low as 0.52. Acid mine Drainage from the waste rock dump was also reported by other researchers

(Nyamadzawo 2000; Ravengai et al., 2004; Meck et al., 2006; Ntengwe and Maseka, 2006: Nyamdzawo et al., 2008).

(ii) AMD from the Mine

The chief source of AMD at Iron-Duke Mine is drainage from underground workings which arises when underground water, used for cooling and trapping rock-dust and oxygen come in contact with the exposed pyrite ore (Mapanda et al. 2007). The consequential oxidation process, which is microbially mediated (Sengupta, 1992), then acidifies the water and this results in the generation of AMD. The water from the underground workings is pumped to the evaporation ponds where the water is supposed to evaporate. However, some of this water has been seeping into the Yellow Jacket River through seepage from the evaporation ponds.

(iii) Evaporation Ponds

The clay-lined evaporation ponds used for wastewater disposal are located on gently undulating terrains of about 2-5% slope and surrounded by agricultural fields where maize (*Zea mays* L.) production is the dominant agricultural activity in summer (November–January). Each pond is about 200 m long, 20-35 m wide and 0.5-0.8 m deep. In 1999 to 2000, only two ponds had wastewater containing AMD, while the third pond was used as a sewage pond (Mapanda et al. 2007). The compacted clay lining had an observed thickness ranging from about 0.2 m to less than 0.05 m, suggesting that the lining has been deteriorating in the past decade, as the lining was about 0.2 m during the time the pond was constructed (Banda, personal communication).

The lining of the ponds with clay was meant to prevent or reduce the leaching of potentially toxic pollutants from the ponds into groundwater. However, when the capacity of a soil to retain the chemical pollutants is diminished, due to excessively high concentrations of the pollutants and pH changes, the soil can release the pollutants into groundwater. Contaminated groundwater may later become surface water through lateral flow into the river (Brady, 1984).

The evaporation ponds are also a source of AMD in the Yellow Jacket River. A study by Mapanda 2000; Mapanda et al. 2007 showed that ground water around the evaporation ponds had the same pH as pond water. Groundwater pH ranged from 2.8 to 3.8 (average, 3.4). Similar results were also reported by Ravengai et al. (2003; 2004: 2005).

(iv) Pyrite Concentrator / Processing Plant

This was introduced in 2000, mainly because most of the market for pyrite e.g. Zimbabwe Phosphate industries (ZIMPHOS), were refusing to buy the pyrite in raw form because they were have having problems of AMD at their processing plants. The concentrator (Jig Processor)was to crush the rock and separate wastes from the ore which was then sold to the markets, however the problem with this method was that it was not so efficient as it produced rock waste with a Sulphur content of ~12% (Maguta, 2010) which are a source of AMD. Acid mine drainage was also produced during the processing as water was used.

The equipment was later upgraded to a new float cell concentrator which is a more efficient and this produces fine wastes with an ore content of ~ 6%. Acid mine drainage is also produced during the processing as water is used in the concentrator. The waste water generated is collected in a new settling pond which is approximately 50 m from the Yellow Jacket River before it is pumped to the evaporation ponds.

(v) Pyrite Concentrator Wastes

The Jig wastes generated from the Jig processor were dumped in a newly created Jig waste dump, 300-500 m from the old rock waste dump. The same dump is also currently used for dumping the fine wastes from the upgraded concentrator. These are a new potential source of AMD.

The tailings from concentrator are also a potential source of AMD. The jig wastes have ~12% Sulphur (S), while the fine wastes have ~6% S, (Maguta, 2010). These wastes are not covered and when it rains, the S can be oxidized to form AMD. The fine particles can also be carried by water into the Yellow Jacket River and are a potential source of AMD. However, very few studies (e.g. Maguta, 2010) have been done to evaluate the effects of the Jig waste and fine waste dump on AMD on the surrounding environment (soils and plants) and none on ground water or water quality of the Yellow Jacket River.

3. Seasonality and AMD in Yellow Jacket River

Yellow Jacket River is perennial, with peak flow occurring during the main rainy season (November-April) whilst the water volume is lowest during the dry season (May -October). Previous studies have shown that the pH of river water ranged from 7.5 upstream of the mine to 3.0 downstream of the mine and this trend was consistent during the dry seasons (Nyamadzawo et al. 2007). There was a general increase in river water pH from January to March (rainy months), the wet months and during this time the pH before the mine and after the mine were comparable, probably due to dilution effect (Mapanda et la. 2007).

Sources of AMD in the Yellow Jacket River have been cited as the Waste Rock dump (Gratwick, 2001, The Farmer 1996; Nyamadzawo et al 2007). Although the Rock waste dump was rehabilitated, previous studies have shown no significant changes in the acidification of ground water down slope of the dump (between the dump and the river) two years after rehabilitation (Nyamdzawo et al. 2007) and ten years after rehabilitation (Chizvondo et al. 2008).

The evaporation ponds are also a source of AMD in the Yellow Jacket River. Ground water around the evaporation ponds had comparable pH, EC, total dissolved solids (TDS), sulphates river water at the "seepage point" (Mapanda et al. 2007) also referred to as "point E" (Mchongwe, 2010). The water also had high very high iron contents. Water moved through subsurface flow and entered the Yellow Jacket River as a spring at a point referred to as the 'Seepage Point' with pH < 3, (Ravengai et al., 2004; Mapanda et al. 2007; Nyamadzawo et al. 2007). The chemical quality of the Yellow Jacket River water notably changed at the site adjacent to the pond. This was also the site where the river water colour was pale-red in July (dry period). The results suggested that lateral flow of contaminated groundwater containing leachates from the ponds into the river increased the concentrations of iron, nickel, sulphates, salts and acidity in the river (Mapanda et al. 2007: Mchongwe, 2010). A summary of some of the measured parameters is shown in Table 1.

Lately, the onsite processing facility has also contributed to an increase in AMD into the Yellow Jacket River. The first aspect is that the pyrite concentrating plant uses water. This waste water is stored in a temporal storage pond before it is pumped to the evaporation ponds. The temporal storage pond is 50 m from the Yellow Jacket River. To date no study has been done to evaluate the impacts of this temporal storage pond on water quality of the Yellow Jacket River though this is a potential source of AMD

4. Biotic Indicators in YJR

Acid mine drainage at IDM has been reported to cause detrimental effects to the environment and health of the plant and aquatic fauna downstream. Pollution of Yellow-Jacket River at Iron Duke Mine could be a potential environmental and health hazard because the river flows into Boroma Estate Dam that supplies Glendale Municipality and with potable water (Mapanda, 2007). A couple of studies have been carried out to evaluate the effects of AMD in the Yellow Jacket River on aquatic fauna (William and Smith, 2000; Ravengai et al. 2005; Mungazi, 2006. Gratwick, 2000). Acid mine drainage from IDM has been reported to result in fish deaths along the Yellow Jacket River (The Farmer magazine, 1998; Williams and Smith, 2000) There was also a decrease in amount of other aquatic species along the river from IDM going downstream when compared to the upstream (Mungazi, 2006). Thus, the need for more studies to evaluate the currents effects of AMD from IDM on aquatic fauna in the Yellow Jacket River.

5. General Discussion

This review highlighted the challenges of AMD that are associated with mining in Zimbabwe and the world over. Acid mine drainage at IDM poses considerable environmental challenges that need a holistic approach to solve. Based on this review, the waste rock dump, evaporation ponds, pyrite concentrating plant and the waste from the concentrating plant (jig waste pile) are all sources of AMD contaminating the Yellow Jacket River. The discharging of acid-mine drainage into the evaporation ponds lined with a thin clay layer has also not been an environmentally effective means of AMD containment and disposal as the water from the ponds polluting ground water which then gets into the Yellow Jacket River.

There is also need for monitoring the treated effluent for acid re-generation in the evaporation ponds. A study by Mchongwe, (2008) has shown that the treated AMD water from IDM re-generated acidity. Though the effluent water is partially treated with lime to a neutral pH before being pumped to the evaporation ponds, a study by Mapanda et al. 2007 showed that evaporation ponds had an average pH of 3.4 from a pH of 7 soon after treatment. Mchongwe (2008) showed that AMD pre-treated water from the mine/the waste rock dump had very high levels of S, TDS and EC. The partial treatment of the water through liming before it is pumped into the evaporation ponds resulted in the improvement of the waste water quality. However, the ponds had high concentrations of TDS, sulphates and EC than the treated effluent.

The construction and design of the evaporation ponds and temporal waste storage ponds from the processing plant at IDM need to be improved. The ponds that are used to store AMD water only have one, thin compacted layer of clay about 0.2 m which became thinner over years to as little as 0.05 m (Mapanda, 2007). Proper design which includes primary and secondary layers of compacted clay, geomembrane (HDPE), drainage monitoring system should be included (Tammemagi, 1999).

The sitting of the temporal waste water storage pond, ~50m from the Yellow Jacket River should be revised. This pond is so close to the river and it could be another direct entry point of effluent into the Yellow Jacket River. Further studies should be carried out to evaluate the effects of the temporal waste water ponds on AMD on the surrounding soil and the Yellow Jacket River.

The management of IDM is also encourage to properly design and line with compacted clay, and geomebrane on the new Pyrite concentrator waste pile to avoid a repeat of the current problems that are occurring at the rock waste dump site. Water entry into the pyrite processing waste pile should be reduced to prevent the contact of water with sulphate containing aggregate and fine particles. Drainage system from this pile should be improved so that that all waste water will be collected and treated before it gets into the Yellow Jacket River.

The waste rock dump should be maintained to reduce the amounts of water that is getting into contact with the waste rock and generate AMD. The condition of the waste rock dump had deteriorated so much from the initial rehabilitation program. Right now the grass that cover the dump is dead, the top layer of soil has been removed or washed away by runoff, the waste dump is collapsing inwards, the contour ridges are no longer diverting water from the waste rock dump, as a result is getting into the dump and the end result is the generation of AMD.

Acid mine drainage in the Yellow Jacket River has resulted in the deterioration of water quality, and invertebrate taxa downstream of IDM when compared to the control area that was before the mine. (Mungazi, 2006) reported that as a result of AMD the area downstream of the mine is dominated by acid tolerant invertebrates. This is not healthy for the Yellow Jacket River thus there is need for a reduction in the amount of AMD that is getting into the river to build species diversity.

5.1. Areas for Further Studies

There is need to explore better water treatment, pond design techniques, and waste dump management practices if the problems of AMD at IDM are to be solved. Acid Mine Drainage's environmental impacts can be through the prevention of the acid-generating process; prevention of acid drainage migration and the collection and treatment of effluent.

The prevention of the acid generation process involves (a) Reduction in the amount or volume of water from the mine, preventing water from getting into the waste rock dump, the pyrite concentrator wastes as this may generate AMD. There is also need for reducing the amount of fine wastes that are produced during processing.

More focus should be placed on the evaporation ponds as they are a major source of AMD migration. The first approach should be improving the design of the evaporation ponds. The current ponds are only lined with compacted clay. The improved design should include compacted clays, a geomembrane, water monitoring system and also a facility to treat any AMD seepage. In line with the improved design on the ponds, there is also need to use water balance model can be used to design ponds that have enough capacity to hold the AMD water that is produced without overflowing or that is lost to deep water percolation into the ground water. Using the water balance model, one can identify periods of water deficiencies or period of excess water. Hence the Model will be borrowed and used to explain a puzzle and possible AMD from Evaporation ponds at Iron Duke Mine. The model can be used to prove if there is pollution of the Yellow Jacket River from excess AMD from the evaporation ponds. Hence the water balance equation in its simplest form of expression is:

$$\text{Change in water in the ponds} = \text{Inputs of water} - \text{Losses of water} \qquad (1)$$

There is also need to further explore, and address cause of AMD regeneration in the evaporation ponds. Mchongwe (2008) showed that the AMD was regenerating after the partial treatment (to pH 7) before the water was pumped into the evaporation ponds. The mine water contains some dissolved solids which contain sulphur and can be oxidized resulting in the regeneration of AMD. The extent of AMD regeneration at IDM regeneration and long term re-treatment options are not known and no effort has been done to address the problem.

CONCLUSION

The Yellow Jacket River is one of the many rivers that are being affected by AMD resulting in the deterioration in water quality and aquatic fauna. The problem of AMD at IDM remains a challenge since the control of AMD is very difficult once the problem has started. Efforts need to be made to reduce the amount of AMD that gets into the Yellow Jacket River either through subsurface flow or through runoff or as fine particles which will be oxidized to form AMD. There is also need for increase efforts to reduce AMD generation at the mine. Continuous monitoring of the effects of AMD on the Yellow Jacket River is required as it will give an indication on whether changes in environmental management, production and processing at IDM is improving or worsening the impacts of AMD on the Yellow Jacket River.

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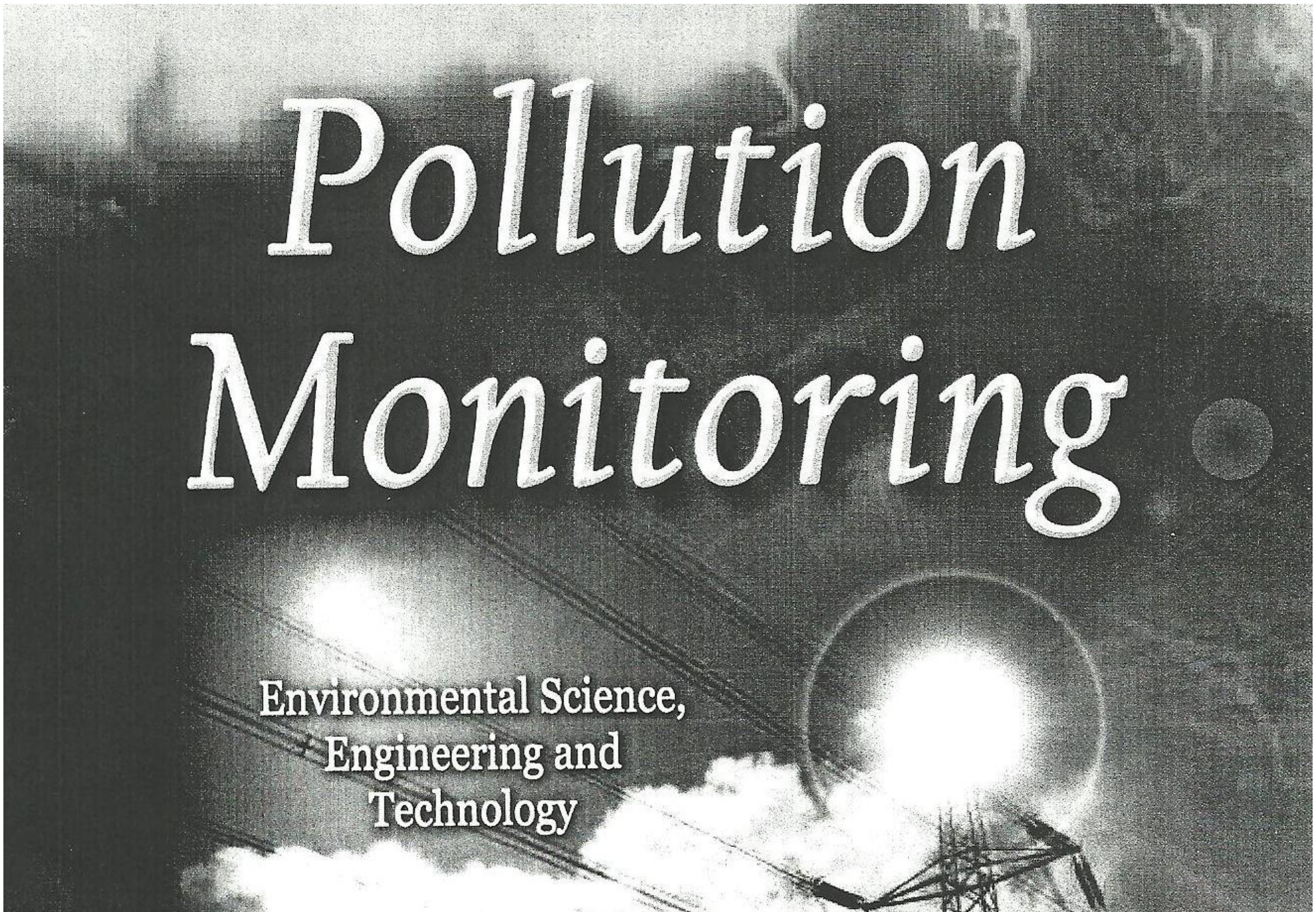

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