Incident

Municipal water disasters — a role for process safety?

Ken Patterson, UK; Paul Stanford Kupakuwana, University of Bolton, UK

Summary

This paper discusses catastrophic maloperation of the public water supply in two cities — one in the richest country in the world, the USA; the second in one of the poorer nations, Zimbabwe. In both cases, it seems that hundreds of people died because of failures in a previously effective drinking water supply system. In both cases changes were made without the degree of assessment that would be expected in the process industries. The paper suggests that if the sort of assessment which is common in Process Safety Management systems had been carried out, and the assessments followed through, the deaths would have been avoided.

Keywords: Process safety management, water supply.

Introduction

Industries which handle hazardous substances have developed comprehensive systems for assessing and managing the potential risks of their operations. The systems cover new processes they intend to carry out; maintaining the safety of the systems in current operation; and managing changes in those processes, whether of the physical plant itself, of the precise details of the process, or of the people managing and operating the processes. These generally go under the title of Process Safety Management (PSM) systems, which IChemE defines in its Fundamentals of Process Safety course as: "A systematic framework for the management of the integrity of hazardous processes". The use of PSM systems is mandatory under legislation in the USA (OSHA PSM), in the EU (The Seveso Directive), and more recently in China and other jurisdictions around the world.

The details of PSM systems vary from industry to industry, depending on the materials being processed, the hazards involved and the possible consequences of any failures. Nonetheless the general outline of a PSM system is common — desktop exercises throughout the design and construction phases to assess and minimise the risks of (or from) the process; strict operational controls to ensure operation within the safe limits of the plant; and allowing changes to the plant equipment, operation or control only after further risk assessment to demonstrate continued safe operation. Detailed techniques for assessing the hazards of the materials, processes and process conditions are available. Similarly, techniques for both consequence analysis and risk assessment have been developed, which can be either qualitative or quantitative, or a mixture of both. Whilst accidents still occur, we can be certain that their number, frequency and severity have all been mitigated by the use of these PSM principles.

Although developed for high hazard industries, these principles and practices are of much wider application. Growing populations and increasing dependence on public utilities such as water, power and increasingly internet access, means that failures or maloperation of public services now have the capacity to affect many people, potentially fatally. These two case studies of failure to operate public water systems safely, which led to hundreds or thousands of deaths, illustrate this and suggest that the principles of PSM should be extended to these areas.

Case study 1 — Flint, Michigan, USA

Background

Flint, Michigan is a city about 100km from Detroit in the north-east of the USA, close to the Canadian border. Like Detroit, Flint has traditionally been very dependent on the car manufacturing industry. General Motors (GM) was founded there and had large plants in the town. At its peak in the 1960s & 70s, the city had nearly 200,000 inhabitants and the GM plants had about 80,000 employees. By 2010 the GM plants employed 8,000 people and the city's population had reduced to just over 100,000. The loss of its manufacturing base and loss of population led to a loss of tax revenues for its local government. This loss led to effective bankruptcy and in 2011 the appointment, by the state governor, of a municipal manager with powers to override the elected council.

Up to the 1960s Flint had generated its own drinking water and had its own treatment plant. Then a long-term contract was signed with Detroit to supply all of Flint's water. The Flint treatment plant was mothballed and kept for emergency use only. However, by 2010 Detroit's revenues had also fallen and the price of the water sold to Flint had risen significantly. Flint and adjacent local authorities formed a new company to extract raw water from Lake Huron and treat it locally, re-starting the mothballed plant. This project was delayed and in 2013 the municipal manager and his team decided to re-start the water treatment plant, mothballed for 50 years, taking water from the local River Flint rather than Lake Huron. The team making this decision did not have significant experience in managing or providing a public water supply; it does not seem that they carried out any hazard or safety studies to assess their proposed actions. Flint switched to domestic water

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from the River Flint, treated in the re-activated plant, on 21 April 2014. This occurred despite the city's utilities manager recommending against the restart and expressing concern that the staff were not sufficiently trained, the monitoring systems were not adequate, and the treatment plant was not ready for operation.

Water supply system

In common with many towns built in the 19th and early 20th centuries, Flint has areas of the city where domestic water is distributed in lead pipes and other areas where cast iron pipes are used. Whilst they are never ideal, water can be distributed in lead pipes relatively safely if the water contains sufficient dissolved minerals, normally calcium carbonate or calcium orthophosphate. These may be naturally occurring or added during treatment. The minerals form an insoluble layer on the inside of the pipe, largely preventing lead dissolving into the water. If the layer is not present, or disappears, lead pipes dissolve into the water, with severe risk of chronic lead poisoning. Lead is a severe neurotoxin and retards brain development; the US federal limit for lead in drinking water is 15 parts per billion (ppb). The mineral layer also protects cast iron pipes which are present in all but the most modern public water systems. Without the mineral layer cast iron pipes are attacked by dissolved oxygen forming internal rust. Iron rust is known to be a habitat in which legionella can develop.

The water in the River Flint is not naturally rich in minerals and can be acidic due to high levels of chloride ion. As there is both human and animal activity upstream of Flint City, the water needed to be treated with chlorine in the re-started treatment plant, to ensure biological purity. However, excess chlorine makes the water acidic and acidic water will dissolve the mineral layer. In order to save $140 per day (~$50,000 per year) corrosion inhibitor (orthophosphate) was not added to the water. Despite the chlorine treatment, by mid-August E coli bacteria, which cause sickness and diarrhoea, was detected in Flint drinking water. Residents in some areas were advised to boil their water for at least 60 seconds before using it. At the same time residents reported that the water had turned brown and had a metallic taste.

The crisis and its effects

To counteract the E coli infection, the rate of chlorine addition was increased, which made the water more acidic and this further dissolved the mineral layer inside the lead and cast iron pipes. Lead levels increased with the result that by 2015 40% of samples from Flint households tested above the federal limit, with one property tested at 13,200 ppb lead. Blood tests on Flint children showed that 5%, and up to 10% in some areas, had high blood lead levels. Foetal deaths were later found to have increased by 58%, which has been attributed to the high levels of lead in the water supply.

Increasing the chlorine addition to deal with the E coli infection, without consideration of the likely consequences, had produced significant adverse side effects. Where pipes were made of cast iron, once the mineral layer had dissolved, they were rapidly attacked by the acidic, chloride ion containing water. This rotted the pipes, causing leaks, turning the water brown and giving it a bad taste. This was not just a problem for Flint residents as the water supply also fed the local General Motors (GM) car engine plants. GM quickly found that the high acidity and chloride content was causing rusting on their engines and other components. GM insisted on returning to Detroit water in October 2014, a full year before the whole Flint system transferred back to the Detroit supply.

The increase in chlorine levels was not even successful in preventing disease. Without corrosion inhibitor the additional chlorine was rapidly consumed in destroying the mineral layer and dissolving the cast iron pipes, leaving the water without disinfectant properties. E coli continued to be detected and Flint suffered an outbreak of Legionnaires disease which was attributed to the water supply; this led to at least 12 deaths; some estimates put the actual number of deaths at well in excess of 100.

Besides the dreadful human effects, the financial effects of the decisions made by the city manager proved disastrous. The switch away from Detroit water was aimed at saving $5million over a 2-year period. Instead the State had to give Flint a $28 million aid package including $17 million for the provision of bottled water and water filters. In October 2015 Flint reconnected to the Detroit water supply at a cost of $9.35 million and at the end of 2017 signed a new 30-year contract with Detroit. Flint's water system was ageing and undoubtedly in need of significant repair and renewal before the switch. However, the two decisions not to use corrosion inhibitor (to save $50,000 per year) and to add additional chlorine to water already containing dissolved chloride iron undoubtedly led to rapid attack on the ageing system. The lead pipes in more than 20,000 houses are being replaced and cast iron mains are having to be renewed. Official estimates of the final cost of renewing the water supply in Flint are currently in excess of $500 million, though other estimates suggest the final cost will be up to three times this amount.

The city managers were facing criminal charges including involuntary manslaughter, but all charges were dropped and the investigation re-started in June 2019. The State attorney general said that it was possible that the officials could be charged again[3]. The city's residents are attempting to sue City, State and Emergency Managers, and also contractors working for the city at the time. Revealingly, one contractor has said "Flint emergency managers routinely ignored doing what was best for the city's water system and instead did what was cheapest", while an internal email by another contractor (Veolia) said "There is no process control, plant operators are not well trained [and] data is not well managed or trended"[4]. These are precisely the types of problem effective PSM systems guard against.

Case study 2 — Harare, Zimbabwe

Background

Harare is the capital of Zimbabwe and had an estimated city population of 1.6 million in 2009[7]. The surrounding metropolitan area has a much larger population, which is estimated at up to 4 million[8]. The city was founded in 1890 by white settlers and became the capital of the country, then known by its pre-independence name of Southern Rhodesia, in 1923. The land in much of the area was marshy and significant work was done to provide both drinking water and sewage disposal systems, together with land drainage. Rainfall is

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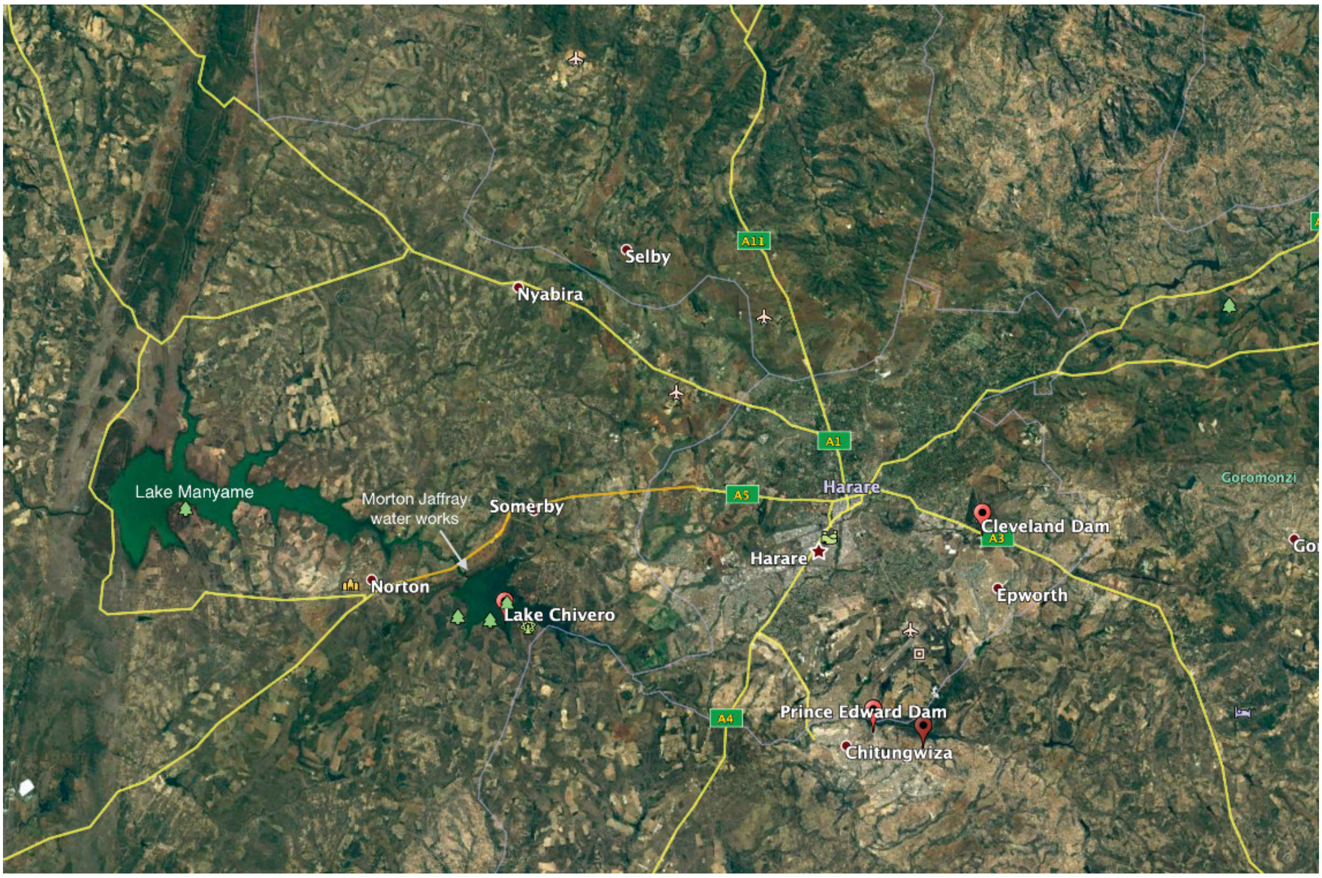

Figure 1 – Harare and its surroundings, taken from Google Earth, image dated March 2019

moderate but adequate at about 825mm a year. However, the rainfall is not equally spread through the year with a dry season running from May to September when rainfall is usually only ~20mm, making water storage essential.

The city is on the Highveld plateau at an elevation of ~1450m. There are higher, more mountainous areas around the city which do provide local watercourses and some water supply. Nonetheless the predominant drainage is away from the city, towards the major rivers which run down to the Indian Ocean. This topography means that the majority of the city's water supply comes from two large reservoirs, Lake Chivero and Lake Manyame which are both downstream from, and hence below, the city. These reservoirs are roughly 35 & 50 kms from Harare centre respectively, and are 100m and 125m below the city. They are shown in Figure 1, a satellite view of the city and its surroundings.

Hydrological system

The rivers which feed into the two lakes, principally the Manyame river, are also the rivers into which the sewage treatment systems from Harare and its surroundings, discharge their effluent. These rivers also accept a significant amount of agricultural run-off, which can be rich in nitrates. Although not visible on Figure 1, a closer view of both lakes shows that, in the summer especially, they both suffer from significant algal bloom and infestation with water hyacinth. Algal bloom affects water quality directly and both affect the ability of water to clear pollutants naturally over time. This hydrological system has a number of important consequences. Most obviously the city is dependent on significant pumping capacity, both to get water from the main water treatment plant (Morton Jaffray, which is situated between the two lakes) to Harare but also to distribute water around the city's local system.

The water supply in Harare and its surrounding area is supplemented by a series of other dammed water courses (some dams can be seen in Figure 1), and by over 200 deep boreholes financed by UNICEF, and shallow wells, usually locally dug. Despite this, it is estimated that some 80-95% of the city region's water is recycled around the system. This clearly means that an integrated system which gives constant, efficient and effective treatment of both the drinking water supply and sewage before disposal, is essential.

Population, system control and funding

In at least one respect the problems in Harare stem from the opposite problem to Flint — a rapidly rising population rather than a falling one. The initial systems were built for a Harare City population of roundly 150,000 in the 1950s, though with a capacity to supply 350,000 people. Capacity was expanded to cope with the increasing population, which quadrupled to just over 600,000 by 1980. Morton Jaffray was further expanded in the 1980s but another doubling of the city's population to 1.4 million by 2000 put the system under great strain and since then the system has been under almost constant crisis.

Access to clean water is recognised as human right, both by the UN in the key Sustainable Development Goals (SDG6), and in the Zimbabwe Constitution (section 77). Despite this the

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percentage of Zimbabwe's urban population with access to clean, safe drinking water fell from over 90% in 1988 to 71% in 2017[9]. Over the period 2000-2017 the proportion of the urban population with access to at least basic sanitation fell from 65% to 46%[9]. The lack of effective sanitation has led to many of the boreholes and wells becoming contaminated and failing to provide clean water. The effects of this on both individuals and the Harare community are set out in detail in the two major reports[5,6].

In the 1980s & 90s, after full independence, the country came under severe pressure from the World Bank and IMF to restructure the country's economy and privatise public utilities. This included water supply, which was passed to a State agency in 1998, though the Harare system was returned to the City Council in 2009. In addition, the whole of Zimbabwe suffered severe economic difficulties, including a 10-year period when the country's economy shrank significantly (-17.3% in 2003 alone)[10] and when the rate of inflation reached a staggering 2 billion (109) per cent in 2008[11]. This has meant that foreign exchange has been in chronically short supply.

The increase in the number of people dependent on the water system has not been matched by anything approaching an equivalent increase in revenues. A significant part of the population is "informal", making the collection of taxes or other revenue difficult. Post-privatisation funding was meant to be entirely from the metered sale of water. However, the Harare metering system is notoriously unreliable, many people are given "average" bills and price rises meant that many were unable to pay their bills. This led to large debts which have high rates of interest, making them even more impossible for consumers to pay. The penalty for non-payment is disconnection, which has led to informal connections to the system or deliberate breakage of pipes, wasting water. Then, in an election campaign, the Government announced that all outstanding bills would be cancelled, removing much of the incentive for other residents to pay their bills. Finally, Zimbabwe is ranked as one of the worst countries in the world for corruption and it is certain that revenues from the water account, which should be "ring-fenced" have been diverted into the general accounts of Harare City Council.

The continuing crisis

Since 2000 the water and sewerage system in Harare has gone from crisis to crisis. Even before 2000 the water in Lake Chivero was known to be polluted with nitrates and phosphates, increasing the chance of algal bloom (and hence eutrophication) and difficulty in producing drinking water[12]. The crisis is continuing with the Mayor of Harare admitting the poor (dangerous) quality of the city's water in January 2018[13]. Problems with water treatment, on occasions caused by lack of foreign exchange to purchase necessary treatment chemicals, have allowed contaminated and corrosive water to enter the system. This has been disastrous to both human health and to the distribution system. Of the 16 pumps at Morton Jaffray often only half are operational. The supply system is reported to lose up to 60% of the purified water pumped by Morton Jaffray, with 200 leaks a day reported to Harare Water but only ~50 repaired. Supply has become intermittent with water only available for a few hours a day or not available at all for several days. Even hospitals have reported being without water for up to a week at a time. When water is available it is often mouldy smelling and discoloured.

The sewage systems are in an equally poor state. There are several effluent treatment plants (ETPs) but all are overloaded and discharge poorly treated wastewater into the local rivers. The failures of water supply, preventing flushing of lavatories; of connection to the sewage works; and of the sewage plants themselves means that toilets are not usable and not used. The consequent significant ground pollution penetrates the ground water, which leads to both boreholes and shallow wells becoming polluted in turn.

The lack of sanitation has led to repeated health crises, as well as a chronic high level of illness and child mortality. The worst single outbreak of cholera in 2008 led to 100,000 cholera cases and 4,000 deaths. Outbreaks have continued with 3,000 cases of typhoid reported in Harare in 2012 and 50,000 cases of diarrhoea recorded in 2017 with 30 people dying. Childhood diarrhoea, caused by poor drinking water quality and lack of sanitation is a major cause of childhood death across Africa.

The crisis in the water supply system continues. The poor quality of water in Lake Chivero means that purification costs are very high, the cost of chemicals is put at $3million per month, and backwashing of the filter beds must be done every few hours rather than every few days. The cleaner water in Lake Manyame has not been accessible to Morton Jaffray works for some years as the connecting tunnel and pumps have fallen into disrepair. The President of Zimbabwe ordered immediate re-instatement of the link in December 2019.

There were severe water shortages in July 2019 due to drought conditions and Morton Jaffray, having operated at reduced capacity for some time, had to close in September 2019 when water treatment chemicals ran out. The city currently owes $74million to its treatment chemical suppliers. The lack of water has meant increased pressure on boreholes and shallow wells with women waiting many hours each day to get water. Many residents have to buy water, including bottle water — not always of acceptable quality and at much higher cost. The regional governor estimated in March 2020 that Harare needs $2.5 billion of investment to provide an effective water system for the city[14,15].

As at Flint, short term expedient decisions have led to death and disease, and higher costs elsewhere in the system.

Lessons learned

Sadly, in both cities the crisis continues at least in part, suggesting that operational lessons remain to be learned. In Flint the problem of lead in the water supply seems to have been dealt with but many people still refuse to drink tap water and use bottled water instead. In Harare the water supply is still reported to be erratic, with taps being dry for days at a time. Lake Chivero continues to receive poorly treated effluent. In both cases, good PSM systems would ensure that the risks and benefits of current operational practices — and changes in operational practice — are evaluated and understood. Making the PSM system publicly visible would help restore public trust in the water supply system.

For the high hazard industries these cases should serve as a reminder that resuming a process after a shutdown of any

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significant duration should be properly assessed, especially if there is any possibility that operational experience has been lost. They also serve to remind us about the danger of trading short term savings against long term risks and costs.

A wider lesson is the applicability of good leadership, with an understanding of process safety principles, not just to the traditional high hazard industries but to all industries or services with the potential to cause significant harm. The OECD process safety guidance for senior leaders[16] provides good guidance on what is required and provides an appropriate starting point for the leaders of every organisation with this potential.

Conclusion

In each of these cases, decisions taken by public officials have led to significant numbers of deaths and significant financial costs to restore a clean water supply and/or an effective sewerage system. From a process safety standpoint, it is clear that in both cases basic process safety principles were ignored. Although knowledge was available, no careful analysis of the likely (or in fact inevitable) outcomes of the actions being proposed was undertaken, instead perceived or promised cost savings and short term expedients were the overriding drivers of the actions taken.

The use of basic hazard analysis techniques, What If? studies and drawing on expert knowledge would have given decision makers good predictions of the likely effects of their decisions. These studies should have been followed by consequence analysis — followed all the way through the chain of consequences — including estimation of the financial and human costs of the predicted outcomes. An interesting discussion of how Bowtie techniques can be used in the water industry, following consequences through the process chain, was given by Hew Cameron Merrett at Hazards 29[17]. This would have given decision makers the appropriate information on which to make their decisions.

Water supply does not obviously fit the "hazardous process" part of the IChemE definition of process safety. Nonetheless the consequences of poor decisions in these two case studies have been equally catastrophic. It seems likely that the use of process safety techniques and principles, possibly enforced by similar legislation as that used for traditional high hazards industries, would have avoided the human and financial catastrophes which actually happened.

Authorial note

This article has been developed from an original article about the Harare water crisis written by Dr Paul Stanford Kupakuwana in 2018. A section on the problems in Flint, Michigan by Dr Ken Patterson was added in 2019. The whole article was completely revised into its present form, with additional material added on recent developments, by Dr. Patterson in early 2020.

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