WATER MANAGEMENT IN ANGLO PLATINUM PROCESS OPERATIONS: EFFECTS OF WATER QUALITY ON PROCESS OPERATIONS

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ABSTRACT

Water is essential to most metallurgical processes, as it may have a direct impact on the efficiency of the processes, and thus a good understanding of the effects of water on the various processes is required.

In general a metallurgical plant receives potable, secondary and recycle waters. Environmental concern, as well as strategic planning in water-scarce countries like South Africa, has led to the need to recycle and reuse waters within metallurgical plants and to use waters other than potable water as make-up water. As water is both a transport and a process medium, this has a profound effect on the efficiency of the process. It is therefore essential that the effects of various waters on a process be assessed and that the water be managed to minimise any detrimental effects. The objective of this study is to identify water qualities acceptable to individual processes and to design any necessary treatment to produce water of a quality that is not detrimental to operational performance.

For this reason Anglo Platinum has been running a project in which the impact of waters on the various processes have been assessed and recommendations as to the management and / or treatment of the waters are being investigated. Due to the fact that each process is unique in terms of ore type, plant situation, water quality etc, each site needs to be individually assessed as generalisations cannot be made. In this paper we review current water usage within metallurgical processes and discuss specific case studies within Anglo Platinum.

1. INTRODUCTION

Water is both a transport and a process medium in the processing of raw minerals, and the properties of different waters can have profound effects on the efficiency of the processing. To ensure that metallurgical processes can be continued and enlarged (where necessary) in an environment where water (particularly potable water) is becoming ever more scarce, and to endeavour to subscribe to a zero release policy, metallurgical plants need to lower water consumption as much as possible and minimise their external intake of water (Atmaca and Kuyumcu, 2003). This means that recycling of waters within metallurgical processes is required. From a strategic perspective it is also advisable to replace, where possible, potable water with treated sewage waters and / or secondary waters. An example of grey water is treated sewage effluent water, whilst underground mine water can be described as secondary waters.

In many cases recycling waters within flotation plants is advantageous as:

- It lowers the need to receive new water into the system;
- It lowers the amount of discharge; and
- It allows retention of some reagents, lowering reagent consumption.

However, water recycling may have a negative effect on raw material beneficiation and this effect may only be seen months after recycling commences (Forssberg and Hallin, 1988). Some disadvantages of recycling waters are:

- A decrease in reagent efficacy as a result of contaminants, such as increased suspended solid, within recycle waters (Atmaca and Kuyumcu, 2003);
- Secondary effects of increased pollutant levels in the recycle waters, e.g. chemical and microbiological oxidation and, in some cases, acid production (Atmaca and Kuyumcu, 2003).

It should be noted that the increasing costs of high quality water are becoming prohibitive and thus there is economic sense in treating certain secondary, grey or recycle waters, to the quality required by the process. This is economically and strategically sensible.

More important than water treatment, however (and more cost-effective) is to ensure that the water reticulation system within a plant is optimised and that the quality of the water used in the various processes is kept constant. One of the major problems regarding water usage on metallurgical plants is the high level of fluctuation in water quality. Metallurgical processes are extremely sensitive to variations in water quality and it is therefore important that water streams are managed in such a way as to minimise quality fluctuations and ensure consistency in quality.

It may take a plant a few weeks to achieve equilibrium after a change in water quality and thus it is self evident that water of a stable quality should be achieved (Johnson, 2003). Any recycle water being taken into the process(es) should be introduced at appropriate points e.g. it is inefficient to introduce a high alkalinity water into an acid circuit. Once a stable water quality has been achieved, reagent regimes can be set up to optimise the process with the water quality available. By optimising reagent regimes, water quality effects can be minimised providing a water of constant quality is fed to the plant.

Water savings can also be achieved if the following requirements are met:

- The process engineering within the plant is optimal;
- Evaporation losses are decreased – either by a physical covering being placed over tanks or dams (e.g. polystyrene balls) or by filtering or paste thickening tailings material or by high rate of rise for residue / tailings impoundments; and
- Dry ore upgrading technologies are researched to decrease the water consumption per ounce or ton of metal produced.

2. AN OVERVIEW OF THE EFFECTS OF RECYCLE WATERS ON FLOTATION

Types of Recycle Waters

Recycle waters are generally sourced from tailings dams and clarification ponds (long recycle or external recycle waters) (Levay, Smart and Skinner, 2001), and thickener overflows, dewatering and filtration units directly connected to the concentrator (short recycle or internal recycle waters) (Johnson, 2003; Levay, Smart and Skinner, 2001; Roderick and Dopson, 1985).

Long Recycle Waters

Typical contaminants in tailings waters are: SO_4^{2-}, Cl^-, F^-, Mg^{2+}, Ca^{2+}, Na^+, K^+, sulphide, thiosalts, base metals, collectors, frothers, activators, depressants, colloidal materials e.g. silicates, clays and iron hydroxides, and natural organic material (Smith and Hertzog, 1985). In some processes metal ions may also be found in the tailings water but in others, where, for example, lime is added to the tailings dam, these metal ions will precipitate out (Forssberg and Hallin, 1988).

With regards the recycling of tailings waters, time effects become important due to the delay in the water being returned to the plant (Forssberg and Hallin, 1988). Tailings return water tends to have low redox potentials and low oxygen contents due to the oxidation processes in the pond. Any higher conductivities in the recycle water compared with potable water are caused by evaporation, although some of the ion species absorb onto the tailings material surfaces as the water percolates through. It should be noted, however, that during times of high rainfall or the snow melt season, the conductivity may decrease due to dilution with “pure” water (A. Copeland, *pers. Comm.*).Another effect of tailings return water is that of environmental input into the water (Forssberg and Hallin, 1988). Most problems connected to the use of recycled water tend to be connected to process chemical residues and different types of oils that may accumulate in tailings return dams (Forssberg and Hallin, 1988).

Short Recycle Waters

In internal recycle waters the flotation reagents have not had time to decompose, leading to decreased reagent usage in the plant. However, the suspended solids levels tend to be high, and this has a consequent negative impact on flotation (Rey and Raffinot, 1966).

Maximum recycling of water from processes within a metallurgical plant occur when:

- There is maximum removal of water from each of the product streams; and
- Water is returned to the processing plant from all of the product streams (Johnson, 2003).

General Effects of Recycle Waters

Water chemistry influences the performance and selectivity of the flotation process as the milled ore is constantly in contact with water. The least effects of water chemistry are observed in recycle waters where:

- Flotation reagents contribute only small amounts of deleterious species; and
- The ore itself contributes minimal quantities of species due to low solubility products within the minerals and limited oxidation of the value and gangue minerals (Johnson, 2003).

Generally, however, ore dissolution and reagent addition cause various elements / compounds to accumulate in solution, which alters the chemistry of the system (Rey and Raffinot, 1966). An example in which ore dissolution has an effect could be in a complex sulphide flotation plant where, during water recycling, small amounts of copper may be dissolved during ore / water interaction. Eventually the level of dissolved copper may become high enough to cause sphalerite (which should be depressed at the start of the float) to be activated (Smith and Hertzog, 1985).

Recycle waters generally have increased levels of total dissolved solids (TDS). This increase in TDS causes an increase in the specific gravity (SG) of water which has an effect on slurries (Rao and Finch, 1989). If the SG of the slurry is kept constant with increasing water SG, it could lead to a lower solids percentage, through put within a plant. Slurry viscosity may also increase with increasing electrolyte concentrations due to particle aggregation, which can affect mineral floatability as well as classification and pumping (Rao and Finch, 1989).

Flotation of minerals from gangue and from each other makes use of their different surface properties (Arnold and Aplan, 1986). These surface properties are affected by solution components e.g. passivation of mineral surfaces may occur due to ion precipitation, and this has a negative effect on flotation as the surface chemistry of the mineral is changed. However, the effect of these components may be somewhat negated by the use of reagents which can be used to modify surface properties (Smith and Hartzog, 1985).

Reagent consumption decreases by about 50% when water from the process is reused compared with potable water (Forssberg and Hallin, 1988). However, these recycled waters can cause very stable froths to form, and so measures need to be taken to ensure that a water causing stable froth formation is not used. Cleaner circuits are the most sensitive to changes in froth properties as the selectivity between sulphide particles and fine-sized gangue mainly depends on the water content in the froth. When the froth is stable and has a high water content, selectivity tends to be reduced. MIBC (methyl isobutyl carbinol) has been used as the frother of choice in a closed water system as over-stable froths do not form (Johnson, 2003).

Factors influencing the quality of recycle waters (Smith and Hertzog, 1985):

- Quality of available make-up water;
- Dissolution of contaminants from the gangue or mineral species;
- Flotation reagents and their degradation products;
- Tailings dam reactions;
- The extent to which recycle water is used and where it is used (this is specific to each metallurgical plant); and
- Biological processes.

When recycling water within a process, monitoring the composition of the process water is a necessity, not only to identify substances having a negative effect on the process, but also to serve as a tool in acquiring information about the process (Forssberg and Hallin, 1988).

Generally, a flotation plant producing a single concentrate appears to be more amenable to recycling than one in which two or more concentrates are produced (Johnson, 2003).

Generally, if more than one concentrate is produced it is essential that the recycle stream(s) either be treated or be matched to the particular concentrate to ensure that deleterious reagents are not introduced into the other concentrate’s water supply.

Effects of High Salinity Waters on Flotation

In some operations very little fresh water is available to the process and so seawater (with a TDS of 35 000 – 45 000 mg/l, Table 1) or highly saline borehole waters are used in grinding (Dunstan, 1999).

Flotation in high salinity waters causes little or no mineral dissolution, indicating little surface alteration (Shackleton, Malysiak and Slatter, 2001). However, high salinity waters tend to contain chlorides, which have a negative effect on a smelter. Thus, to limit these negative effects, the concentrate is often washed in a low chloride water before it is sent to the smelter. The chlorides are also responsible for corrosion and thus all materials from which the mills, flotation cells, launders etc are made, need to be corrosion resistant i.e. plastics and rubber, which all adds to the capital costs of the process.

Effects of Various Ions / Compounds on Flotation

Solution chemistry is extremely complex and no one rule applies for all systems or for a circuit as a whole.

An investigation into the effects of synthetic waters on synthetic minerals indicated that the adsorption of calcium onto pentlandite and pyrrhotite surfaces increases the minerals hydrophilicity and thus more xanthate is required to induce hydrophobicity of the minerals (Malysiak, Shackleton and de Vaux, 2003). However, a study on Enonkoski drill core samples showed that the addition of calcium and thiosulphate ions improved copper and nickel sulphide floatability after grinding in a steel mill, as activation due to galvanic interaction occurred (Kirjavainen, Schreithofer and Heiskanen, 2002). The same study found that grinding in a ceramic mill with added calcium and thiosulphate ions caused depression. It is thought that the galvanic interaction retards sulphide oxidation along with initial xanthate adsorption. It appears that calcium enhances thiosulphate adsorption.

Research has shown that calcium and thiosulphate ions affect sulphide flotation in different ways:

- Calcium activates the adsorption of collector ions when the galvanic effect of mill iron is effective;
- Thiosulphate, which tends to be generated in flotation cells (Forssberg and Hallin, 1985), decreases the adsorption of hydrophilic compounds e.g. metal hydroxides (Kirjavainen, Schreithofer and Heiskanen, 2002).

In one process it was found that substituting soda ash for lime decreases the amount of calcium in the process, which increases value recovery as calcium tends to precipitate on the mineral surface causing depression (Smart, Skinner and Levay, 1999).

Effect of Treated Sewage Effluent Water on Flotation

There are conflicting reports on the use of treated sewage effluent water in flotation. The most complex aspect of treated sewage effluent water is the total organic carbon (TOC) content in the water, as it is impossible to identify all the carbon components present - yet some of the organics have a detrimental effect on flotation e.g. humic, fumic, tannic and stearic acids (Hoover, 1980). High TOC levels also seem to cause frothing problems (Forssberg and Hallin, 1988). In some cases treated sewage effluent may need to be further treated with activated carbon or ion exchange before it can be used in metallurgical processes. Different sources of activated carbon need to be tested to find the one most suitable for site-specific TOC removal e.g. sugar-based activated carbon was most suitable for the removal of organic sulphur and organic halides (Ng'andu, 2001). Interestingly, in one set of tests on molybdenite flotation using sewage water, it was found that the removal of anions from the sewage effluent water with ion exchange was more beneficial than removal of TOC with activated carbon (Schnitzler, Lévay, Kühn and Sontheimer, 1983). This finding was also observed for platinum flotation when treating process water with an anion exchange resin Slatter, 2001).

In some cases it is seen that sewage effluent waters cause frothing problems across a flotation bank. Work has been performed that shows foam fraction may improve the frothing problem but not the decrease in metal recovery.

3. ANGLO PLATINUM CASE STUDIES: PROCESS EFFECTS OF VARIOUS WATERS ON ANGLO PLATINUM METALLURGICAL PLANTS

The underlying principles of water management within Anglo Platinum are given in Figure 1 below. With this strategic framework, water management within every operation must not only comply with legal and regulatory conditions, but go beyond compliance by highlighting and debating the economical and environmental impact of current water management practices.

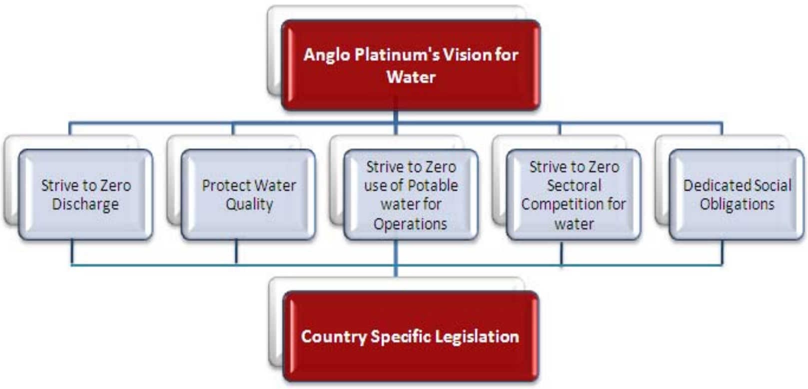

Figure 1: Water Management Principles for Anglo Platinum

The consequences of implementing the above principles pose a challenge to find alternative sources to replace and augment water supply and it is with this in mind that various waters have been tested for use in flotation on the various Anglo Platinum plants – see later. A hierarchical approach towards water, as suggested by Moran (2008) has been applied as a framework for Anglo Platinum (Figure 2). There are five levels in this model moving from the broad to the specific. **Level 5** looks at global and national issues. **Level 4** covers regional issues, which includes all stakeholders such as government, other major industries and communities. **Level 3** covers Anglo Platinum specific issues for a region, such as Rustenburg or Mogalakwena. **Level 2** addresses single operations such as shafts, open pits, concentrators, smelters and refineries. **Level 1**, or unit operations, will be considered from a research perspective and will identify where alternative technology can significantly reduce water usage (e.g. dry processing).

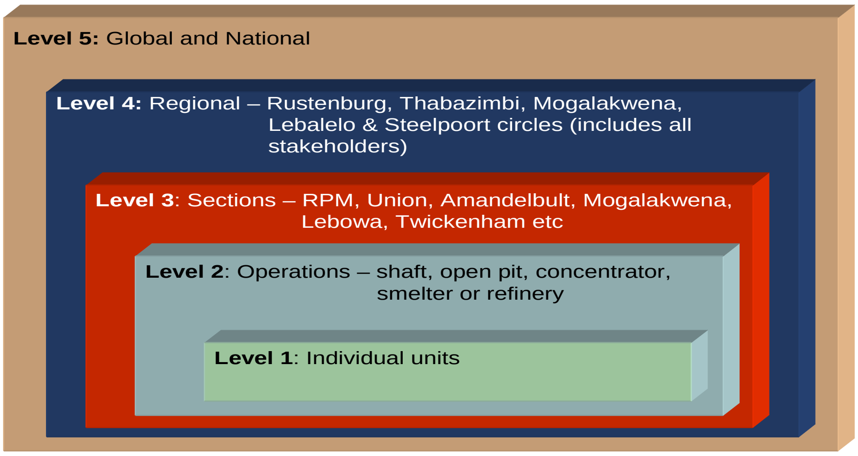

Figure 2. Hierarchical Water Model for Anglo Platinum

Methodology for the Case Studies for Process Plants (Level 2, See *Figure 2*)

Assessment of Water Quality

In order to assess and then manage water in a circuit an integrated approach is required (Smart, Skinner and Levay, 1999). Figure 3 summarises this integrated approach in which solution survey and modelling, microbiological survey, mineral surface analysis and modelling and process response are examined.

Figure 4 shows the contributions to solutions, precipitates and mineral surfaces. The primary water supplies are the make up waters that enter the system i.e. new water, whilst the recycle waters are those produced by the plant itself. The effect of the solutions on the mineral surfaces can be analysed via XPS, ToF SIMS and EDTA extraction. It should be noted that the initial experiments to test the effect of a water on a process are performed at laboratory scale and the predicted effects from these tests may not be as severe on the plant, due to chemical species in the water continuously being removed from the circuit via adsorption onto mineral particles (Shackleton, Malysiak and Slatter, 2001). These mineral particles are continuously removed through tailings and final concentrate. Another limitation of laboratory test work is in the evaluation of water quality effects on cleaner circuits (Liu, Rao and Finch, 1993).

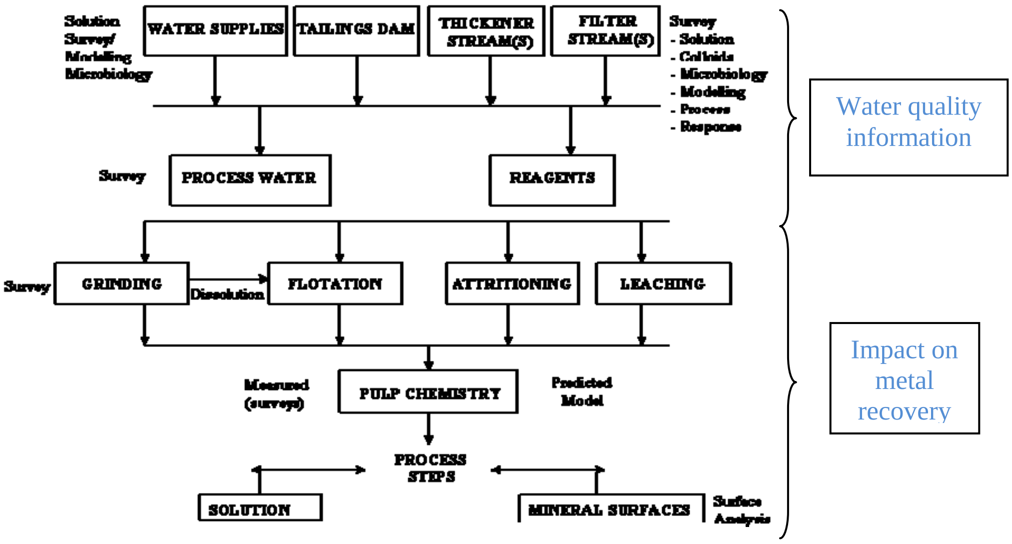

Figure 3. Methodology (Smart, Skinner and Levay, 1999)

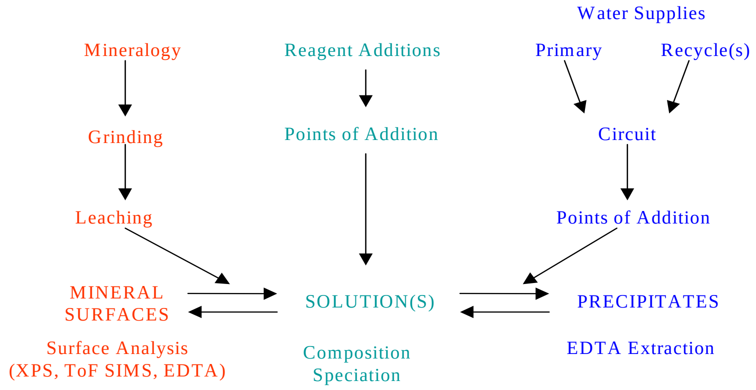

Figure 4. Schematic of the Contributions to Solution, Precipitates and Mineral Surfaces
(Smart, Skinner and Levay, 1999)

Finally it should be noted that management of water is essential to reduce water quality fluctuations within a plant. By reducing the quality fluctuations a process can often be chemically manipulated to decrease the effect of water quality. Seasonal changes can be catered for providing the water quality is again monitored and then appropriate reagent changes made. In this way a plant, in terms of water quality, is able to reach equilibrium.

Case Study 1: Assessment of Water Quality at Amandelbult

This study was conducted to determine the effect of a long water recycle (return dam water) on flotation and to decide whether or not the potable water that was being used as a make up water at the time could be replaced with #2 Shaft water in order to reduce the volume of potable water used within the process. In order to compare the results of these test waters the normal process water was used as a baseline.

From Figure 5 it can be seen that the waters gave very similar responses in platinum flotation – the kinetics of flotation were also similar indicating that the long term reuse water (return dam water) had no detrimental effect at Amandelbult. It was also encouraging to note that the #2 Shaft water gave a similar flotation response as the normal process water as this meant that the potable water used as make up water in the process could be substituted with #2 Shaft water, decreasing the amount of potable water required. Table 1 shows that the total dissolved solids levels (TDS) are fairly similar amongst the waters, with the #2 Shaft water having lower chloride and sulphate levels compared with return dam and process waters. The pH values do vary amongst the three waters but the ore is a very basic ore and thus, during milling, the pH tends to rise to about pH 9.5 no matter the pH of the starting water.

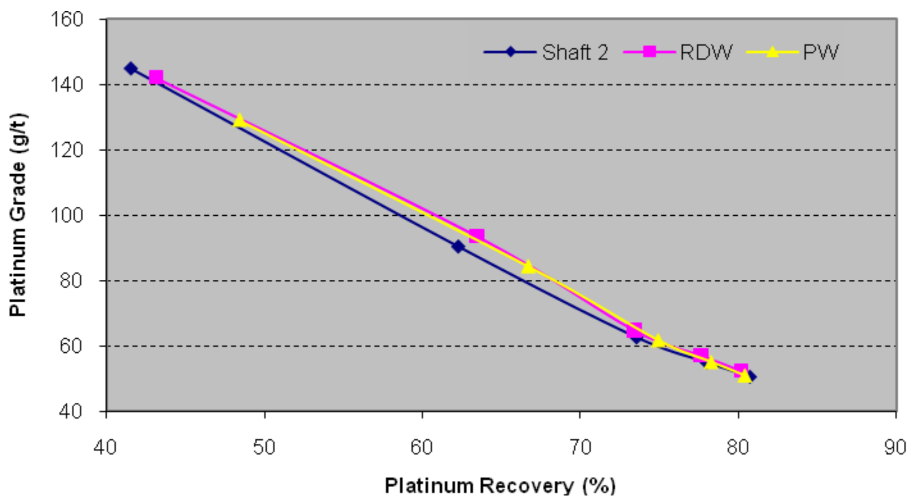

Figure 5. Effects of Underground Water (Shaft 2), Return Dam Water (RDW) and Process Water on Platinum Flotation at Amandelbult

Table 1: Condensed Water Analyses for the Waters Tested

SAMPLE	$pH_{(new)}$	TDS	TOC	TSS	Na	Ca	Cl	SO_4
		(mg/l)	*(mg/l)*	*(mg/l)*	*(mg/l)*	*(mg/l)*	*(mg/l)*	*(mg/l)*
Process Water	8.20	1592	1.6	43	271	100	460	448
Return Dam Water	9.25	1936	6.9	22	303	89	471	628
#2 Shaft Water	7.60	1280	NA	20	247	130	343	157

Case Study 2: Assessment of Using Treated Sewage Effluent from Rustenburg Municipality in Flotation

Rustenburg is an extremely water short area and thus Anglo Platinum has decided to replace all potable water used in the process. One water that is available for use as a make up water is treated sewage effluent from the Rustenburg Municipality. Thus tests have been conducted to assess the viabilty of using this water within the process. The Mogalakwena Mine also has no potable water entering its system – the only make up water that is available for processing is treated sewage effluent from Mokopane and Polokwane.

From Figure 6 it can be seen that the treated sewage effluent gives a slightly lower kinetic platinum flotation rate compared with the process water and the overall platinum recovery is about 2 % lower than in process water, although the overall grade is similar. The 2% falls within experimental error (Tim Napier Munn submitted for publication).

With regards the differences between the waters, flotation studies have shown that flotation reagents are more effective in waters with high (up to about 5000 mg/l) ionic strengths (Slatter, 2001) rather than low ionic strengths. The main difference between the treated sewage effluent and the Merensky process water is the ionic strength – 570 mg/l versus 3732 mg/l respectively (Table 1). This decreased ionic strength in the treated sewage effluent is thought to negatively affect the flotation reagents and would account for the dereased platinum recovery as well as the slower kinetics. In order to test this theory more test work would need to be performed in terms of performing flotation tests in potable water with a similar ionic strength and also by increasing the ionic strength of the treated sewage effluent. The bacterial count in the treated sewage effluent was also found to be relatively high and this may also have had an adverse effect on flotation as the bacteria may have adsorbed some of the reagents leaving less reagent available for flotation. To test if this is the case the treated sewage effluent should be treated with activated carbon prior to flotation tests and the results of treated and untreated effluent could be compared. Finally it must be noted that the treated sewage effluent is only a make-up water (about 5%) and thus once it has been added to the process the decrease in ionic strength would be negligible Thus, the effects of the sewage water would be negligible on the process; a pilot study using the treated sewage effluent at the correct dilution levels is planned to confirm this.

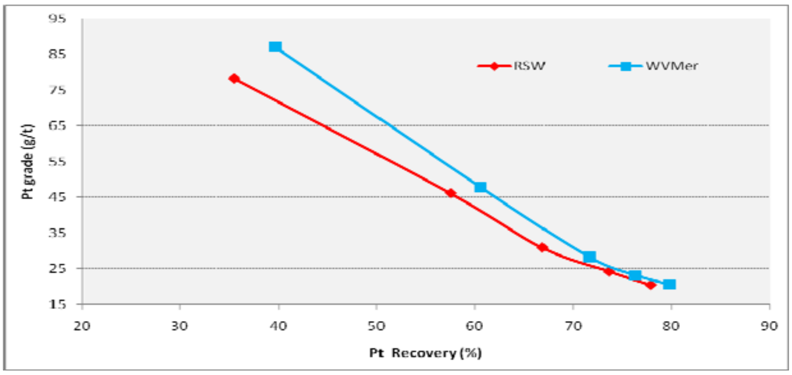

Figure 6. Effects of Rustenburg Treated Sewage Effluent (RSW) and Waterval Merensky Process Water on Platinum Flotation at Rustenburg

Table 1. Condensed Water Analyses for the Merensky Process water and the Treated Sewage Effluent from Rustenburg Municipality

	pH_{at25}	TDS	TSS	Ca	Na	Cl	NO_3	SO_4	TOC
		mg/l	*mg/l*	*mg/l*	*mg/l*	*mg/l*	*mg/l*	*mg/l*	*mg/l C*
Process Water	7.18	3732	34	575	451	1077	181	1211	1.2
Treated Sewage	7.60	570	< 10	46	107	146	37	113	4.5

Case Study 3: The Effects of Managing Waters in Processing Plants

Work is also being performed within Anglo Platinum to replace all potable water for non-domestic use with an alternative water source – generally treated sewage effluent. On many plants potable water was used for the gland service water; but now the potable has been replaced with treated sewage effluent that has been passed through a sand filter prior to use in the gland service. Figure 7 shows the average monthly potable water consumption on the Rustenburg concentrators for 2006 and 2007 was about 212 000 Ml per month. In 2008 and 2009 this figure has decreased to about 140 000 Ml per month as, in January 2008 the potable water for gland service was replaced with treated sewage effluent at the Rustenburg concentrators. There was a spike in potable consumption during July, August and September 2008 due to the replacement of the sand filters, which meant that potable water was again used as the treated sewage effluent could not be used without first undergoing filtration. The concentrators are now assessing the possibility of using treated sewage effluent for reagent make-up. If this water can be used in reagent make-up then the only potable water that will be used on the concentrators will be for human consumption. The exact potable water usage figures for reagent make-up are not known as the concentrators do not have flow meters off these lines. However, these figures should become available as more work is performed on replacing potable water with treated sewage effluent.

Finally, in order to ensure better water management, Anglo Platinum is ensuring that all operations have an accurate water balance. Mogalakwena is the Anglo Platinum trial site for Goldsim, a modelling tool for compiling water balance scenarios. The water balance should start at Level 2 in the hierarchical model and lead up to encompass all levels through to level 5. An essential element of a good water balance is to ensure that sufficient flow meters are in use on a plant and that the flow meters preferably automatically feed into the water balance.

The precious metal refinery (PMR) has produced its own water balance that accounts for 90 % of its water usage. At PMR there are about 40 flow meters in use and all are connected to the SCADA system. By producing a water balance PMR was able to identify the high water use areas and examine the reason for the high volumes of water used and they were able to identify whether the potable water could be replaced with an alternative water. For example pipelines that need to be flushed can be flushed with dam water as opposed to potable water and this has led to a decrease in potable water consumption. Thus a water balance is able to identify areas that can be made more water efficient and also allow examination of the absolute quality of water that is required.

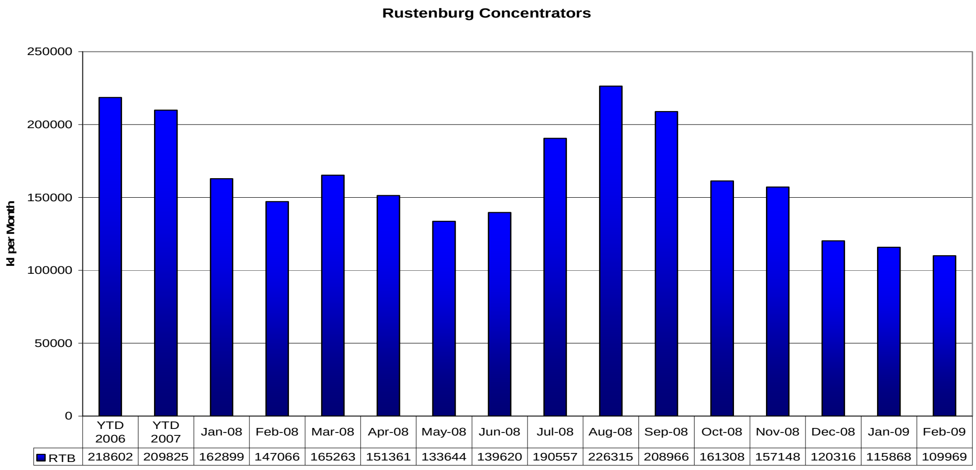

Figure 7. Potable Water Consumption Before and After Replacement with Treated Sewage Effluent for Gland Service Water

4. CONCLUSIONS

From the above it can be seen that it is essential that water be fully understood in order to optimise its usage on a plant and improve water efficiencies in general. It is imperative that the correct quality of water be used within a process i.e. it is not necessary to use potable water in a flotation process and it has been found that waters of a higher ionic strength improve flotation. Work is still being performed to determine the upper limit for ionic strength; this is complex as the components making up ionic strength need to be assessed as some constituents have less of an effect on flotation than others e.g. sulphate tends to have a more negative effect than chloride. In light of the findings for ionic strength it is imperative that a “fit for use programme” should be initiated at all plants in which the optimal water quality for each section be determined. In order to maintain a stable process, which allows lower quality waters to be utilised, it is essential to ensure that a constant water quality be maintained. This necessitates the use of a good water management programme, and the starting point for good water management is to have a comprehensive water balance.

From all the work that has been performed on the Anglo Platinum plants since 1999, it would appear that waters from the thickener overflows and the return dams have little negative impact on flotation. The only problem that can be envisaged with thickener overflow water is if the thickeners do not operate optimally and the suspended solid loading in the water increases. This would impact on the reagent consumption in flotation. Thus no further treatment of thickener overflow water is required, providing the thickeners are performing optimally. With regards the return dam water, the problems there are likely to be organic in nature i.e. either algae, bacteria or natural organic compounds such as humic acid that is produced from the degradation of plant (e.g. reeds) material. At no stage in the test work were any of these problems observed and thus no further treatment of the return dam water is required. However, test work could be performed to determine if the water quality for flotation could be improved by treating this water with activated carbon to remove any potential organic material.

From the water shortages within South Africa it is essential that where possible, all potable water should be removed from the mining and processing plants. To do this it is imperative that all areas understand the real water quality that is required for a particular process e.g. drilling, grinding, reagent make-up, gland service etc and that a suitable water for the process be identified. Where necessary, water treatment may be needed e.g. further disinfection, removal of suspended solids, removal of organic material etc. However, very seldom does a process require potable water and test work on available waters should be performed before a potable water is used. Thus, no general comment can be made as to whether or not secondary waters can indeed be used but, what can be said, is that each section is unique and the water they receive is unique and tests need to be performed to ascertain the water that can be used that requires the least treatment.

Finally, although all the above results given in the case studies were for platinum flotation, the same trend was generally followed for nickel, copper, palladium and sulphur flotation.

5. REFERENCE LIST

Arnold, BJ and Aplan, FF. (1986). “The Effect of Clay Slimes on Coal Flotation, Part II: The Role of Water Quality”. International Journal of Mineral Processing 17, 243 – 260.

Atmaca, T and Kuyumcu, HZ. (2003). “Investigations on Water Consumption in Mineral Processing Plants”. *Erzmetall 56 Nr 9*.

Dunstan, A. (1999). “The Effects of Water Quality on Mineral Processing”. In WAMMO ’99 Proceedings. 24 – 25 August 1999 pp 236 – 242.

Forssberg, K.S.E., Jönsson, H.R. and Pålsson, B.I. (1985). “Full Scale Test of Process Water Reuse in a Complex Sulphide Ore Circuit.” In: K.S.E. Forssberg (Editor), Flotation of Sulphide Minerals. Elsevier, Amsterdam, Holland, pp. 197 – 217.

Forssberg, KSE and Hallin, MI. (1988). “Process Water Recirculation in a Lead-Zinc Plant and other Sulphide Flotation Plants”. In “*Challenges in Mineral Processing*” – Proceedings of a Symposium. Sastry, KVS and Fuerstenau, MC (Eds). Publishers: Society of Mining Engineers, 1989.

Heathcote, CR and Overbeek, G (1985). “Use of Reclaimed Sewage Water in Flotation”. From *“Water Management and Treatment for Mining and Metallurgical Operations”* Volume 6, von Michaelis, H (Ed). Randol International Ltd, Colorado, USA, pp 3188 – 3210.

Hoover, MR. (1980). “Water Chemistry Effects in the Flotation of Sulphide Ores – A Review and Discussion for Molybdenite”. From *Complex Sulphide Ores conference, 5 – 8 October 1980, Institute of Mining and Metallurgy.* Jones, MJ (Ed) pp 100 – 112.

Johnson, NW. (2003). “Issues in Maximisation of Recycling of Water in a Mineral Processing Plant”. In *Proceedings of Water in Mining 2003*. 13 – 15 October 2003, Brisbane, Queensland. The Australasian Institute of Mining and Metallurgy, Publication Series No 6/2003 pp 239 – 245.

Kirjavainen, V; Schreithofer, N and Heiskanen, K. (2002). “The effect of calcium and thiosulphate ions on flotation selectivity of nickel-copper ores”. Minerals Engineering 15 pp 1 – 5.

Levay, G; Smart, RStC and Skinner, WM. (2001).”The Impact of Water Quality on Flotation Performance”. Journal of the South African Institute of Mining and Metallurgy Vol. 101, N^{o} 2 pp 69 – 75.

Liu, L; Rao, SR and Finch, JA. (1993). “Technical Note: Laboratory Study Effect of Recycle Water on Flotation of a Cu / Zn Sulphide Ore”. *Minerals Engineering Vol. 6 No. 11* pp 1183 – 1190.

Malysiak, V; Shackleton, NJ and de Vaux, D. (2003). “Effect of Water Quality on Pentlandite-Pyroxene Floatability with an Emphasis on Calcium Ions”. Proceedings of the 22nd International Mineral Processing Congress. ISBN: 0-958-46092-2

Moran, C. (2008). “Water and Water Quality in the Minerals Industry.” *SAIMM Workshop*. 6 August 2008. Cape Town.

Ng’andu, DE. (2001). “The Effect of Underground Mine Water on Performance of the Mufulira Flotation Process”. Journal of the South African Institute of Mining and Metallurgy Vol. 101, N^{o} 7 pp 367 – 380.

Rao, SR and Finch, JA. (1989). “A Review of Water Reuse in Flotation”. Minerals Engineering 2(1) 65 – 85.

Rey, M and Raffinot, P (1966). Published again in 1985: “Flotation of Ores in Sea-Water”. From *“Water Management and Treatment for Mining and Metallurgical Operations”* Volume 6, von Michaelis, H (Ed). Randol International Ltd, Colorado, USA, pp 3167 – 3174.

Roderick, AJ and Dopson, G (1985). "Factors Influencing Water Quality". From *"Water Management and Treatment for Mining and Metallurgical Operations"* Volume 6, von Michaelis, H (Ed). Randol International Ltd, Colorado, USA, pp 3052 – 3056.

Schnitzler, M; Lévay, G; Kühn, W and Sontheimer, H. (1983). "Determination of Organic Halogen and Sulphur Compounds in Water by Group Parameters". Vom Wasser 61 Band pp 263 – 276.

Shackleton, NJ; Malysiak, V and Slatter, KA. (2001). "Effect of Water Quality and Surface Passivation on Flotation Behaviour". Anglo American Metallurgical Symposium, 1 November 2001, Session 4, Paper 2.

Slatter, KA. (2001). "The Effect Various Waters in the Amandebult Merensky Circuit have on Grade and Recovery". *Internal Report* MP/1/01.

Slatter, KA. (2001). "Flotation of Waterval Mill Feed with Filtered Process Water and Process Water Treated by Ion Exchange". *Internal Report* MP/09/01.

Slatter, KA. (2007). "A Review: Water Quality Effects on Metallurgical Processes". *Internal Report* Number R200601024, Report No. 1.

Smart, RStC; Skinner, WM and Levay, G. (1999). "Process Water Quality and Treatment: Issues and Methodology". *Proceedings of WAMMO '99* pp 226 – 235.

Smith, M and Hertzog, LD. (1985). "Seawater in Flotation". From *"Water Management and Treatment for Mining and Metallurgical Operations"* Volume 6, von Michaelis, H (Ed). Randol International Ltd, Colorado, USA, pp 3163 – 3164.