

# Investigation of the Potential of Monomeric and Polymeric Coagulants in the Treatment of Raw Water used at a Coal-Fired Power Station

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**Abstract**—Vast amounts of water are used to operate power stations, such as Grootvlei Power Station. It is essential for the industry to reduce the amount of surface water used due to the scarcity of water in South Africa. The raw water feed to the Grootvlei Power Station is obtained from the Lower Vaal. Surface water commonly have turbidity levels of 20 – 200 NTU owing to suspended solids in the water comprising of biological material and undissolved minerals. This study investigates a variety of monomeric and polymeric coagulants and flocculants that can be used to treat the raw water feed to the Grootvlei Power Station. The mechanism of coagulation and flocculation is applicable during the treatment of raw water. The treatment of the raw water is optimized with regard to coagulant and flocculent type, dosage of coagulant and flocculent and mixing conditions. The optimum coagulant is determined as poly-aluminium chloride at 30 mg/L and the flocculent as polyamine at 0.8 mg/L. The optimum jar test conditions were determined as 60 s rapid mixing after the coagulant was added, followed by the addition of the flocculent and a further period of 30 s rapid mixing. The sample was then slowly mixed for 20 min after which it was allowed to settle.

**Keywords**—coagulation; flocculation; raw water; jar test.

## I. INTRODUCTION

Coal and water are used at primary energy sources in power plants [1]. The vast amounts of water used to operate power plants is especially concerning with water scarcity in South Africa increasing daily [2 - 15]. Eskom aims to achieve a zero-liquid effluent discharge by supplementing the raw water feed to the plant with treated process water. This requires that the raw water be treated to an acceptable standard. Three major concerns exist when untreated raw water is sent to the plant: corrosion, scaling and biological fouling resulting in

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deterioration of equipment, deposits on equipment and accumulation of microorganisms in the reverse-osmosis membranes and ion-exchange resins [16, 17]. The treatment of raw water at Grootvlei Power Station is focused on removing the scale forming agents from the water in an attempt to reduce the damage caused to the RO-membrane in the downstream processes [16]. Coagulation-flocculation has been the conventional method for over a century to remove suspended solids from raw water, improving the turbidity and colour of water [17]. The mechanism involves the destabilization of suspended solids, by reducing the forces that keep them apart, to form aggregates [17]. Aluminium sulphate and ferric chlorides are commonly used inorganic coagulants in the treatment of wastewater and drinking water. Aluminium is especially desirable due to its low cost and ease of application [18]. Flocculation occur when a polymeric chain is added to the destabilized suspended solids. The suspended solids collide to form larger aggregates, referred to as flocs, which can be separated from the water [3, 19 - 25]. Flocculation will follow coagulation, as the suspended solids form particles large enough to promote adequate settling of the suspended solids [17, 26]. The flocculation mechanism must be effective to the extent that the flocs formed settle out at a satisfactory settling velocity after which the settled particles can be separated from the water in a clarifier. Coagulant aids, such as polyamines, can be added to the primary coagulant to achieve denser, more stable flocs which will settle faster [27].

## II. COAGULANTS AND FLOCCULANTS

### A. Monomeric Coagulants

Most commonly used monomeric, inorganic coagulants are multivalent cations such as aluminium and iron based salts [27]. When added to water aluminium and iron salts hydrolyse and form soluble monomers and polymers. The hydrolysed salts bind strongly with the negatively charged suspended solids and promote settling [17, 27].

### B. Polymeric Coagulants

Due to the limitations of traditional flocculants and the increase in variation of physicochemical properties of water (wastewater, mine drainage, surface water etc.) alternatives to traditional flocculants are now considered. Recent years have seen variations of polymeric aluminium and iron based coagulants gain popularity. Poly-aluminium chloride is advantageous over monomeric flocculants as it i) is more thoroughly dispersed, ii) doesn't have an impact on the clarifier, iii) forms no insoluble residues and iv) achieves better turbidity removal than alum. However, it is less effective in improving the water colour than traditional flocculants [27, 28].

### C. Coagulant Aids

The coagulation mechanism on its own is not always adequate to promote a satisfactory settling velocity of aggregates. Coagulant aids provide increased floc sizes to promote faster settling [29]. Commonly used coagulant aids include a range of polyamines, chitosan and bentonite clay. The driving force behind the production of the polyamine based flocculent stemmed from the need of a flocculent not affecting the downstream reverse-osmosis membrane and ion-exchange resins as severely [16]. The use of inorganic coagulants promotes concerns with secondary pollution, hence recent years have seen several investigations into the use of organic flocculants. Organic flocculants are advantageous over metal-based flocculants, as they have no degradable effect on the environment [16]. The macromolecular structures of organic polymers consist of several functional groups [30]. When added to water, these functional groups combine with impurities to form flocs [17, 30]. Chitosan effectively neutralize and destabilize suspended solids in water, adsorb impurities and precipitate out of the water as it has a high cationic charge. The presence of amino groups in chitosan gives the polymer the ability to be protonated in acidic conditions and therefore allowing for interaction with negatively charged impurities [16, 17]. However, the presence of amino groups in organic polymers make the coagulant especially pH sensitive and at pH above 6.0 most organic polymers lose their charge when dissolved in water [16].

### III. WATER CHARACTERIZATION

The raw water was characterized according to pH, temperature and turbidity. The water samples were collected on four occasions to which slight variations in the turbidity occurred. However, the pH and temperature variations is due to seasonal changes. TABLE 1 show the initial water characteristics as measured upon the day of sampling.

TABLE 1: INITIAL WATER CHARACTERIZATION

	Sample 1	Sample 2	Sample 3	Sample 4
pH	7.55	7.98	8.01	7.65
Temperature (°C)	16.8	13.9	16.4	15.5
Turbidity (NTU)	21.07	30.69	15.58	22.46

### IV. METHODOLOGY

The samples were collected from the raw water feed line at the Grootvlei Power Station. The samples were transported in 25 L containers. The samples were covered with black plastic bags and stored in a fridge to prevent microorganism growth.

A LoviBond SensoDirect 150 water quality meter was used to measure the pH and temperature of the water [31 - 36]. The turbidity of the water was measured with a Hach 2100Q turbidimeter.

The jar tests were conducted using a 6 beaker jar test apparatus with stirring paddles. The jar test apparatus has a speed range of 50 – 300 rpm. 1 L beakers were used that were filled with 500 mL of raw water sample. The jar tests were conducted to optimize the coagulant type and dosage, the flocculent type and dosage as well as the time between addition of the coagulant and flocculent.

#### A. Coagulation Optimization

A single jar test run consisted of 6 water samples treated with the same coagulant at different dosages. The coagulants tested include: poly-aluminium chloride (PAC), aluminium chlorohydrate (ACH), sodium aluminate and alum. The samples were treated with coagulant, followed by 60 s rapid mixing at 150 rpm, 20 min slow mixing at 50 rpm and allowed to settle for 30 min where no further disturbances were allowed.

#### B. Flocculent Optimization

The water samples were treated with the optimum coagulant dosage and varying coagulant aid dosages. The coagulant aids that were tested in conjunction with the optimum coagulant include: RHEOFLOC 5414, ARFLOC 100 and chitosan. The samples were treated with coagulant, followed by 60 s rapid mixing at 150 rpm, after which the coagulant aid was added. The samples were rapidly mixed at 150 rpm for a further 30 s followed by slow mixing for 20 min at 50 rpm and allowed to settle for 30 min where no further disturbances were allowed.

#### C. Time Between Addition Optimization

The water samples were treated with the optimum dosage of coagulant and coagulant aid. The time between addition of the coagulant and coagulant was varied from 0 – 90 s followed by a further 30 s of rapid mixing at 150 rpm and slow mixing at 50 rpm for 20 min. The samples were allowed to settle undisturbed for 30 min.

V. RESULTS AND DISCUSSION

A. Coagulant Screening

PAC, ACH, aluminum sulphate and sodium aluminate were tested to see which coagulant delivers the optimum suspended solids removal. The initial average turbidity of the raw water prior to coagulant screening was 21.07. Fig 1 show the turbidity as noted after completion of the jar test where each sample was treated with a varying dosage of coagulant. Alum was tested across a dosage range of 2 – 25 mg/L. Sodium aluminate and PAC was tested from 5 – 30 mg/L. ACH was tested from 5 – 40 mg/L.

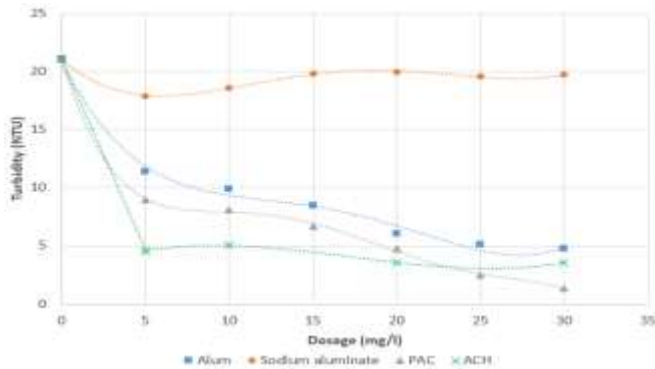


Fig 1: Coagulant screening

Sodium aluminate show a slight increase in the turbidity of the water. This is an indication of ineffective coagulation and more suspended solids is released with the addition of sodium aluminate. Alum show an insignificant turbidity removal. At a dosage of 30 mg/L PAC performed better than ACH with the turbidity reaching 1.31 NTU. PAC at 30 mg/L was selected as the optimum coagulant.

B. Flocculent Screening

The optimum coagulant, PAC was combined with three flocculants: ARFLOC 100, RHEOFLOC 5414 and chitosan. The flocculants were dosed in the range of 0.2 – 1.2 mg/L. Fig 2 show the turbidity removal for each combination of PAC with ARFLOC 100, RHEOFLOC 5414 and chitosan.

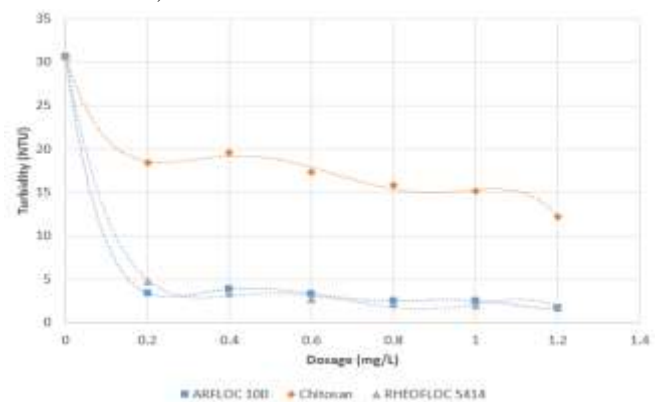


Fig 2: Flocculent screening

Chitosan removed the least turbidity and initially increase the turbidity at 0.4 mg/L. ARFLOC 100 and RHEOFLOC 5414 performed very similar with RHEOFLOC 5414 delivering slightly better performance at 0.4 – 1 mg/L dosages. Since the plant is only capable of handling flocculants up to dosages of 0.8 mg/L the optimum flocculent dosage was determined as 0.8 mg/L. With PAC dosed at 30 mg/L and RHEOFLOC dosed at 0.8 mg/L a final turbidity of 2.13 NTU is achieved.

C. Time Between Addition of Coagulant and Flocculent

The time between the addition of PAC and RHEOFLOC 5414 was varied in the range 0 – 90 s. At 0 s PAC and RHEOFLOC 5414 was added simultaneously where after RHEOFLOC 5414 was added in 15 s increments.

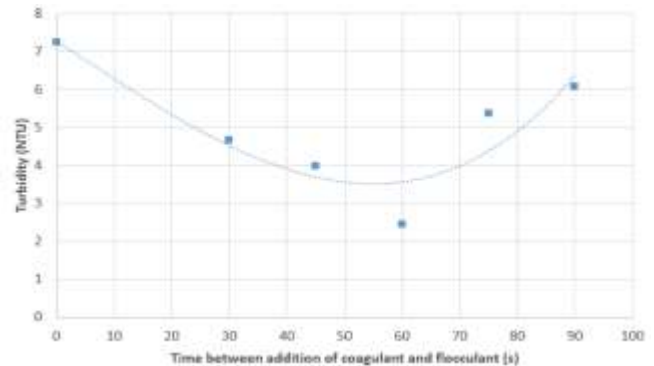


Fig 3: Time between addition of coagulant and flocculent

When PAC and RHEOFLOC 5414 is added simultaneously during rapid mixing a turbidity of 7.24 NTU is obtained. This is a result of the bonds between the suspended solids not completely broken before flocculation can occur. For a period of 60 s between the addition of PAC and RHEOFLOC 5414 the lowest turbidity is achieved, 2.46 NTU.

VI. CONCLUSION AND RECOMMENDATIONS

The following can be concluded about the characteristics of the raw water:

- The raw water has an average turbidity of 20 NTU, but vary over time
- The pH of the raw water is in the range of 7.8 – 8.2 throughout the study

The optimum coagulant to use for the treatment of the raw water was determined as PAC at 30 mg/L. The best performing flocculent in combination with the PAC was determined as RHEOFLOC 5414 at 0.8 mg/L. This is the same flocculent and dosage that is currently implemented at Grootvlei Power Station. The jar test conditions achieved optimal turbidity removal when the flocculent was added during rapid mixing, 60 s after the addition of PAC. At the optimum conditions, it is possible to achieve a turbidity removal of 2 NTU.

The following point are recommended to be revised for a similar study:

- The slowest mixing speed of the jar test was 50 rpm. It is recommended that a speed of 20 – 30 rpm is investigated which could lead to better floc formation.
- There is a small-time delay when adding the coagulant/flocculent to the different samples. A system that injects the coagulant/flocculent at exactly the same time would ensure that all the samples are treated for exactly the same time period.

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#### REFERENCES

- [1] Thopil, G.A. and A. Pouris, *A 20 year forecast of water usage in electricity generation for South Africa amidst water scarce conditions*. Renewable and Sustainable Energy Reviews, 2016. **62**: p. 1106-1121.
- [2] Etheridge, J. *Drought grips South Africa*. 15 November 2015; Available from: <http://www.news24.com/SouthAfrica/News/drought-grips-south-africa-20151115>.
- [3] Fosso-Kankeu E, Jagals P, Du Preez H. 2008. Exposure of rural households to toxic cyanobacteria in container-stored water. *Water SA*, Vol 34 (5), pp 631-636.
- [4] Fosso-Kankeu E, Mulaba-Bafubiandi A, Mamba BB, Barnard TG. 2009. Mitigation of Ca, Fe, and Mg loads in surface waters around mining areas using indigenous microorganism strains. *Journal of Physics and Chemistry of the Earth*, Vol 34, pp 825-829.
- [5] Fosso-Kankeu E, Du Preez H, Jagals P. 2010. The health implication of relationships between bacterial endotoxin, cyanobacteria, coliforms and water stored in domestic containers of rural households in South Africa. *Journal of Water and Health*, Vol 8 (4), pp 601-610.
- [6] Fosso-Kankeu E, Mulaba-Bafubiandi A, Mamba BB, Marjanovic L, Barnard TG. 2010. A comprehensive study of physical and physiological parameters that affect biosorption of metal pollutants from aqueous solutions. *Journal of Physics and Chemistry of the Earth*, Vol 35, pp 672-678.
- [7] E. Fosso-Kankeu, AF Mulaba-Bafubiandi, BB Mamba and TG Barnard. 2011. Prediction of metal-adsorption behaviour in the remediation of water contamination using indigenous microorganisms. *Journal of Environmental Management*, 92 (10), pp 2786-2793.
- [8] H. Mittal, E. Fosso-Kankeu, Shivani B. Mishra, Ajay K. Mishra. 2013. Biosorption potential of Gum ghatti-g-poly (acrylic acid) and susceptibility to biodegradation by *B. subtilis*. *International Journal of Biological Macromolecules*. 62: 370-378.
- [9] E. Fosso-Kankeu, AF Mulaba-Bafubiandi and TG Barnard. 2014. Clayey materials in river basin enhancing microbiological contamination of river water. *Journal of Physics and Chemistry of the Earth*. 67-69: 236-241.
- [10] E. Fosso-Kankeu, AF Mulaba-Bafubiandi, G Tlou and L Piater. 2012 The next step in the bioremediation of heavy metal polluted water: Development of suitable microbial-sorbent. International Mine Water Conference, October 2012 Bunbury-Australia (**Award Winning Paper**). Editors, McCullough, Lund and Wyse. ISBN: 978-0-7298-0707-4. Pp593-599.
- [11] Elvis Fosso-Kankeu, Lwandle Simelane (2013): Kinetic study of methylene blue removal by Gram-negative and Gram-positive bacteria. International Multi-conference on Education, Law, Environment and Metallurgical Engineering (IMELEME' 2013); 27-28 November 2013, Johannesburg-South Africa. (**Award Winning Paper**). Editors: Sandhu S and Muzenda E. ISBN: 978-93-82242-50-5.
- [12] E. Fosso-Kankeu, R. Kaitano, F. Waanders, A.F. Mulaba-Bafubiandi. 2014. Soil Quality in the Basin of Mine Effluents and the Potential of Alleviation of Metal Dispersion. An Interdisciplinary Response to Mine Water Challenges. International Mine Water Conference, August 2014 Xuzhou China. Editors, Sui, Sun & Wang (Eds). 2014 China University of Mining and Technology Press, Xuzhou, ISBN: 978-7-5646-2437-8. Pp374-378.
- [13] E. Fosso-Kankeu, F. Waanders. 2014. Metal Ions Adsorption Affinity of Clay Materials from the North West Province of South Africa. An Interdisciplinary Response to Mine Water Challenges. International Mine Water Conference, August 2014 Xuzhou China. Editors, Sui, Sun & Wang (Eds). 2014 China University of Mining and Technology Press, Xuzhou, ISBN: 978-7-5646-2437-8. Pp374-378.
- [14] Fosso-Kankeu E, Waanders F, Reitz M. 2014. Selective adsorption of heavy and light metals by natural zeolites. 6<sup>th</sup> International Conference on Green Technology, Renewable Energy and Environmental Engineering (ICGTREEE'2014). 27-28 November 2014, Cape Town-South Africa. (**Award Winning Paper**). Editors: Muzenda E. and Sandhu S. ISBN: 978-93-84468-08-8. Pp 271-274.
- [15] Elvis Fosso-Kankeu, Frans Waanders, Corinne Fraser. 2014. Bentonite clay adsorption affinity for anionic and cationic dyes. 6<sup>th</sup> International Conference on Green Technology, Renewable Energy and Environmental Engineering (ICGTREEE'2014). 27-28 November 2014, Cape Town-South Africa. Editors: Muzenda E. and Sandhu S. ISBN: 978-93-84468-08-8. Pp 257-260. Pp 257-260.
- [16] Chesters, S.P., et al., *The safe use of cationic flocculants with reverse osmosis membranes*. Desalination and Water Treatment, 2009. **6**: p. 144-151.
- [17] Fosso-Kankeu, E., et al., *Flocculation performance of polymers and nanomaterials for the treatment of industrial wastewaters*, in *Smart Materials for Waste Water Applications*, A. Mishra, Editor. 2016, John Wiley & Sons Inc. p. 213-235.
- [18] Lin, J., S.J. Couperthwaite, and G.J. Millar, *Effectiveness of aluminium based coagulants for pre-treatment of coal seam water*. Separation and Purification Technology, 2017. **177**: p. 207-222.
- [19] E. Fosso-Kankeu, Hemant Mittal, S. Marx and Suprakas Sinha Ray. 2016. Hydrogel-based bioflocculants for the removal of organic pollutants from biodiesel wastewater. *Journal of Polymer and Environment*. DOI 10.1007/s10924-016-0870-8.
- [20] Ntwampe IO, Waanders FB, Fosso-Kankeu E and Bunt JR. 2015. Turbidity removal efficiency of clay and a synthetic af-PFCl Polymer of Magnesium Hydroxide in AMD Treatment. *International Scientific Research Journal*. 4: 38-55.
- [21] I.O. Ntwampe, F.B. Waanders, E. Fosso-Kankeu, J.R. Bunt. 2015. Reaction dynamics of iron and aluminium salts dosage in AMD using shaking as an alternative technique in the destabilization-hydrolysis process. *International Scientific Research Journal*. 1(8): 5-23.
- [22] E. Fosso-Kankeu, H. Mittal, F. Waanders, I.O. Ntwampe, S.S. Ray. 2016. Preparation and characterization of gum karaya hydrogel nanocomposite flocculant for metal ions removal from mine effluents. *International Journal of Environmental Science and Technology*. 13: 711-724.
- [23] Elvis Fosso-Kankeu; Oupa Ntwampe; Frans Waanders, and Alicea Webster. 2015. The Performance of Polyaluminium Chloride and Bentonite clay Coagulant in the Removal of Cationic and Anionic Dyes. 7<sup>th</sup> International Conference on Latest Trends in Engineering and Technology (ICLTET' 2015), November 26-27, 2015 Irene, Pretoria

- (South Africa). Editors: E. Muzenda and T Yingthawornsuk. ISBN: 978-93-84422-58-5.
- [24] Fosso-Kankeu E, Waanders F, Van Niekerk D, Rogers D, Gericke D. 2016. Treatment of raw and processed waters from coal power plant using PACI supplemented with cationic organic polymer and bentonite. International Conference on Advances in Science, Engineering, Technology and Natural Resources (ICASETNR-16) Nov. 24-25, 2016, Parys – South Africa. ISBN: 978-93-84468-79-8.
- [25] Fosso-Kankeu E, Waanders F, Swiegers R, Ntwampe IO, Rogers D, Gericke G. 2016. Impact of the physico-chemical properties of water on the flocculation performance of lime, clay and other polymers. International Conference on Advances in Science, Engineering, Technology and Natural Resources (ICASETNR-16) Nov. 24-25, 2016, Parys – South Africa. ISBN: 978-93-84468-79-8.
- [26] Langelier, W.F. and H.F. Ludwig, *Mechanism of flocculation in the clarification of turbid waters*. J.A.W.W.A, 1949. **41**: p. 163-181.
- [27] Manda, I.K.M., et al., *Comparative assessment of water treatment using polymeric and inorganic coagulants*. Physics and Chemistry of the Earth, 2016. **93**: p. 119-129.
- [28] Gabelich, C.J., et al., *Control of residual aluminium from conventional treatment to improve reverse osmosis performance*. Desalination, 2006. **190**: p. 147-160.
- [29] Bu, F., et al., *Impacts of epichlorohydrin-dimethylamine on coagulation performance and membrane fouling in coagulation/filtration combined process with different Al-based coagulants*. CHemosphere, 2016. **159**: p. 228-234.
- [30] Feng, B., et al., *The settling behavior of quartz using chitosan as flocculant*. Journal of Materials Research and Technology, 2017. **6**(1): p. 71-76.
- [31] Alusani Manyatshe, Elvis Fosso-Kankeu, Divan van der Berg, Nico Lemmer, Frans Waanders, Hlanganani Tutu. 2017. Metal retention potential of sediment and water quality in the Mooi River, South Africa. Desalination and Water Treatment. doi: 10.5004/dwt2017.20222.
- [32] Elvis Fosso-Kankeu, Alusani Manyatshe, Frans Waanders. 2017. Mobility potential of metals in acid mine drainage occurring in the Highveld area of Mpumalanga Province in South Africa: Implication of sediments and efflorescent crusts. International Biodeterioration and Biodegradation. 119: 661-670.
- [33] A. Manyatshe, E. Fosso-Kankeu, D. van der Berg, N. Lemmer, F. Waanders, H. Tutu. 2017. Dispersion of inorganic contaminants in surface water in the vicinity of Potchefstroom. Physics and Chemistry of the Earth. 100: 86-93.
- [34] Elvis Fosso-Kankeu, Divan P. Van der Berg, Frans Waanders, Alusani Manyatshe, Nico Lemmer, and H. Tutu. 2015. Mapping of surface water quality in the vicinity of Potchefstroom based on mining pollutants. 7<sup>th</sup> International Conference on Latest Trends in Engineering and Technology (ICLTET' 2015), November 26-27, 2015 Irene, Pretoria (South Africa). Editors: E. Muzenda and T Yingthawornsuk. ISBN: 978-93-84422-58-5.
- [35] Elvis Fosso-Kankeu, Alusani Manyatshe, Divan van der Berg, Nico Lemmer, Frans Waanders, and Tutu Hlanganani. 2015. Contaminants in Sediments across the Mooi and Vaal Rivers Network in The Vicinity of Potchefstroom. 7<sup>th</sup> International Conference on Latest Trends in Engineering and Technology (ICLTET' 2015), November 26-27, 2015 Irene, Pretoria (South Africa). Editors: E. Muzenda and T Yingthawornsuk. ISBN: 978-93-84422-58-5.
- [36] Manyatshe A, Fosso-Kankeu E, Van Der Berg D, Lemmer N, Waanders F, Tutu H. 2016. Assessment of seasonal variation in surface water quality of the Mooi and Vaal Rivers network, South Africa. International Conference on Advances in Science, Engineering, Technology and Natural Resources (ICASETNR-16) Nov. 24-25, 2016, Parys – South Africa. ISBN: 978-93-84468-79-8.

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