Assessment of Self-Purification Capacity of the Mooi River Catchment of South Africa

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Abstract: Dissolved oxygen is the most essential element in natural water bodies for one of the most important reasons, namely aquatic life. This content is usually affected by the type and amount of pollution introduced in natural water bodies. The dissolved oxygen level is usually lowered at any point where a natural water body such as a river is contaminated (deoxygenation); however, using natural purification forces, rivers work hard to gain back the amount of oxygen lost in the water due to pollution (re-oxygenation). This study articulated the self-purification capacity of the Mooi River catchment as a function of the rate of change of the amount of dissolved oxygen in flowing water to illustrate the purification strength of a river flow segment between sampling points. This is to subsequently present the impact of inflowing pollution from different types of adjacent sources and tributary rivers. This was achieved by conducting measurements of dissolved oxygen and temperature directly from the river, using an electrolyte dissolved oxygen meter. Respective samples (three-litre samples) were also collected at every sampling point for a biochemical oxygen demand laboratory analysis taken over five days. Using the biochemical oxygen demand and oxygen deficit analysis, deoxygenation and re-oxygenation factors or constants were determined for every flow segment. The mathematical ratio between the two constants were then used to calculate the self-purification capacity of every segment. Because the hydraulic dynamics of the river also influence the strength of the river to purify itself, a re-oxygenation model of hydraulic properties, such as flow velocity hydraulic depth and radius, was developed and presented by means of a regression analysis. The findings have proven that the river has the capacity to purify itself along its existing length for both dry and wet seasons. The purification fluctuations were high during the wet seasons due to the increase in hydraulic flow depth and pollution by run-off. Oxygen deficiency was very low before the Mooi River confluences with the Vaal River; therefore, it did not significantly affect the oxygen content of the Vaal River.

1 INTRODUCTION

South africa is listed as one of the most water scarce countries on the continent (Dube, 2020). To mitigate this scarcity and implement effective water resource planning, re-oxygenation coefficient modelling can be utilised as an integral scientific tool. This model allows one to predict and monitor pollution loads, nutrient constituents, and dissolved oxygen recovery in fresh surface water masses (Ugbebor, Agunwamba, & amah, 2012). Using a re-oxygenation coefficient model, this study assesses the self-purification capacity of the Mooi river catchment which is situated along the western Gauteng and North West provinces. This catchment is a vital water supply for the surrounding population and ecosystem.

The condition of a freshwater mass (ie: a river) at any point in time, is the result of a balance between its oxygen resources and the demand made upon them by the organic polluting matter carried by the stream (Al-Zboon & Al-Suhaili, 2009). In other words, a river's capacity to receive and oxidise organic matter depends upon its oxygen resources. When organic pollution is discharged into a natural water source, organic compounds are oxidised by the dissolved oxygen present in the water.

This process causes a deficiency of dissolved oxygen (do) in the flowing water and the loss of oxygen or deoxygenation happens. This deficiency is typically dismissed by the atmospheric oxygen being absorbed into the water (re-oxygenation i.e. Gain of oxygenation). The rate at which the do absorbed into

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the water can automatically oxidise the organic matter present in the water is termed the self-purification rate.

This phenomenon narrates the outcome of the de-oxygenation and re-oxygenation processes taking place continuously in a simultaneous manner. Along with other hydraulics-driven models of re-oxygenation, Steeter and Phelps' model which is based on the relation between DO and BOD is used as a basis for assessment in this study. The model is given as:

$$D = \frac{k_1 L_0}{k_1 - k_2} . (e^{-k_1 t} - e^{-k_2 t}) + D_0 . e^{-k_2 t} \quad (1)$$

D_0 = initial DO deficit;
D = the DO deficit;
k_1= the BOD degradation constant;
k_2 = the atmospheric re-aeration constant;
L_0 = the ultimate BOD; and
t = the hydraulic retention time.

As a vital water source, the Mooi River catchment has been subjected to a lot of pollution over more than 30 years (DWA, Green Drop Progress Report, 2012a; DWA, Classification of Significant Water Resources (River, Wetlands, Groundwater and Lakes) in the Upper, Middle and Lower Vaal Water Management Areas (WMA) 8, 9, 10, 2012b). Wondersfontein River, a tributary to the Mooi River, is known through research to be a much-polluted river containing contaminants from the gold mining sectors and the Flip Human Wastewater Treatment Works, thus influencing the quality of the water in the Mooi River at the point of their confluence (Barnard, Venter, & Van Ginke, 2013). Furthermore, with the effluent from Kokosi Wastewater Treatment Works, the Loopspruit River subsequently repeats this influence downstream of the Mooi River. Based on these influences, this study aims to provide a clearer perspective on the catchment's ability to purify itself and continue being useful to its surrounding population.

2 MATERIALS AND METHODS

The study was conducted on the Mooi River catchment which is formed by the Mooi River together with Wondersfontein River and Loopspruit River as tributaries. The Wondersfontein River confluxes with the Mooi River's upstream section from the northeast side, creating one volume of water mass concentration. The downstream section of the Mooi River is further joined by the Loopspruit River, which also influences the quality of the Mooi River.

Along its length lies three storage dams namely; Klerkskraal, Boskop and Potchefstroom dams. These dams receive water directly from the Mooi River (DWA, Green Drop Progress Report, 2012a; DWA, Classification of Significant Water Resources (River, Wetlands, Groundwater and Lakes) in the Upper, Middle and Lower Vaal Water Management Areas (WMA) 8, 9, 10, 2012b)and their capacities are 8ML, 21ML and 2ML respectively (Annandale & Nealer, 2011).

Fieldwork: 10 sampling points were benchmarked along the course of the river based on the locations of interest. The interest was determined by the locations' closeness to major water points such as dams, proximity to pollution sources such as wastewater plants, as well as confluences, etc. The sampling points are labelled SPL1 to SPL10.

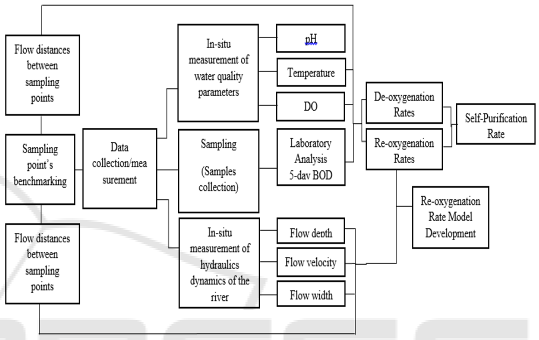

Figure 1.

Table 1 below shows the sampling points and their descriptions. (Refer to tables 2 and 3 for flow distances).

Table 1: Sampling points

Sampling point	Sampling point description
SPL1	Klerkskraal Dam Outlet
SPL2	Mooi River Bridge
SPL3	Mooi River Before Boskop Dam and Before Wondersfontein River Confluence
SPL4	Boskop Dam Inlet/Outlet
SPL5	Potch Dam Inlet/Outlet
SPL6	Mooi River at Potchefstroom City Mooi River Mall
SPL7	Mooi River + Loopspruit River before Potch WWTW effluent dilution
SPL8	Mooi River + Potch WWTW effluent
SPL9	Mooi River + Potch WWTW effluent before Vaal
SPL10	Mooi River + Vaal confluence

Table 2: Dry season water quality and self-purification indicators.

Sampling point	Temp. (°C)	Satu-ration DO (mg/l)	Actual/ in situ DO (mg/l)	Five-day DO (mg/l)	DO deficit (mg/l)	BOD (mg/l)	Velocity (m/s)	Accumul-ated distance (km)	Time (days)	Deoxyge-na-tion constant k_1	Reoxy gena-tion consta nt k_2	Self-purific-ation factor, f
SPL1	21.1	8.880	7.50	6.9	1.380	0.6	0.54	0	0.00			0
SPL2	20.8	8.940	6.60	5.8	2.340	0.8	0.36	12.0	0.39	-0.744	-1.366	1.835
SPL3	20.2	9.060	6.40	5.5	2.660	0.9	0.34	23.6	0.39	-0.299	-0.325	1.088
SPL4	20.5	9.000	7.10	6.4	1.900	0.7	0.26	32.7	0.41	0.618	0.827	1.339
SPL5	22.1	8.690	7.30	6.4	1.390	0.9	0.15	46.4	1.06	-0.238	0.296	-1.244
SPL6	22.4	8.660	6.70	5.7	1.960	1	0.16	49.0	0.19	-0.569	-1.856	3.262
SPL7	21.7	8.760	6.50	5.9	2.260	0.6	0.11	54.8	0.61	0.834	-0.233	-0.279
SPL8	22.3	8.670	5.50	4.3	3.170	1.2	0.1	56.8	0.24	-2.919	-1.425	0.488
SPL9	23.4	8.520	6.40	5.8	2.120	0.6	0.09	110.4	6.89	0.101	0.058	0.580
SPL10	23.9	8.420	6.70	5.9	1.720	0.8	0.83	112.3	0.03	-11.182	8.127	-0.727

Table 3: Wet season water quality and self-purification indicators.

Sampling point	Temp. (°C)	Satura ti-on DO (mg/l)	Actual/ in situ DO (mg/l)	Five-day DO (mg/l)	DO deficit (mg/l)	BOD (mg/l)	Velocity (m/s)	Accumul-ated distance (km)	Time (days)	Deoxyge na-tion constant K_1	Reoxy gena-tion consta nt K_2	Self-purific-ation factor, f
SPL1	23.6	8.520	7.4	5.3	1.120	2.1	0.53	0	0.00			0
SPL2	21	8.900	5.2	4.8	3.700	0.4	0.52	12.0	0.27	6.196	− 4.465	− 0.721
SPL3	21.1	8.850	4.3	3.6	4.550	0.7	0.61	23.6	0.22	-2.551	-0.943	0.370
SPL4	19.5	9.200	7.4	5.4	1.800	2	0.6	32.7	0.18	-5.958	5.263	-0.883
SPL5	23.2	8.560	7	6.1	1.560	0.9	0.17	46.4	0.93	0.857	0.154	0.179
SPL6	23.3	8.540	3.1	1.7	5.440	1.4	0.17	49.0	0.17	-2.535	-7.167	2.827
SPL7	23.2	8.560	2.7	1.8	5.860	0.9	0.2	54.8	0.34	1.312	-0.221	-0.168
SPL8	24.2	8.380	2.6	1.6	5.780	1	0.3	56.8	0.08	-1.331	0.177	-0.130
SPL9	23.8	8.440	4.7	3.9	3.740	0.8	0.35	110.4	1.77	0.126	0.246	1.951
SPL10	26.7	8.030	5.2	4.6	2.830	0.6	0.34	112.3	0.06	4.580	4.439	0.969

Mooi River stretches from the first sampling point (SPL1) at Klerkskraal Dam to the last sampling point (SPL10) at the Vaal River confluence. . The analysis of these results discovered through this study yields a clear identification and understanding of all the weak spots along the river length in terms of pollution subjection and purification strength. This further allows us to indicate how each river segment reacts to different types of pollution and other factors affecting its self-purification. Knowing whether the levels of these indicators increase or decrease at each segment enables us to know how the purification is affected by either pollution or other factors.

2.1 Calculating the De-Oxygenation (k_1) and Re-Oxygenation (k_2) Constants

In addition to the fieldwork, laboratory work was conducted to determine the BOD using the BOD5 (non-dilution) analysis method, where the DO of a sample was measured before and after it was incubated at 20°C for 5 days. The difference between the two DOs was taken as the BOD value for each sample.

The laboratory analysis, which was conducted using Microsoft Excel, allowed us to develop the re-oxygenation constant model (k_2) for the study area. The model validation was conducted by running Microsoft Excel Regression Analysis between k_2 values obtained using the developed model and the k_2 values calculated using the actual field data. Before determining the re-oxygenation rate using the proposed models, the de-oxygenation constant (k_1) was calculated and the results show that the rate at which the BOD in the water is decomposed is directly proportional to the amount of BOD present/remaining in the water. This means that the de-oxygenation rate is high when the BOD level is high.

3 RESULTS AND DISCUSSIONS

The re-oxygenation constant (k_2) can be calculated by using the DO deficits of the water on the upstream sampling points of the catchment determined on the field together with the DO deficits determined by the downstream sampling points. The formula is derived from the rate relationship between the DO deficit and the rate at which the atmospheric air enters the water (re-oxygenation). The rate at which the atmospheric air enters the water is directly proportional to the DO deficit in the water. In summation, the deoxygenation coefficient k_1 is dependent on the pollution or waste characteristics alone, while the re-oxygenation coefficient k_2, is dependent on factors such as stream velocity, stream depth and water temperature. Hence, there is a need to model k_2 differently and this could be achieved by data gathering on such parameters as dissolved oxygen, stream velocity, water depth and temperature.

For both seasons, the quality of the water deteriorates by constantly losing oxygen for a flow distance of about 23,6 km from the first sampling point at Klerkskraal Dam. This results in high dissolved oxygen deficit levels. The oxygen deficit level of the wet season is also affected by the low flow rate and deep hydraulic depth of the river at this point. The flow rate is as low as 0,16 m/s with a hydraulic depth of 0,5 m during the dry season period. The Reoxygenation rate is less in deep slow-moving waters due to the insufficiencies of turbulence, oxygen dilution, and dispersion in water. All this results in high dissolved oxygen deficit levels. The oxygen deficit then declines towards the Vaal River confluence. The flow distance between sampling points 8 and 10 allows for sufficient re-oxygenation and recovery from organic matter present in the water. The highest DO deficit was recorded during the wet season because of an increase in the hydraulic depths of the water. High quantities of water in rivers make it difficult for self-purification to take place effectively.

4 CONCLUSIONS

The major sources of non-point pollution in the Mooi River catchment are agricultural activities and urban runoff during the wet season. The high levels of phosphorus and nitrogen induced by the excessive use of agricultural pesticides result in eutrophication. Furthermore, the Mooi River is a slow flowing river in some segments, some parts of it are close to stagnant. At deep hydraulic depths, this results in slow atmospheric oxygen infusion, algal blooming, and growth of aquatic plants thus causing rapid depletion of dissolved oxygen. This affects the natural self-purification of the catchment.

The quality management system of South Africa should urgently employ intense purification modelling of its river systems. This will assist in identifying pollution sources that are fatal to the quality of the water in South African water masses. Furthermore, it will help the water treatment sectors to identify reliable points of raw water extraction for portable water treatment, thus reducing the treatment costs.

Due to South Africa's energy deficiency, reducing the water treatment intensity means using less electricity and chemicals during treatment. Recreational economic activities influenced by aquatic life such as fish, at places like Boskop Dam and Potch Dam, have also been affected by the pollution induced on the Mooi River.

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