Analysis of auto-purification response of the Apies River, Gauteng, South Africa, to treated wastewater effluent

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ABSTRACT

The assimilative capacity of water bodies is an important factor in the integrated management of surface water resources. The current study examined the auto-recovery processes of the Apies River from wastewater discharged into it from a municipal wastewater treatment facility, using a series of equations, including the modified Streeter-Phelps equation. Field data obtained include dissolved oxygen (DO), temperature, stream velocity, depth, and width. Water samples were also obtained at 10 sampling stations for the determination of biochemical oxygen demand (BOD) using standard methods. It was observed that the DO and BOD level (5.59 mg/L and 8.5 mg/L respectively) of the effluent from the wastewater treatment facility indicated better water quality than the Apies River background DO level (5.42 mg/L) and BOD level (13 mg/L). Also, at 270 m downstream of the effluent discharge point, another effluent stream (Skinnerspruit) adversely impacted on the Apies River with DO and BOD levels of 6.5 mg/L and 9.0 mg/L, respectively, compared to the Apies River background values of 6.81 mg/L and 8.0 mg/L, respectively. The stream, however, recovered well from both the background and imposed pollution sources as it had a computed positive auto-recovery factor of 1.74. Furthermore, the measured DO deficit was plotted against predicted DO deficit. The plot revealed a close match between the measured and predicted DO deficit, indicating that the model could be used for predicting DO deficit along other segments of the river. To further improve on the natural auto-recovery processes of the Apies River, it was recommended that flow along the Skinnerspruit should be enhanced by clearing the observed aquatic plants growing within the channel. Also, suspected pollution activities taking place further upstream on the Apies River should be investigated and appropriately addressed.

Keywords: de-oxygenation; re-aeration; auto-purification; dissolved oxygen; biochemical oxygen demand; stream

INTRODUCTION

Surface water is a vital natural resource for South Africa as 70% of the country's GDP, 70% of the country's population, and 74% of all water demand are supported by this resource (NWRS, 2004). Being a semi-arid country, successive governments in the country have recognised the need to be prudent and proactive in the management of the nation's water resources. The major demands for water in South Africa come from agriculture (62%); domestic, industrial and other urban needs (27%); mining, large industries and power generation (8%); and forestry and ecological needs (3%) (DWAF, 2004; Oelofse and Strydom, 2010; Swatuk, 2010). As required by law, the ecological allocation of water is the portion of water that must be left un-harnessed in its natural channels for ecological reasons. Depending on the level of water stress in the area, the law requires that as much as 20% of the stream discharge must be kept as the ecological Reserve (DWAF, 2004). This requirement puts further strain on the availability of water. The water catchment systems of South Africa are divided into 9 water management areas (WMA). While the south-eastern parts of the country have sufficient water, the north-western parts (as one approaches the Kalahari Desert) are drier (Swatuk, 2010). Gauteng Province, for instance, has only 600–700 mm of annual rainfall (Bamuza and Abiye, 2012). When compared to the global average of 860 mm/annum, Gauteng can be described as a semi-arid environment (Oelofse and Strydom, 2010). This makes surface water a critical resource in such an environment. For this reason, the transfer of water from WMAs having excess water to areas that are deficient is practised in order to relieve water-stressed areas (Oelofse and Strydom, 2010). Furthermore, the continued availability and sustainability of freshwater supply in South Africa is being challenged in the face of pollution activities, precipitated mainly as a result of human activities such as mining, agriculture, manufacturing wastes and domestic effluents (Oelofse and Strydom, 2010).

Although the law specifies that all effluent must be treated before being discharged into nearby receiving streams, there have been reports of increased pollution level in dams situated downstream of urban areas as well as outbreaks of water-related diseases among the populace (Oelofse and Strydom, 2010; Swatuk, 2010; Bamuza and Abiye, 2012). One of the management tools that could be employed in the monitoring and management of surface water bodies around the country is re-aeration (Jha et al., 2007; Omole et al., 2013). This is based on the principle that imposed biological waste loads deplete the dissolved oxygen (DO) content of natural water systems in the process of breaking down the wastes. The amount of oxygen needed to completely break down the imposed biological waste loads is referred to as biochemical oxygen demand (BOD). In other words, BOD is an indication of pollution strength (Lin and Lee, 2007). Since all streams have a natural capacity to be auto-purified from waste loads imposed on them, it is advantageous to study the process in order to know how the natural process of stream re-aeration can be enhanced (Agunwamba et al., 2007).

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The auto-purification capacity (AC) of each river system is defined by factors such as stream velocity, stream depth, and water temperature (Longe and Omole, 2008). Generally, faster and shallower streams get re-aerated faster while cooler streams contain more dissolved oxygen at saturation point than warmer streams (Longe and Omole, 2008). Streeter and Phelps (1925) established the relationship and interaction between the level of dissolved oxygen (DO) and biochemical oxygen demand (BOD) in a river system (Waite and Freeman, 1977; Lin and Lee, 2007; Omole and Longe, 2012). Subsequent studies further provided models that could be used to predict the DO deficit levels at every point along the channel, provided the re-aeration and de-oxygenation coefficients of the stream are known (Lin and Lee, 2007; Omole and Longe, 2012; Omole, et al., 2012). Studying the AC of streams aids water managers in measuring the impact of effluent discharges from domestic and industrial sources on streams. It also assists in quantitatively determining the capacity of a stream to recover from imposed waste loads and, by extension, helps in determining the maximum allowable waste loads permitted to be discharged into specific streams by polluters. Therefore, the current study applied the science of AC in analysing the response of the Apies River to treated domestic effluent being discharged from the Daspoort Wastewater Treatment Works (DWTW) in Pretoria, Gauteng Province, South Africa. This was done to assess the rate of recovery of the river from imposed waste loads and to evaluate factors that can further improve the rate of recovery.

MATERIALS AND METHODS

Study area

The study was carried out mainly on the Apies River (Fig. 1), which is a major river that runs through parts of the city of Pretoria in Gauteng Province. Effluent from various human activities is discharged into the river. This includes effluent from the Laudium industrial estate in Pretoria West and the DWTW in central Pretoria. The study focused on the section of the river that passes the DWTW and the M1 roadway marker. The field study took place during the spring season and just at the beginning of the rainy season, in November 2014. The DWTW is one of 10 treatment plants that cater for the treatment of municipal wastewater in the city of Tshwane in Pretoria. The DWTW treats 58 m. L/day of wastewater. At the end of the treatment process, the treated effluent is discharged into the Apies River (Fig. 2).

Theoretical framework

At the point of entry of biological wastes into a stream, deoxygenation begins. The deoxygenation constant for any particular stream is denoted as k_1. The waste starts to use the DO in the stream. The ultimate DO needed to completely breakdown the waste can be denoted as L_a. After a short distance, the process of breaking down the waste has commenced but is incomplete. The amount of oxygen used up after some time is the BOD(t) while the amount of oxygen still needed at instantaneous time t to complete the breakdown of the waste load can be denoted as $z(t)$ or L_t. This interrelationship is represented by Eq. 1 (Weiner and Matthews, 2003).

$$\mathrm{BOD}(t) = L_a - z(t) \tag{1}$$

But k_1 is a function of the rate of change of z which is represented by Eq. 2 (Weiner and Matthews, 2003).

and

$$L_t = L_a 10^{-k_1 t} \tag{2}$$

Therefore, Eq. 1 becomes

$$\mathrm{BOD}(t) = L_a(1-10^{-k_1 t}) \tag{3}$$

In the same vein, while the DO is being used up by the biological waste, the stream acquires more DO by trapping it from the atmosphere. This process is known as reaeration. The reaeration constant for any particular stream is denoted as k_2. Reaeration rate is dependent on the current DO levels, d, of the stream and the maximum DO, d_s, that the stream can hold at saturation point. This relationship is represented in Eq. 4.

$$\frac{d}{dt}d(t) = k_2(d_s - d(t)) = k_2 D(t) \tag{4}$$

Reaeration rate is also aided by stream velocity, as atmospheric oxygen is trapped faster by the river in direct proportion to turbulence. Closer to the point of waste discharge into the stream, the rate of deoxygenation of DO is greater than the rate of reaeration. As the process progresses downstream, the reaeration rate accelerates and usually surpasses the deoxygenation rate. The instantaneous state of DO in the stream can be represented by the relationship in Eq. 5.

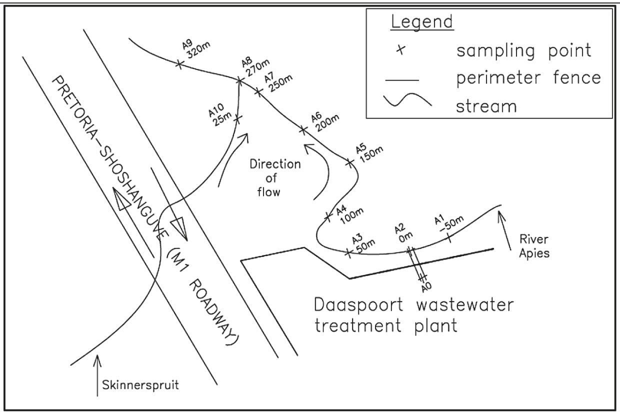

Figure 1

Plan view of the Apies River (right) and Skinnerspruit (left) along with sampling stations (not drawn to scale)

Figure 2

Discharge point of DWTW into the Apies River

$$\frac{d}{dt}D(t) = k_1 z(t) - k_2 D(t) \tag{5}$$

The ratio of k_2 to k_1 is an indication of the stream's potential to naturally become purified (auto-purification). This is represented by Eq. 6. When Eq. 6 is greater than zero, the stream will ultimately recover and return to its unpolluted state. However, if Eq. 6 is zero, the stream may tend towards eutrophication.

$$f = \frac{k_2}{k_1} \tag{6}$$

Equation 7 is obtained from the integration of Equation 5 (Waite and Freeman, 1977; Longe and Omole, 2008; Omole and Longe, 2012). Equation 7 is also known as the modified Streeter-Phelps equation.

$$D = \frac{L_a}{f-1}\,10^{-k_2 t}\left(1 - 10^{[-)f-1)k2t]}\left[1-(f-1)\frac{D_a}{L_a}\right]\right) \tag{7}$$

Equation 7 is used to predict the DO deficit at any point along the stream. This is useful in predicting the trends in DO patterns (within the river segment) where sampling did not take place. Time of travel, t, of the stream is represented by Eq. 9 (Lin and Lee, 2007).

$$t = \frac{V}{Q} \times \frac{1}{86400} \tag{9}$$

Where V = stream reach volume (m^3); Q = average stream flow in the segment (m^3/s); unit of measurement of k_1 and k_2 is d^{-1} (per day); unit of measurement of t is days. D_o or D_a = initial DO deficit at point of pollution at the upstream. Usually, the time of travel is calculated for each segment (or reach) of the studied section of the river. One segment is the distance between two sampling stations. From the cumulative time of travel, a mean time of travel for the studied section of the river can be determined by finding the mean of all of the time values.

The most critical drop in the DO level of the stream arising from the waste load is denoted as D_c and is represented by Eq. 10 (Waite and Free, 1977; Longe and Omole, 2008; Omole and Longe, 2012).

$$D_c = \frac{L_a}{f\left(f\left[1-(f-1)\frac{D_a}{L_a}\right]\right)^{\frac{1}{(f-1)}}} \tag{10}$$

Data which are collected in the field include DO, temperature, stream velocity, and stream depth. The BOD is determined in the laboratory on the 5th day (BOD_5) using Eq. 1, field-measured DO values and the laboratory method detailed in APHA (2005). The flow chart (Fig. 3) summarizes the process followed in order to predict DO deficit at any point along the stream. Having obtained all field and laboratory data, time of travel is computed, using

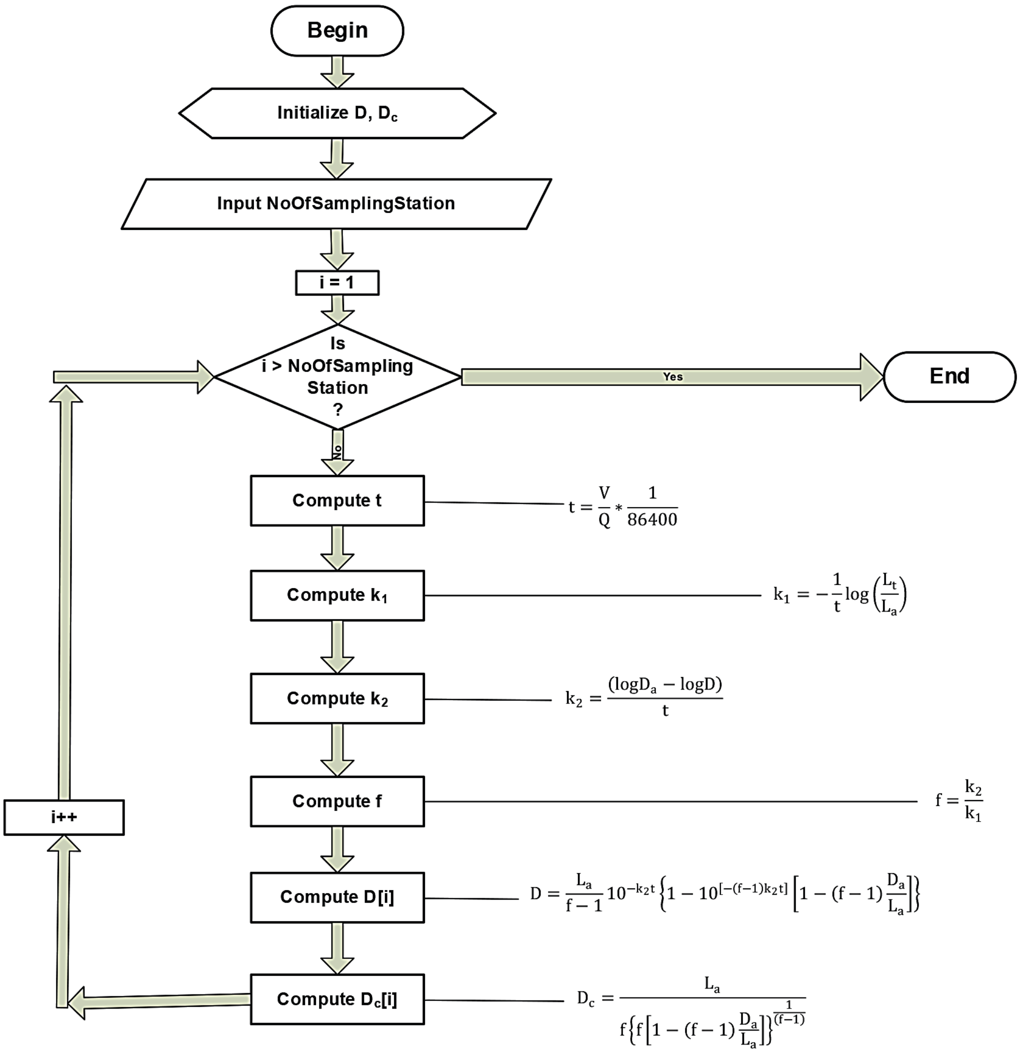

Figure 3

Analysis procedure in flow chart format

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Eq. 9. Subsequently, k_1 and k_2 are determined using Eq. 2 and Eq. 4, respectively, to obtain (Lin and Lee, 2007; Agunwamba et al., 2007):

$$k_1 = \frac{1}{t} \log\left(\frac{L_t}{L_a}\right) \tag{11}$$

and:

$$k_2 = \frac{(\log D_a - \log D)}{t} \tag{12}$$

where: L_t and L_a are as defined previously, D_a = initial DO deficit at point of pollution at the upstream; D = DO deficit at any point downstream of the point of pollution. The unit of measurement is mg/L. DO deficit, D_a and D are obtained by subtracting the measured DO from the DO at saturation. DO at saturation depends on temperature of the water body. Colder streams have higher DO saturation values. Weiner and Matthews (2003) provided saturated DO values ranging between 14.6 mg/L at 0°C to 7.6 mg/L at 30°C. Also, Lin and Lee (2007) suggested an equation to determine DO saturation for any river at specified temperatures (Eq. 13).

$$DO_{sat} = 14.612 - 0.41022T + 0.0079919T^2 - 0.000077774T^3 \tag{13}$$

where: DO_{sat} = dissolved oxygen saturation concentration and T = water temperature in degrees Celsius. Equations 11 and 12 are used to obtain f and all these values are inputted into Equations 7 and 10 to obtain the DO deficit along any point on the river, and the critical DO deficit, respectively.

Field sampling and laboratory analysis

Sampling stations were marked out at strategic positions as shown (Fig.1). The first sampling station, designated as A1, was selected 50 m upstream of the effluent discharge point. Information from this point was required to give an idea of the background conditions of the Apies River before contact with the wastewater effluent discharge. Station A2 is the area where the wastewater effluent from DWTW and the Apies River converge (Figs 1–2). Subsequent sampling stations (A3–A7) were situated at 50 m intervals until A7, which is 20 m before the confluence of Apies River and a smaller stream known as Skinnerspruit. The 50 m interval was adopted because it is short enough to capture the dynamics in the stream and to reduce the costs associated with increased sampling points (Jha et al., 2007; Omole et al., 2013). The confluence of these two rivers was designated as Station A8 and the final station (A9) was placed 50 m downstream of the merged streams. Two additional sampling stations, A0 and A10, were marked out on DWTW and Skinnerspruit, respectively. Information from these two additional points described the conditions at the respective stations just before contact with the Apies River. The stream data obtained during the field sampling exercise from each sampling station include width, depth and velocity. The width was measured using a measuring tape; the depth was taken using a Speedtech portable depth sounder at 5 different points along the same cross-section. The stream velocity was measured using Geopacks stream flow sensor. The flow sensor impeller was placed at two-thirds of the water depth for the measurement of the velocity. This was done because that is where the bulk of the flow happens (Omole, 2011). Three separate velocity measurements were taken at each sampling station and the mean value was used in calculations. Also, from each sampling station, two batches of water samples were obtained from the same point where the stream velocity was measured.

All water samples were transported to the DWTW laboratory for the determination of biochemical oxygen demand (BOD) and coliforms. The water samples meant for the determination of BOD and other parameters were collected in 500 mL plastic bottles and placed in a vacuum storage maintained at 4°C, while the water samples meant for coliform determination were collected in 50 ml glass bottles which were sealed on-site using foil and rubber bands. All water samples were transported to the laboratory for analysis within an hour after collection. The dissolved oxygen (DO), electrical conductivity, temperature and pH were determined in-situ using the handheld HACH HQ40d portable meter with IntelliCAL probe. The BOD was determined in the laboratory using titrimetric method (Azide Modification). Also, bacteriological assays were done to determine thermotolerant coliform bacteria and *Escherichia coli*. Other parameters were determined using standard methods (APHA, 2005). All the results were compared with the South African Water Quality Guidelines for Aquatic Ecosystems, Volume 7 (DWAF, 1996).

Data analysis

The analyses of all data obtained in-situ and from the laboratory were documented and analysed using Microsoft Excel. The progressive steps taken in analysing the gathered data are shown in the flowchart (Fig. 3).

RESULTS AND DISCUSSION

The hydraulic data obtained along the studied segment of the Apies River are presented in Table 1. The river width and

TABLE 1
Hydraulic data

Station number	Sampling station code	Cumulative Distance (m)	Width (m)	Mean depth (m)	Cross-sectional area (m²)	Mean Velocity (m/s)	Discharge (m³/s)
1	A1	−50	11.5	0.300	5.41	0.254	1.374
2	A2	0	8.6	0.240	3.24	0.377	1.222
3	A3	50	8.6	0.310	4.19	0.406	1.700
4	A4	100	10.2	0.284	4.55	0.533	2.425
5	A5	150	10.9	0.176	3.01	0.181	0.545
6	A6	200	7.4	0.570	6.62	0.264	1.748
7	A7	250	11.4	0.514	9.20	0.137	1.261
8	A8	270	21.0	0.648	21.36	0.071	1.520
9	A9	320	24.0	0.568	21.40	0.077	1.647

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mean depth were measured directly while the cross-sectional area was calculated from the measured dimensions. Similarly, the discharge was calculated from the product of cross-sectional area and stream velocity. The river was close to baseflow at the time of sampling because of low run-off occasioned by low precipitation. The depth ranged between 0.176 m and 0.57 m at the deepest part. However, the depth of the river increases significantly during rainy periods (as evidenced in Fig. 4 where debris carried by high flows is left hanging on tree roots, which, in turn, were exposed by erosion). The data also showed that the depth and cross-sectional width of the river segment generally increased as it progresses downstream of the effluent discharge point. The stream velocity, however, generally decreased as the depth increased. This is expected and corroborated by the coefficient of determination of 0.76 (Fig. 5).

Further, Table 2 shows the sampling stations and the values of DO, BOD and temperature found for each. The highest BOD value and the lowest DO value along the entire studied segment were observed at Station A1. This means that the level of pollution of the Apies River was found to be higher than the wastewater effluent from DWTW. However, the turbulence from the discharge of the effluent (Fig. 2) and the accompanying increase in velocity at A2 caused the increased rate of re-aeration and the increase in DO level observed at A2. Turbulence in rivers enhances re-aeration through the process of trapping and dissolving atmospheric oxygen, at a faster rate than for laminar flows (Omole, 2011). It can also be observed that the temperature of the river at A1 is higher than at A2–A6. This suggests that the river is probably being polluted by an effluent discharge from a heating activity upstream of the river. Increased temperature hinders AC of rivers as the saturated DO level of the stream is lowered in direct proportion to increased temperature (Weiner and Matthews, 2003).

The descriptive statistics for some of the other parameters measured on the river are presented in Table 3. The mean river water temperature during the study was 21.44°C. Using Eq. 13, the DO saturation of the river was calculated to be 8.75 mg/L. The deficits between the measured and saturated DO for all the sampled points were relatively high (Table 2), with the highest deficit occurring at A2, which is

Figure 4

Tree roots eroded during high flows; debris left behind after high flows (background); and solid waste materials from collapsed weir (left)

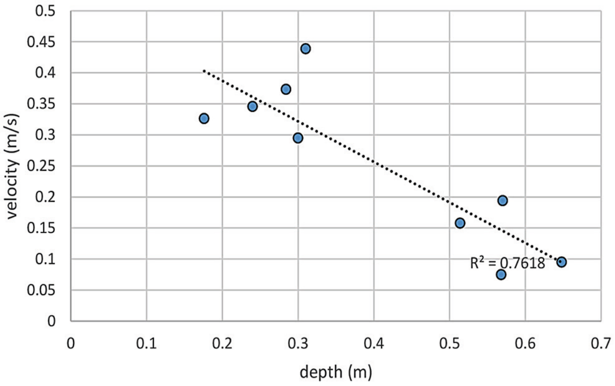

Figure 5

Variation of stream depth with velocity

Table 2
Sampling station description and some pollution indicators found there

Station number	Sampling station code	Distance (m)	Station description	DO (mg/L)	DO deficit	BOD (mg/L)	Temperature (°C)
1	A1	50	Background levels in the Apies River before encountering effluent from DWTW	5.42	3.33	13.0	21.6
2	A2	0	Mixing point of effluent from DWTW and the Apies River	6.51	2.24	8.5	20.4
3	A3	50		6.94	1.81	4.0	21.1
4	A4	100		6.98	1.77	6.5	21.1
5	A5	150		6.86	1.89	3.0	21.2
6	A6	200		6.95	1.8	4.0	21.4
7	A7	250		6.92	1.83	6.5	21.8
8	A8	270	Mixing point of the Apies River and Skinnerspruit	6.81	1.94	8.0	22.0
9	A9	320	Downstream of mixing point	6.98	1.77	7.5	22.4
10	A10	25	Along Skinnerspruit	6.54	2.21	9.0	21.7
11	A0		Effluent from DWTW	5.59	3.16	8.5	22.0

the location where effluent from DWTW merged with the Apies River (Fig. 6). Local, but minor, increments in DO deficits were also observed at A6 and A8 (Fig. 6). The local increase in DO deficit at A6 could be explained by the damming effect of the collapsed weir (Fig. 4). The collapsed weir trapped some decaying materials and slowed down the velocity of the river. Also, the local increase in DO deficit at A8 and A9 could be explained by the impact of the Skinnerspruit which merged with the Apies River at A8. The DO of Skinnerspruit was less than that of the Apies River just before the merging of the two streams (Table 2). The mixing of the more polluted Skinnerspruit with the Apies River could lower the DO of the latter river and increase its DO deficit values.

Auto-purification of the Apies River

Using Eqs 11 and 12, k_1 and k_2 were calculated to be 0.023 and 0.04 day^{-1}, respectively, while the auto-purification factor (Eq. 6) was calculated to be 1.74.

The calculated values of t, k_1, k_2, and f were substituted into Equations 7 and 10 in order to predict the DO deficit and the critical DO deficit (D_c) respectively, along the river. The plot of measured and predicted DO deficit for each sampling point is shown in Fig. 7. The predicted DO deficit model and the measured DO deficit were a relatively close match.

Using Eq. 10, the predicted critical DO deficit was 3.62 mg/L and it occurred at A1; while the measured DO deficit was 3.33 mg/L and it also occurred at Station A1. This suggests that the critical sections of the Apies River where attenuation efforts need to be focused are the portions of the river prior to Station A1.

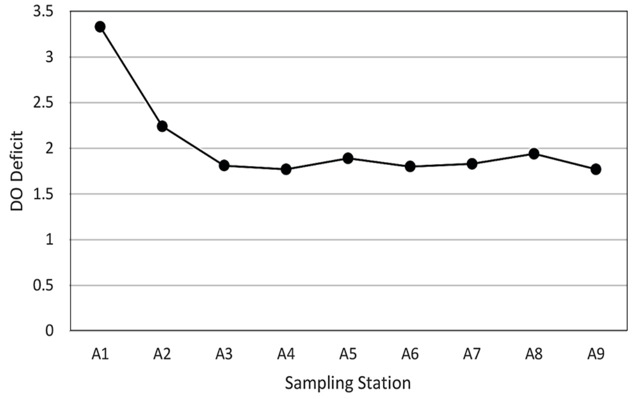

Figure 6

Measured DO deficit along the stream

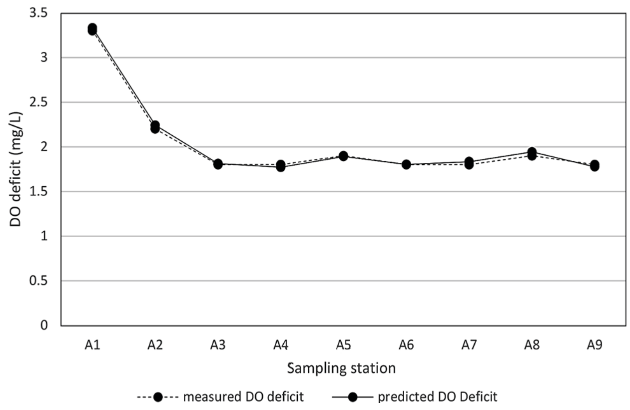

Figure 7

Plot of measured and predicted DO deficit against sampling stations

CONCLUSIONS

It was demonstrated that the Apies River recovered within a 150 m distance after the confluence point with the treated wastewater being disposed into it from DWTW (Fig. 6). The auto-recovery process of the river was enhanced, largely because the effluent discharge from DWTW had been treated to recommended standards specified by DWAF (1996). However, the recovery process of wider sections of the Apies River could be further enhanced by looking into the causes of the problems upstream of Station A1 that led to the relatively high faecal coliform, BOD and DO deficit values at that point. There is a possibility that the DO condition upstream of Station A1 is much worse than that at A1. Also, the relatively higher temperature at Station A1 suggests that whatever pollution is being discharged upstream of A1 is warmer than the natural temperature of the river. This suggests that effluent originating from an industrial or abattoir activity occurs before A1. It is therefore recommended that an investigation should be undertaken to understand the causes of pollution at the prior segments in order to redress the problems. Furthermore, the study showed that the condition of the water flowing from Skinnerspruit (A10) slightly retards the recovery process along the Apies River at Station A8. Some of the observed problems along the Skinnerspruit, however, were slow stream flow, growth of aquatic plants and odour, which indicates eutrophication. The restrained flow along Skinnerspruit, possibly caused by growth of aquatic plants along its channel, could be the cause of the odour and relatively high BOD measured along it. It is therefore recommended that the Skinnerspruit channel be cleared to enhance the stream flow and, by extension, its auto-purification factor.

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