Suspended silt concentrations in the lower Olifants River (Mpumalanga) and the impact of silt releases from the Phalaborwa Barrage on water quality and fish survival

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Silt loads in the Olifants and Sabie river systems inside the Kruger National Park, were monitored by collecting water samples every consecutive week for a period of 20 months. The variation in silt concentration, changes in selected physico-chemical water quality variables and fish mortalities during flushing (i.e. release of silt, by sluicing) of the Phalaborwa Barrage, were also monitored. The Olifants River inside the Kruger National Park carried high silt loads in summer; in the dry season the suspensoid load was greatly reduced. A similar pattern was observed in the Sabie River, but the silt loads were generally lower. It was apparent that silt loads released from the Phalaborwa Barrage led to large variations in the natural silt loads of the Olifants River. These increased amounts of silt (25 000 mg/l to >70 000 mg/l) caused drastic reductions in the dissolved oxygen concentration of the water, ranging from >6 mg/l to 0 mg/l. Depending on the severity and duration of the flushing, fish succumb to such silt loads. These findings, as well as published information, indicate that the management strategy of flushing to improve storage capacity is ecological unacceptable. It is therefore suggested that the use of the Phalaborwa Barrage as a future reservoir should be critically re-evaluated.

Key words: flood control, river, silt, fish, water quality

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Introduction

The rivers flowing through the Kruger National Park (KNP) are important water sources for several users. They are of great importance to human populations in South Africa and Mozambique and for game watering and ecosystems maintenance (Moore 1990). The deterioration of the water quality of the main rivers of the Kruger National Park—the Shingwedzi,

Luvuvhu, Letaba, Olifants, Sabie and Crocodile—is of national concern. Increased pressure on the riparian habitats and catchment areas due to anthropogenic factors such as irrigation, poor land-use practices, industries and in general urbanisation developments to the west of the park, subject these rivers to pollution even before they enter the park (Gertenbach 1991).

The Olifants River catchment has areas varying from unspoilt to badly eroded. Degraded areas were caused by poor land-use practices which have resulted in high sediment loads in the central parts of the basin. The degree of erosion hazard along the upper catchment appears to be low to moderate, although the sediment yield is high to very high throughout the basin (Rooseboom 1991a). These high sediment loads lead to the silting up of barrages (eg. Phalaborwa Barrage), dams and pools in the river, as well as the clogging of pumps used for water extraction. During 1964, the Phalaborwa Barrage was built within the Olifants River only 5 km outside the KNP boundary, to provide potable water for human use and partly-purified or unpurified water for domestic, urban, industrial and mining purposes within the Phalaborwa magisterial district. The construction was such that deposited silt can be washed through because the sluice gates open at the bottom of the Barrage. This design allows for the barrage to be partially cleared of silt during flood periods. To ensure sufficient storage capacity and therefore adequate supply of good quality water to the Phalaborwa town region, the Phalaborwa Water Board has been forced to release the trapped sediment by flushing from the barrage.

The natural flow regime of the Olifants River varies greatly, both seasonally and annually, due to natural variation in rainfall and flood or droughts which are not unnatural. During the summer months, the Olifants River is fast flowing with high silt loads, but during the winter months the flow is generally low with reduced silt loads. The Olifants River below the Phalaborwa Barrage and inside the KNP is subject to very high sediment loads because of the occasional flushing (i.e. release of silt by sluicing) of the Phalaborwa Barrage. This variation in flow regime and silt loads,

together with the regulation of the water released from the Phalaborwa Barrage, must influence the riverine fauna. Suspended solids can cause marked changes in both the aquatic habitats and biota of many streams, especially in areas where river waters have changed from clear to turbid for all or a greater part of the year (Ellis 1936). Chutter (1969) found that increased silt negatively influences macro-invertebrate diversity. Of all the major rivers of the KNP, the Olifants River had the second lowest macro-invertebrate diversity (Moore & Chutter 1988). Heavy suspended loads of solids may be lethal to fish; sublethal effects may result from continuous exposure to lower concentrations. Sublethal effects of suspended solids on fish are varied and include negative impacts on reproduction, egg survival, growth, oxygen consumption, haematology, feeding rate and social behaviour (Heimstra *et al.* 1969; O'Connor *et al.* 1976, 1977; Crouse *et al.* 1981; Wilber 1983). Indirect effects include reduced food availability, reduced aerial predation, clogging of gillrakes and gill filaments resulting in death, reduced growth rate and resistance to disease and disturbances of natural movements and migrations of fish (Alabaster & Lloyd 1980; Bruton 1985). High silt loads (24000-77000 mg/l) in the Olifants River have been associated with fish kills (Du Preez *pers. obs.* Dec. 1990; Moore *et al.* 1991; KNP annual reports). There has been a long history of fish mortalities in the KNP, particularly in the Olifants River, caused by large amounts of suspended particles present in the water (KNP annual reports).

Due to the complex nature of the relationship between suspended solids and their effects on biota, this study focused only on the possible direct effects of high silt loads released from the Phalaborwa Barrage. To achieve this objective, special emphasis was placed on: (1) silt loads in the Olifants

system inside the KNP; (2) the variation in silt concentration and selected physico-chemical properties of the water during flushing of the Phalaborwa Barrage; and (3) the possibility of fish mortalities during the flushing process. Preliminary data for the Sabie River was also collected for comparison.

Materials and methods

Water and silt collection

Water was sampled every alternate week from three predetermined sites along the Olifants River within the KNP boundaries (February 1992 - September 1993), for a period of 20 months. The sites along the Olifants River were (1) Mamba, to the west where the river enters the park; (2) Balule in the central region; and (3) the Olifants Trail Camp, to the east before the river leaves the park. Two sites—Kruger Gate weir and Lower Sabie weir—in the Sabie River were chosen as control sites because this river is at present the least polluted in the KNP and carries a naturally low silt load (May 1992 - September 1992) (Fig. 1).

At each of the sites, 2-litre water samples were taken 10 cm below the water surface, at 2-weekly intervals. In the laboratory, turbidity was recorded using a Nephelometric turbidimeter (Novasina analite model 152). The amount of suspensoids (mg/l) and percentage organic and inorganic fractions were calculated using standard procedures (American Public Health Association 1989). Silt was sampled opposite the angling club situated within the basin of the Phalaborwa Barrage, in March 1992 and March and June 1993. Silt samples were collected from the substrate at a water depth of approximately 2-3 m using a Birge-Eckman GRAB (grab-surface area of 225 cm²). Samples of the silt were analysed for particle size, percentage size distribution (Coulter-counter multisizer instrument) organic and inorganic content, and percentage moisture.

Silt flushing impact studies

The studies on the impact of silt flushing entailed two major aspects: measurement of selected variables concerning the physical and chemical aspects of water quality, and observations on the behaviour of fish. The physical and chemical variables included water flow and colour, conductivity, pH, dissolved oxygen concentration, and turbidity. These variables were measured and water samples were taken for silt analysis every 60 minutes, depending on the intensity of the flood. The time between measurements was lengthened as the intensity of the flood and silt concentration decreased. Conductivity and pH were measured with Hanna mini conductivity and pH meters. Temperature was measured with a Hanna mini E1Th electronic thermometer, and dissolved oxygen-concentration with a WTW OXI 96, Microprocessor Oximeter. Light penetration was estimated with a secchi disc, while turbidity was measured with a Nephelometric turbidimeter. Water-flow data was that measured at the Phalaborwa Barrage by the Phalaborwa Water Board, during water releases.

During flushing events, the studies on fish were concentrated on behavioural changes (e.g. swimming at the surface, gulping for air), species affected, and the removal of moribund and dead fish from the water to determine whether mortalities were caused by silt particles clogging the gills. Dead fish were collected with a hand-net, identified and measured. A representative number (>5 if possible) of fish of as many different species as possible were collected. After measurements were made, the fish were decapitated and the heads frozen in order to determine the particle sizes of silt present on the gills. The impact study continued for 48 hrs or until all visible effects of the flood had significantly diminished. All data was statistically analysed by applying student *t*-tests described by Zar (1984).

Results

Seasonal variation of suspended silt concentrations in the Olifants and Sabie rivers

Monitoring of silt concentrations and turbidity of the Olifants River has revealed

Fig. 1 Sampling sites in the lower Olifants and Sabie rivers.

large variations throughout the period of 20 months (Table 1). No significant differences ($P>0.05$) were found in silt concentrations between the various localities within a river for both years. However, the total load of silt carried by each river for the period of study during 1992 and 1993 respectively, proved to be significantly different ($P<0.05$). During the dry season (March–October), silt concentrations and turbidity were low, while marked increases were apparent during the rainy season (Nov.–Feb.). Values for the Sabie River were in general lower than those recorded for the Olifants River (Table 1).

The highest suspended silt concentrations for the Olifants River was recorded during Dec. 1992 at the Olifants Trail Camp (64224 mg/l); the lowest (1 mg/l) was recorded during Aug. 1992 at Balule. The highest silt concentration for the Sabie River occurred during Jan. 1993 at Kruger gate (1038 mg/l), and the lowest (3 mg/l) during July 1992 and May 1993 at the same site. The highest mean silt concentration in the Olifants River was recorded at the Olifants Trail Camp, 1992 (5854 ± 19359 mg/l), and in the Sabie River at Kruger Gate, 1993 (164 ± 333 mg/l). The higher mean silt values for 1992 (4196 ± 13612 mg/l) at Balule may be due to silt being trapped in the reed beds, which is subsequently released through bioturbation and resuspension; this may also be due to animal (e.g. hippopotami) activity which causes resuspension of deposited material and silt in the shallow water (Table 1).

Turbidity values followed the same trend as the silt concentrations, with highest values recorded at the Olifants Trail Camp and Balule during Dec. 1992, and at all three sites (Table 1) during Feb. 1993 (>1999 NTU). Even though no significant differences ($P>0.05$) were recorded between 1992 and 1993, overall mean silt values recorded for the Sabie River during 1992 were lower than

those for 1993. This may be attributed to the drought conditions during 1992. A wetter season followed in 1993, causing increased silt and turbidity values. This phenomenon was only detected at Mamba in the Olifants River. The wetter season during 1993 may explain this. The occasional water releases from the Phalaborwa Barrage may also account for this difference in mean silt values between the Olifants River sites. During November 1992 and January 1993, higher values, compared to the Olifants River, were recorded in the Sabie River. This may be attributed to cloudbursts which had occurred during those periods. The high summer values recorded in the Olifants River may be due to rain showers during this period, as well as to the Phalaborwa Barrage flushing operations during February and March; 31000 mg/l silt at Mamba and turbidity values of >1999 NTU were recorded at all three sites in the Olifants River during this time.

The percentage organic and inorganic fractions of water samples from both rivers also showed considerable variation throughout the 20 months of recording. The highest mean organic fraction for the Olifants River was recorded at Balule ($14 \pm 13\%$) while the highest Sabie River value was recorded at Lower Sabie ($19 \pm 19\%$). The highest inorganic percentages were subsequently found at the same sites.

Flow recorded at Mamba fluctuated between 0.17 cumec during August 1992 and 1.12 cumec during June 1992. Total dissolved salts (TDS) and electrical conductivity (EC), recorded at Mamba were highest during May 1992 (TDS: 1938mg/l; EC: 250 mS/m), and lowest during February 1993 (TDS: 232 mg/l), and March 1993 (EC: 31 mS/m) respectively. The lowest pH recording (7.6) was during March 1992, while the highest pH (9.2) was detected during August 1993 (Fig. 2).

Table 1
Monthly turbidity (NTU) and silt (mg/l) variation of the Olifants and Sabie rivers at
the selected sampling sites, for the period February 1992 - September 1993

Sampling Period	Sampling Sites									
	Mamba		Olifants River				Sabie River			
			^a OTC		Balule		Lower Sabie		Kruger Gate	
	mg/l	NTU	mg/l	NTU	mg/l	NTU	mg/l	NTU	mg/l	NTU
Feb. 1992	44	36	10	23	24	11	17	3	25	3
March 1992	13	9	2	9	17	11	100	2	102	3
April 1992	15	7	14	6	13	13	44	4	32	3
May 1992	14	9	8	6	27	6	9	3	11	3
June 1992	12	15	13	8	9	3	4	9	8	10
July 1992	16	7	6	8	32	21	3	4	5	5
Aug. 1992	4	3	5	3	1	2	74	6	86	6
Sept. 1992	3	20	6	4	400	35	8	5	7	7
Oct. 1992	12	5	58	3	121	5	7	6	7	6
Nov. 1992	86	22	43	605	278	925	436	1125	206	574
Dec. 1992	88	6	64224	>1999	45236	>1999	48	25	70	49
x	28		5854		4196		68		51	
±SD	31		19359		13612		126		62	
Jan. 1993	123	52	365	>1999	217	1362	261	540	1038	>1999
Feb. 1993	31000	>1999	14670	>1999	18600	>1999	150	145	180	102
March 1993	220	20	125	231	318	201	359	60	103	72
April 1993	28	11	5	4	64	12	45	10	56	8
May 1993	8	20	56	7	178	11	18	5	3	3
June 1993	355	45	114	8	555	4	32	6	8	4
July 1993	68	12	75	4	40	2	30	8	11	5
Aug. 1993	16	15	146	104	242	1205	37	10	33	8
Sept. 1993	11	10	182	230	341	1275	43	14	40	7
x	3537		1749		2284		108		164	
±SD	10299		4847		6120		123		333	

^a OTC = Olifants Trail Camp

Study of the frequency distribution of the silt particles at Mamba revealed that 50% of the sample particles ranged between 1.89-3.97 μm , and 10% of the particles between 3.12-11.22 μm . The largest particles ranged from 13.29 μm to 21.24 μm . Particle size distribution for Balule was 3.28-5.35 μm in the 10% group, and between 1.73-3.28 μm for the 50% group; the largest sizes recorded were between 13.12-33.42 μm . Frequency distribution for the Olifants Trail Camp ranged from 2.94-11.22 μm in the 10% group, and from 2.07-4.14 μm in the 50% group; the largest particle being 32.46 μm

(Table 2). From the different size group distributions, it appears that the 50% group of particles at the Olifants Trail Camp was larger than at the other two sites even though the largest particle sizes recorded for the three sites were of approximately the same order. No significant differences ($P>0.05$) were found between the three sites and for different years. The highest mean particle size distribution for the 50% group was recorded during 1993 ($3.11 \pm 0.75 \mu\text{m}$), while the highest mean for the 10% group was ($6.4 \pm 2.29 \mu\text{m}$) both recorded at Mamba (Table 2).

Table 2
Monthly particle size (μm) distribution at the selected sites in the lower Olifants and Sabie rivers

Sampling Period	Mamba			Olifants River Sampling Sites ^a OTC			Balule			Sabie River Sampling Sites Lower Sabie			Kruger Gate		
	Size Group			Size Group			Size Group			Size Group			Size Group		
	10%	50%	<0.005% (largest)	10%	50%	<0.005% (largest)	10%	50%	<0.005% (largest)	10%	50%	<0.005% (largest)	10%	50%	<0.005% (largest)
	Particle Size (μm)			Particle Size (μm)			Particle Size (μm)			Particle Size (μm)			Particle Size (μm)		
June 1992	5.35	2.25	20.72	4.32	2.07	1.29	3.28	1.73	14.85	†	†	†	†	†	†
July 1992	3.89	2.07	13.29	4.32	2.07	1.29	3.28	1.73	14.85	†	†	†	†	†	†
Aug. 1992	7.08	2.76	21.24	9.84	2.42	32.46	5.18	2.42	13.64	5.18	2.42	28.66	5.35	2.42	41.62
Sept. 1992	4.32	2.25	18.99	3.97	2.07	15.02	5.35	2.59	16.23	5.01	2.25	17.96	3.97	2.25	17.44
Oct. 1992	4.14	2.25	13.81	3.45	2.07	11.22	3.97	2.07	17.27	4.52	2.16	17.45	3.63	2.07	18.45
Nov. 1992	3.18	1.89	16.23	2.94	2.25	14.51	3.45	2.07	13.12	3.28	2.07	16.92	3.45	2.07	21.93
Dec. 1992	3.28	1.89	15.37	4.84	2.76	19.86	5.01	2.42	16.06	5.35	2.25	20.37	2.07	1.55	10.88
x	4.46	2.19	17.09	4.81	2.24	16.98	4.22	2.15	15.15	4.62	2.23	20.27	3.69	2.07	22.06
±SD	1.36	0.3	3.23	2.3	0.26	7.35	0.93	0.34	1.48	0.84	0.13	4.87	1.17	0.33	11.64
Jan. 1993	4.66	2.42	20.72	5.53	2.94	30.56	3.45	2.07	16.41	5.87	4.49	13.98	4.32	2.25	22.27
Feb. 1993	6.04	3.97	21.24	5.01	2.94	22.45	5.01	2.42	28.15	3.79	2.07	21.58	3.28	1.89	15.37
March 1993	5.56	2.42	18.98	3.63	2.07	21.06	3.63	2.07	31.94	3.45	2.07	17.27	4.32	2.07	16.45
April 1993	4.32	2.07	16.45	4.49	2.07	21.76	3.97	3.28	33.42	2.16	1.55	17.45	3.45	2.07	13.12
May 1993	4.14	3.11	20.74	3.79	2.07	20.55	3.79	2.76	21.24	5.56	2.42	18.98	3.28	1.73	14.85
June 1993	7.43	3.28	18.99	3.79	2.07	17.27	5.35	2.59	26.25	3.79	1.89	18.31	3.28	1.89	17.61
July 1993	6.04	2.76	16.23	5.01	2.42	16.06	5.01	2.42	16.23	6.04	3.97	21.24	6.04	3.97	21.24
Aug. 1993	8.46	3.79	17.27	11.22	4.14	19.61	5.01	2.45	14.85	5.35	2.59	16.23	11.22	4.14	19.61
Sept. 1993	11.22	4.14	19.61	5.18	2.42	14.85	5.35	2.59	15.37	4.14	2.25	13.81	5.18	2.42	14.85
x	6.4	3.11	18.91	5.2	2.57	20.46	4.44	2.52	22.65	4.46	2.54	17.65	4.93	2.47	17.26
±SD	2.29	0.75	1.89	2.3	0.69	4.61	0.86	0.37	7.43	1.31	0.94	2.76	2.55	0.91	3.15

† Data not available
a Olifants Trail Camp

Fig. 2 Bi-weekly variation in waterflow, total dissolved salts (TDS) and electrical conductivity (EC) recorded at Mamba for the period February 1992 - September 1993.

The frequency of particle size distribution during the period of study at the Lower Sabie site ranged between 1.55-4.49 μm for the 50% group and between 2.16-6.04 μm for the 10% distribution group. The largest particles ranged from 13.81 to 28.66 μm . Particle size distributions for Kruger Gate in the 50% group ranged between 1.55-4.14 μm and the 10% group between 2.07-11.22 μm , largest sizes recorded were between 10.88-41.62 μm (Table 2). The highest mean for 50% of the sample particles was recorded during 1993 at Lower Sabie, ($2.58 \pm 0.98 \mu\text{m}$) while the highest for the 10% group was recorded at Kruger Gate ($4.93 \pm 2.55 \mu\text{m}$). The various sites of the Olifants River, compared with those in the Sabie River, do not differ significantly from each other ($P > 0.05$). The majority of particles in each silt sample thus have approximately the same frequency size distribution.

Variation in silt concentrations in the Olifants River during flushing of the Phalaborwa Barrage

October, 1992 - Water release

Flushing operations were not performed during 1992, but large amounts of water were released (P. Grobler *pers. comm.* 1992). The first monitored release (23 October 1992) was occasioned by local rain showers in the Phalaborwa district, together with heavy rain showers and hailstorms in the Pietersburg area. Rain for this period along the Olifants River catchment was 12 mm close to Steelpoort and 6.5 mm near Blydepoort Dam (Weather Bureau). A marked flow increase from 2.95 to 63.02 cumec just before water was released from the barrage was apparent. The water release was started at 09:30 (23 October 1992) at a flow volume of 46 cumec for approximately 4-5 hours. Flow recorded at Mamba showed

Table 3
Fish mortalities linked to water releases from the
Phalaborwa Barrage

Date of fish mortalities	Turbidity of water released (NTU values)	Suspended silt concentration (mg/l)
1983	*	78 700
1984	*	26 851
1987	*	24 665
1987	*	44 707
24 Oct 1989	21 400	52 310
25 Oct 1989	19 200	48 890
16 Dec 1990	9 100	23 380
17 Dec 1990	5 800	17 460
18 Dec 1990	4 500	12 610
19 Dec 1990	8 600	28 800
20 Dec 1990	9 800	30 420
21 Dec 1990	12 700	38 400
28 Jan 1991	20 000	94 280

* Data not available

a definite sudden increase after the release and peaked at 63.02 cumec, nine hours after the release was started. During the release flow stayed high. It slowly decreased during the two days following the day on which the release occurred.

Approximately 24 hrs after the first release, water had moved 42 km downstream into the Kruger National Park (KNP). Monitoring of the release commenced on 24 October 1992 at Hardekooldraai, approximately 60 km downstream from Mamba (near Balule). During the first recording temperature did not vary much throughout and stayed within $29 \pm 1^\circ\text{C}$. Conductivity increased from 95 to 131 mS/m, then decreased to 82 mS/m, which is below the starting point. The increase might be ascribed to the dissolving of a white precipitate (from the dry river bed) in the shallow rising water. No trend was apparent from the pH values of the water. Light penetration showed a reduction from 34 cm to 9 cm. Initially the organic content of the water was very low (11.7%), but increased up to 57.2%, probably due to

the increased organic material being swept downstream by the moving mass of water (Fig. 3).

Suspended silt concentrations recorded at Mica were 34000 mg/l; the influx of this water appeared to move along the bottom of the impoundment held by the barrage (Phalaborwa Water Board *pers. comm.* 1992). This indicated that the silt concentrations of water entering the barrage were very high. This influx of silt-laden water resulted in increased silt loads of the barrage water, causing the silt content of the released water to be very high (7000 mg/l). No additional discharge had occurred from the Selati River (Deacon *pers. obs.* 1992). Turbidity, which was caused mainly by suspended solids, increased gradually from 12 to 21.5 NTU. Silt contents of the water ranged from 15 mg/l to a maximum of 99 mg/l, whereafter they decreased. The impact study conducted at Hardekooldraai (± 60 km downstream from Mamba) revealed that as flow and subsequently turbidity of the water increased, so did the

Fig. 3 Water level and selected water quality variables measured at Hardekooldraai during the October 1992 water release.

silt concentrations. Foam was visible on the water surface, but no abnormal behaviour by fish or other animals was noticed. Smaller fish tended to stay in the shallow water. Since the silt increase of the water was relatively low and no fish mortalities were noted, monitoring was terminated after only two hours of observation.

January, 1993 - Water release

On 10 January 1993, 89 mm of rain fell in the Phalaborwa area, and another 37 mm followed early the next morning. Rainfall at Mica was not measured, but the Phalaborwa Water Board assumed that it was of the same order. The upstream catchment of the Olifants River received the following amounts of rainfall, contributing to the conditions: 36.5 mm near Steelpoort, 57 mm near Blydepoort Dam and 2.5 mm near the Selati River. The combined rainfall in the area caused flooding of tributaries and filling of the river downstream from Mica. This resulted in a dramatic increase in flow at Mica from 100-164 cumec, and 220- >500 cumec at Mamba.

Water flow was rapid, very turbid and reached both river banks and at 06:52 water flow at Mamba was recorded at 225 cumec. Water release started at 08:00 (11 January 1993) with a flow rate of 500 cumec, and free-flow occurring two hours later. The sluice gates were closed after the required four hours of flooding. A sudden increase in flow, however, occurred at 16:00, probably because the barrage had reached a level where water could again be released. Thereafter water conditions seemed to stabilise, even though the water was still flowing strongly.

Temperature varied between 26.6-28.1 °C, showing a slight increase. Conductivity at Mamba decreased from 41 mS/m to 31 mS/m, whereafter it increased again to 35 mS/m.

Light penetration also reduced from 2 cm to < 1 cm (Fig. 4). Particle size distribution of the silt did not reveal any particular trend. Samples taken at Mamba were more or less of the same magnitude, ranging between 2.07-2.25 µm. A sample, taken downstream at Balule, indicated slightly larger particles in the 50% size group (4.14 µm) and also the largest particle size (32.64 µm) recorded during the release. A sample from the Selati River indicated that 50% of the particles from the sample had a grain size almost three times larger (7.94 µm) than those recorded at Mamba.

Suspended silt concentrations in the barrage prior to the water release were relatively low (3355 mg/l) and increased dramatically to 100060 mg/l as water was released. During free-flow, a maximum of 126515 mg/l silt was released. The average flow through the barrage at the time of release was 322 cumec (Phalaborwa Water Board *pers. comm.*). Turbidity was high (1725 NTU) even before the flood release, and stayed high (>1999 NTU) throughout the period of flood monitoring. Silt concentrations at Mamba increased from 1800 to 26180 mg/l whereafter they decreased slightly to a low of 17254 mg/l. Even though the flood level decreased, the silt contents of the water stayed high, between 21552 mg/l and 26180 mg/l (Fig. 4).

The first signs of fish in distress were noted at Mamba about an hour after the sluice gates were closed. Fish species such as large scaled yellowfish (*Barbus marequensis*) and brown squeaker (*Synodontis zambezensis*) were gulping air at the water's surface. Minnow and silver catfish (*Schilbe intermedius*) showed the same signs of stressed behaviour. The first fish mortalities included large-scaled yellowfish, silver catfish, brown squeaker and Mozambique tilapia (*Oreochromis mossambicus*). Large

Fig. 4 Selected water quality variables measured at Mamba and Balule during the January 1993 water release.

amounts of suspended solid particles were observed on the yellowfish gills.

Small tributaries enter the river along its length and it was noted that some fish moved to these streams of cleaner water, probably as a refuse from the silt-laden flood water. By doing this, the gills were rinsed with clean water and respiration was improved. Fish observed behaving in this manner were catlets (*Chiloglanis* spp.), silver labeo (*Labeo ruddi*), rednose labeo (*L. rosae*), leaden labeo (*L. molybdinus*), large-scaled yellowfish, minnows (*Barbus* spp.) and river sardine (*Mesobola brevianalis*). Twenty-four hours after the start of the flushing, large numbers of dead fish floated downstream. At the same time, some fish were still noticed utilising the top layer of surface water. At Hardekooldraai, near Balule, debris and dead fish were found stranded two metres above the flow level at the time. The flood level must therefore have been very high at one stage, and these mortalities thus probably occurred during peak flow. The water colour was reddish-brown compared to the dark brown observed at Mamba.

Data from the Phalaborwa Water Board indicated that during this flushing operation the barrage had an increase in silt load, rather than the reduction which was intended (Phalaborwa Water Board *pers. comm.*). Even though not much desiltation of the area impounded by the Phalaborwa Barrage had occurred, several fish kills were observed along the length of the lower Olifants River. Animals such as hippopotamuses and crocodiles

were probably also stressed since they were leaving the water.

February, 1993 - Water release

Fifty-eight cumec of water were released from the barrage on the 18 February 1993 following rainfall of 10 mm in the Blydepoort area and 143 mm in the Phalaborwa area. Monitoring of the release which started at 10:35 on 18 February 1993, was conducted at Hardekooldraai (± 60 km downstream from Mamba) and Balule (further downstream). The various water quality variables taken hourly did not show drastic changes. Temperature recorded at Balule stayed constant at 25.1 °C; at Hardekooldraai temperatures increased slightly whereafter they decreased to 24.1 °C and increased again to 25.6 °C (Fig. 5). Conductivity at Hardekooldraai decreased slightly from 60-51 mS/m, thereafter it increased to 55 mS/m. Light penetration was only 1.5 cm at Balule and Hardekooldraai, and decreased to below 1 cm. The 50% silt particle size group varied between 2.07 μ m and 6.38 μ m during this water release. The largest size recorded at Mamba was 35.23 μ m.

Turbidity values at Balule were high (1198 NTU) from the start. Turbidity at Hardekooldraai remained very high (>1999 NTU) throughout the period of observation. Suspended silt concentration at Balule was 2592 mg/l and increased to 4400 mg/l even though turbidity appeared to decrease. The silt concentration at Hardekooldraai ranged from 8148 mg/l to a high of 18194 mg/l, whereafter it decreased (Fig. 5).

The fish first showed signs of stress at 17:00 the same day. Small fish were active on the water surface and foam puffs on the surface seemed to attract flies. The next distress signs to occur were at midnight, when large fish swam at the surface, extending their dorsal fins above the water. Despite these

observations that fish were obviously stressed, no mortalities were observed.

March, 1993 - Water release

A few weeks after the flushing in February, a second desiltation operation took place in March 1993, probably because the first was not very successful. The first flushing was induced after a short flood burst in the Makutsi River in the upper catchment area, together with showers in the Phalaborwa area, the flood volume of which was not very large; the period of flushing was kept short due to a need for water storage. The second scouring operation was of longer duration and of much larger volume, due to heavy rain showers in the Blydepoort Dam catchment. A long period of flooding is important to complete the desiltation process effectively. This particular water release caused severe floods downstream from the barrage.

Rainfall during and prior to the flood conditions was as follows: Blydepoort Dam catchment 257.5 mm, at Inyoku near Mica 48.0 mm, Gravelotte near Selati 21.0 mm and 23.4 mm at Phalaborwa. The Phalaborwa Water Board started monitoring of flood conditions at 13:00 (2 March 1993) at Mica weir. Hourly measurements were taken and water release started at 15:00 (2 March 1993). During the first three hours of the flood the water level increased from 1.4-2.17 m. The flood level then increased to 2.65 m with the flow at the barrage almost three times that of Mamba (P. Grobler *pers. comm.* 1993). As flow at the barrage decreased, flow at Mamba increased from 133.01 to 619.0 cumec in only four hours (Figs. 6 & 7). Large volumes of water were released by means of flood-gate manipulation from south to north, for approximately 16 hours, after which a total of 1829617 tons of silt was released, as

Fig. 5 Selected water quality variables measured at Mamba and Balule during the February 1993 water release.

calculated by the Phalaborwa Water Board. When flood-gate manipulation takes place the sluices are opened alternatively and large amounts of deposited silt are thereby removed. A channel is formed through the middle of the impoundment floor where the main stream flows. This causes the thick layers of deposited silt on the sides to loosen and move to the middle, where it gets swept away via the channel downstream. The loosening of these silt walls takes place from the barrage wall to the inflow of the impoundment. This process continues for as long as the sluices are left open. During this time the silt contents of the water at the barrage wall is much higher than at Mica. The water leaving the barrage carries very high silt loads, which cause marked turbidity increases.

Throughout the first few hours of the flood, temperature varied at $25 \pm 2^\circ\text{C}$. Conductivity decreased from 39 mS/m to only 11 mS/m (Fig. 6), while pH initially decreased from 8.4 to 8.1, thereafter increased to 8.7 and decreased again to 8.5 (Fig. 6). The dissolved oxygen content decreased from normal levels to only 1% (0.1–0.4 mg/l) and thereafter to 0%, but increased again from 1% to 76% (6.5 mg/l) (Fig. 6). Percentage inorganic fraction varied throughout, the highest value recorded being 91% at Hardekooldraai (15:00) and the lowest 75% at Mamba (Fig. 7).

Turbidity was high from the beginning of the release (1158 NTU) and increased to >1999 NTU. Even though the flood level and flow reduced, turbidities stayed constant at over 1999 NTU (Fig. 7). It was only 17 hours after the first flood waters were

released that turbidity decreased to 1105 NTU. The last sample taken downstream (3 March 1993) near Balule showed a high turbidity value (>1999 NTU) and silt concentration of 8851 mg/l with low oxygen concentrations (33%). The highest silt concentration was recorded early on (70200 mg/l), whereafter it decreased to a minimum of 2468 mg/l. As flow increased, so did the silt concentrations. Flow continued to fluctuate, while the silt concentrations after reaching a peak, decreased (Fig. 7). Within the silt samples, 50% of the particles ranged between 3.28 and 2.07 μm for the March scouring as determined by the frequency distribution of the particles. A sample taken further downstream near Balule showed no divergence from this. The 10% group ranged between 4.49–6.91 μm and the largest particle recorded was 25.55 μm at 23:30.

From the data it appears that the flood took approximately 12 hours to reach its peak, whereafter conditions stabilised and water quality showed a slight improvement. Further downstream where dead fish were found, the water was turbid and dark red-brown, with lots of debris floating downstream and washed out on the river banks. Dead fish, including *Labeo ruddi*, *L. rosae*, *L. molybdinus*, *O. mossambicus* and *Chiloglanus* spp., were collected within 2.5 km up and downstream from the Hardekooldraai site. On investigation, the gills of these fish were found to be coated with suspended silt particles. From the data it is evident that both larger and smaller fish species were adversely affected. It appeared that *Labeo* species were affected most, but this may be due to the abundance of this group.

Discussion

River systems fluctuate naturally in daily, seasonal, annual and other cycles, in

response to cyclical environmental and biotic processes. Under normal circumstances such cycles are repetitive, and therefore the biota of the systems are adapted to such changes. Drastic alterations in the continuity, rate and degree of change will, however, have profound consequences for the resilience of the ecosystem. Such alterations will also impact on its ability to keep functioning in such a way that its diverse communities are sustained (Davies & Day 1986).

The average daily flow rates in the Olifants River normally vary between 1.0 m³/s in winter and 30 m³/s in summer. Recurrent floods in the order of 700 m³/s usually occur at least once every five years (Rooseboom 1991b). During the study period, flow decreased to below 0.25 m³/s during normal river flow, which has been established as the absolute minimum winter flow during extreme drought conditions necessary to sustain life in riffle zones. Even during the summer flow period, the minimum flow of 10 m³/s (Rooseboom 1991b) was not achieved. During flood conditions when water releases had occurred, flow increased up to 619 m³/s (Fig. 6). The high flow rate recorded during water releases may thus prove to have been beneficial to the system in that it opens up habitats and provides riparian vegetation growth requirements through bedfilling. However, this is only the case should this flood volume not exceed the natural recurrence interval of three years (Rooseboom 1991b). The below-average flow during 1992 may have been due to the severe drought conditions during this period.

Temperatures recorded for the Olifants River during the flushing of the Phalaborwa Barrage showed little fluctuation, and were within the guideline of 5 °C of the background water temperature proposed by Kühn (1991). A sudden decline in water temperature—for instance after a severe

Fig. 6 Water flow and selected water quality variables measured at Mamba during the March 1993 water release.

hailstorm—can cause fish mortalities in the Olifants River (Deacon *pers. obs.* 1989).

After sudden heavy rains, the conductivity of a river investigated by Ellis (1936)

decreased, and did not increase again although the silt load and consequently the turbidity rose greatly. This observation supports results from the present study which also indicated reductions in

conductivity after water releases from the barrage (Fig.6). This, furthermore, indicates that under erosive conditions, rains and flood waters add proportionally more insoluble material (i.e. silt) than soluble electrolytes. The decrease in conductivity and TDS after the release from the Phalaborwa Barrage also indicates a dilution effect of the poor-quality Selati River water which result in lower water quality in the lower Olifants River during reduced flows (Seymore *et al.* 1994). The effects of TDS usually depend on the rate of exchange of concentrations, rather than the absolute values of determinants, and tolerance to TDS is species-specific. The limited tolerance range of organisms in fresh water should be between 350-550 mg/l (DWA&F 1986) but set for the Olifants River at 800 mg/l (Kühn 1991). A strong seasonal variation in TDS concentrations was recorded for the Olifants River, ranging between the median concentration of 482 to the 90th percentile concentration of 1267 mg/l (Van Veelen 1990). TDS concentrations recorded for the Olifants River under normal conditions during the period of study exceeded the median concentration almost throughout the total study period. It was only during December 1992 and February, March and May 1993, that TDS concentrations were within the recommended guideline (800 mg/l) of Kühn (1991). Compared to the Olifants River, which is highly mineralised, the Sabie River is the least mineralised in the KNP, with a 90th percentile TDS concentration of 88 mg/l and little seasonal variation (Van Veelen 1990).

One of the most important water quality variables for the survival of aquatic organisms is dissolved oxygen concentration (DO). The dissolved oxygen requirements of fishes have been reviewed (Hughes 1973) and the most pertinent findings were increased fish activity in oxygen-deficient water. It was suggested that fish have a

directed response away from the low oxygen areas (O'Conner *et al.* 1977). Standards in South Africa require that DO concentrations should be > 4.0 mg/l (Dallas & Day 1993), and the target guideline for warm-water species is > 5.0 mg/l (Kempster *et al.* 1980). With the release of high silt loads (e.g. 70000 mg/l) from the Phalaborwa Barrage, DO decreased drastically to 1%, i.e. 0.1 mg/l only, resulting in extreme hypoxic conditions (Fig. 6). Fish mortalities are thus thought to be caused by a combination of high silt loads and the associated very low DO levels. It has been shown (O'Conner *et al.* 1977; Du Preez 1995) that there is a risk of deoxygenation of water when solids are introduced, since these particles exert an oxygen demand both when in suspension and when settled. Under normal circumstances, there is a balance between the consumption of oxygen by the suspensoids and the entry of oxygen through the air-water interface (Alabaster 1972). This balance is disturbed with the release of abnormally high suspensoid loads from the barrage, hence the resultant extreme hypoxic conditions. Since fish need well oxygenated water, the extreme hypoxic conditions caused by the presence of high suspensoid loads prove to be fatal to the fish.

No significant differences of particle size distributions ($P > 0.05$) were found between the Olifants and Sabie rivers, although the 50% frequency group distributions for the Sabie River were slightly lower (i.e. $2.58 \pm 0.98 \mu\text{m}$) than for the Olifants River ($3.11 \pm 0.75 \mu\text{m}$). Even though flow conditions during the water releases from the barrage were much greater than 14 cumec, the particle size distribution of the various releases at the 50% group was never larger than 8 mm. Transport of material larger than 8 mm does not become significant until flows of about 14 m³/s are reached (Coats *et al.* 1985). The larger particle sizes recorded ranged from above 10 μm to under 40 μm . When comparing these size distributions to

Fig. 7 Water flow and selected water quality variables measured at Mamba during the March 1993 water release.

the natural seasonal size distribution (Table 2), i.e. $<4.1 \mu\text{m}$ for the 50% size group, it does seem that during water releases particles slightly larger than usual (i.e. $3.11 \pm 0.75 \mu\text{m}$) are also released from

the barrage. The suspended particles released during a flood are mostly small and fine grained. According to the Wentworth grain size classification (Church *et al.* 1987) they are classified mainly as silt which is

transported downstream. Furthermore, the composition of the silt-laden water changes as it flows downstream, due to the settling-out phenomena of the particles. During the transportation of suspended solids, larger particles settle out first, and the finer ones are transported further downstream (O'Connor *et al.* 1977). In the natural environment, fine-grained suspended material usually starts to settle out at flow velocities of 0.1-0.15 m/s (Eisma 1992). However, experimental investigations have also shown that even at low suspended sediment concentrations (<300 mg/l), deposition can be rapid regardless of the gross hydraulic properties of flow or the particle size of the suspended silt (Carling 1984). Continued water releases combined with flushing operations will, therefore, result in extensive changes in the sediment transport regime, as well as the aquatic communities in the Olifants River system within the KNP.

Monitoring of the Olifants and Sabie rivers has revealed seasonal variation in silt loads (from very low, i.e. one to several tens of mg/l, to high concentrations of several 100 mg/l). Suspended silt concentrations have been shown to vary with the change in flow pattern. The lower Olifants River carries heavy silt loads in summer, while in the dry seasons the suspenoid load is greatly reduced and the water increases in transparency. A similar pattern was observed in the Sabie River, the silt loads, however, being generally lower. Direct comparison between the Olifants and Sabie rivers, and among the various sites within a river, is not completely valid as measurements were not taken on exactly the same day and time. The variables are, moreover, linked to the rainfall pattern. During the dry summer period of the study, even the Olifants River, which normally has high silt loads during this period, had low silt concentrations. It is also important to note that during flood periods, the Sabie River, which normally has low silt

concentrations of 5-100 mg/l, may have high silt loads (206-1038 mg/l), e.g. during November 1992 and January 1993. These concentrations may be higher than usual since the floods occurred just after the drought period. It can also be assumed that overgrazing during the drought period was an important factor contributing to the increased silt loads in the Sabie River catchment due to increased erosion after the first rains. However, the extent of erosion in the Sabie River catchment must still be investigated.

The suspended solid loads of the Olifants River in the KNP are, furthermore, closely linked to the operations of the Phalaborwa Barrage. The occasional scouring of the barrage results in dramatic increases in the suspenoid loads of the lower Olifants River inside the KNP (Figs. 3-7). Silt concentrations released during flushing operations were, however, never below several thousand mg/l, the highest concentration (70200 mg/l) being recorded during the March 1993 scouring. Recommended suspenoid concentrations for aquatic life in South Africa range between 10-25 mg/l (DWA&F 1991) or not more than 10% where the background level is greater than 100 mg/l (Canadian Guidelines 1987). The target guideline recommended by Alabaster & Lloyd (1980) is 25-80 mg/l. It is thus clear that the increase in silt loads during such operations is dramatic and highly unnatural.

The physical and biological effects of the suspenoids will be dependent on the present state and needs of the particular system. The differences in channel response and fish behaviour are thus related, to a large extent, to the differences in sediment supply from the source of the flood. The amount of sediment is dependent on the soil type, vegetation cover, relief and climate conditions within the catchment area (Rooseboom 1978). This suspenoid-

sediment supply, furthermore, depend upon the events or circumstances preceding the flood or silt release. A relatively small flood could transport a large amount of sediment after a lengthy dry period, while a large flood after a wet period would transport only a small amount of sediment. It is thus important to take events and conditions in the upper catchment of the Olifants River into account prior to flushing of the Phalaborwa Barrage.

The maximum storage capacity of the barrage is maintained by the occasional flushing operations whereby excessive amounts of sediment are released from the barrage. The decision to flush accumulated silt loads from the barrage is determined firstly by the levels of the upstream water supply reservoirs, and secondly by the quantity of floodwater available (at the Oxford gauging weir). It is only when both of these factors are favourable that scouring will take place (Phalaborwa Mining and Industrial Complex Report 1992). Flow rate at the sluice-gates is controlled so as not to exceed the flow at Oxford gauging weir. Each flow rate is thus dependent on the extent of each individual flood. Careful consideration of flood conditions prior to flushing activities is essential for a healthy ecosystem downstream from the Phalaborwa Barrage. When a potential flood is registered at the Mica weir and both prerequisites for scouring are met, desiltation of the barrage takes place. During a normal flushing operation, increased water releases are almost always started at the northern-most sluices (1-4). The water level is lowered slowly to ensure removal of upper deposits of suspended silt. This is maintained until water flows freely from the sluice gates (this phenomenon is known as free-flow). This may continue until water storage needs to be maintained, or the quantity of floodwater becomes too small (Phalaborwa Mining and Industrial Complex Report 1992). During

this time, the river downstream from the barrage does not receive water which will improve the poor water conditions caused by the silt releases, as has been indicated by the water variables monitored during releases. Water abstraction is maintained until the water level drops too low or the water quality starts to deteriorate, which would be the signal to close the sluice gates. When storage capacity is regained, the sluices are re-opened to release relatively silt-free water to improve the water quality and silt conditions downstream. For the Olifants River this is essential since the water with low silt concentrations and high dissolved oxygen levels will cause an increase in the very low dissolved oxygen concentrations which resulted from the flushing activities.

Interspersion and dilution from tributaries such as the Selati, Klaserie, Nhlalalumi and Timbavati may make it possible for the fish to escape from the silt-laden Olifants River water. Observations at Mamba indicated that fish definitely use such tributaries and small side streams to escape from the silt. The effect of dilution by these various tributaries would, however, not be the same throughout the river downstream. This was shown during the February flushing operation when the most severe effects were observed at Mamba where no dilution took place. Flushing should therefore be coordinated with flow in these tributaries, but since they are intermittent, this might be difficult in practice.

The effects of suspensoids on fish released from dredging operations have been investigated by numerous studies (Ingle 1952; Ingle *et al.* 1955; Ritchie 1970) and it was found that fish avoided these areas and were therefore not affected by the suspensoids. Studies on the status of brown trout populations in rivers which were continuously polluted with the wastes from china-clay mining, indicated a lower

abundance in stretches containing about 1000 and 6000 mg/l (Herbert *et al.* 1961). The 1983 flood in the Olifants River was due to a cloudburst in Sekhukhuneland, which resulted in silt concentrations of 78700 mg/l 50 km downstream from the barrage, and 20000 mg/l upstream from the barrage (Deacon 1991). Mass fish mortalities of the following fish species were observed: yellowfish, mudfish, tigerfish, silver barbel, eel and bream. During the same year, reports stated that all hippo pools were silted up due to the slow flow and high silt loads caused by the flood. Fish kills in 1984 (Moore *et al.* 1991) were again due to the release of high silt loads i.e. 26851 mg/l (Table 3). In 1987, two silt releases of 24665 mg/l and 44707 mg/l respectively occurred in the Olifants River which caused several fish species to die (Moore *et al.* 1991). On 25 October 1989, turbidity values at the needle valve outlet reached a high of 19200 NTU. Annual reports from the KNP for December 1990 and January 1991 asserted that heavy silt loads were the cause of fish mortalities during this period. Results from the impact studies revealed that silt concentrations in excess of 20000 mg/l released from the Phalaborwa Barrage had adverse effects on the fish communities present in the Olifants River, since fish mortalities were noted during both water releases which exceeded this concentration. There is thus evidence (Table 3) that high concentrations of suspended solids released from the Phalaborwa Barrage can be linked to fish mortalities in the Olifants River. It must be stressed, however, that lower concentrations might have adverse effects on the fish population even though no mortalities occur.

The flood conditions change downstream due to the settling out of particles, and also because of the dilution effect of tributaries along the way. It is moreover important to realise that the river changes downstream from Mamba. A sandy reach with few islets

forms the first part for approximately 60 km. Downstream from Hardekooldraai (near Balule), a considerable number of islets covered with reed beds occur. The absence of dead fish in this stretch of river during both scouring operations might have been due to the presence of high densities of reed beds which may trap dead fish and thus prevent them from being washed onto the banks or observed from the river banks. The dispersed placement of dead fish downstream could have several possible explanations. Many were found high up on the river banks, which suggests that they died while the flood peaked, or they succumbed upstream and were swept downstream and left behind on the banks as the flood level dropped. Other fish were found in small inlets, and between the riparian vegetation and debris. The question arises as to whether they died upstream and were trapped while floating downstream, or whether they died there because of the very turbid, silt-laden water. These mortalities may also be due to the silt conditions changing as the flood moves downstream. The suspended particles would thus be caught by the dense reed beds that were causing less severe silt conditions in the area, and hence the lower fish mortalities that were observed. Or it may be that dissolved oxygen concentrations increase as the water flows downstream. The water may also have been diluted by tributaries, thus reducing the adverse conditions downstream by increasing dissolved oxygen concentrations.

The absence of *Brycinus imberi* was ascribed to the high silt load of the Olifants River during the 1983 flood. Furthermore, the population decline of *Tilapia rendalli swiersrae* could not be explained other than by reference to the possible effects of the silt in the water (Russel 1987). The absence of *Brycinus* and other fish species may be attributed to the high TDS in water from the

Selati River (Seymore *et al.* 1994). The tolerance of these species to TDS should be investigated. River flooding of two Eastern Cape estuaries affected the fish populations in two very different ways. In the case of the Sundays River, the rich surface benthos layer in the channel-like estuary was washed away, causing a reduction in the food source of the Mugilidae which led to a decline in their numbers. Mud and silt deposited in the Swartkops River served as a food source for the mullet, thereby increasing their numbers (Marais 1982).

The absence of certain species, such as tigerfish (*Hydrocynus vittatus*), among the fish mortalities in the Olifants River may be due to several reasons. This species may have a high tolerance level to such silt conditions, or it may be able to move away from the turbid waters and escape. It may well be that a particular species has a dispersed distribution, and there are thus few or no individuals of the species at a particular site. Lastly, it is possible that they may succumb to the adverse silt conditions in places where they are just never found. The absence of certain species in a particular area may thus be due either to the direct or indirect effects of the silt released as shown in the above example, or due to several other reasons.

The direct mortalities resulting from asphyxiation of the fish aside, indirect effects on fish habitat are just as significant. Some of the changes in sediment transport and channel morphology that affect fish habitat are not continuous, but occur during and after large storms or anthropogenic interference from impoundments. Anadromous fish habitat is not as strongly influenced by total sediment transport as by the grain size distribution of sediment and its effect on pools and riffles. It was found that when the percentage of fine sediment in spawning riffles is greater than 20-30%,

survival and emergence of salmonid embryos begins to decline. Also, the abundance of juvenile salmon in small streams declines in direct proportion to the loss of pool volume due to filling by fine sediment particles (Bjornn *et al.* 1977). To maintain aquatic habitat in a stream dominated by high sediment loads, there must be flows of sufficient duration to transport sediment that may fill pools. There must also be occasional flows large enough to dilate the channel and remove sediment from riffles (Coats *et al.* 1985). Although settling of silt during flushing was observed during this study, the potential of silt settling and subsequent effects was not investigated. It must be stressed that settling of silt can have catastrophic effects on benthic communities and fish populations (Ackers & Thompson 1987). Most organisms living among the stones in current (riffle) areas cannot tolerate the deposition of silt and will be most affected (Dallas & Day 1993). The silting of pools and riffles dramatically changes the available habitat for specific fish species, and this may change the species diversity, composition and biomass of the river system. Silt deposited on the river banks further influences riparian vegetation, and this in turn will influence other factors such as animal activity, protection and food availability.

Results from the impact studies have thus revealed that the mass fish mortalities associated with water releases from the barrage are due to the combination of high suspended silt loads (e.g. >15000 mg/l) and very low dissolved oxygen concentrations (i.e. <0.1 mg/l). The high suspended solid loads induce extremely hypoxic conditions because of the oxygen absorbency ability of the particles in suspension. Depending on the degree of flushing, which determines silt loads, fish succumb to the adverse conditions due to impaired respiration, which is caused by clogging and abrasion of

the gills and opercular cavities, and by the hypoxic water conditions.

To minimise the possibility of fish kills, the water released from the Phalaborwa Barrage should ideally contain less than 15000 mg/l suspended sediment; this will permit dissolved oxygen concentration levels that most of the fish species can tolerate. The release of such relatively low silt concentrations would probably be ineffective since the input to the barrage may be higher during floods. Nevertheless, the present findings as well as data in the literature, clearly indicate that the present flushing of the Phalaborwa Barrage to improve storage capacity is ecologically an unacceptable management practice. It is therefore suggested that the use of the Phalaborwa Barrage as a reservoir be critically re-evaluated. Management alternatives such as off-stream storage, direct use of the Blyde River system, re-use of water and subsequent pollution prevention (eg. of the Selati River), should be investigated.

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