Sediments as a Source of Phosphate: A Study of 38 Impoundments

D.C. GROBLER and ELIZABETH DAVIES
Hydrological Research Institute, Department of Water Affairs, Forestry and Environmental Conservation, Private Bag X313, Pretoria 0001

Abstract

The component of the sediment phosphate available for algal growth was measured on sediments obtained from 38 South African impoundments. Good correlations between the algal available phosphate fraction and the inorganic phosphate content of the sediments were found whenever the impoundments were grouped in accordance with the geological formation of their catchments. Two regression equations are given which may be used to estimate the algal available phosphate content of the sediments if the inorganic phosphate content of the sediment is known.

Introduction

Phosphate adsorbed onto sediments can make up a large proportion of the total phosphate available for algal growth in an impoundment (Porcella, Kumagai and Middlebrooks, 1970; Sagher, Harris and Armstrong, 1975; Cowen and Lee, 1976; Golterman, 1976; Lee, Rast and Jones, 1978). Grobler and Davies (1979) established that some of the phosphate adsorbed onto the sediments of three South African impoundments was available to algae.

Recently Walmsley and Butty (1979) developed a model for prediction of mean chlorophyll concentrations from the orthophosphate loading and Secchi depth as input variables for impoundments with Secchi depths of less than 0,8 m. In the model, a decrease in Secchi depths (indicating increased suspended sediment concentration) results in a decrease of mean chlorophyll concentration which may develop from a given orthophosphate loading. The decrease in mean chlorophyll concentration with decrease in Secchi depth can be due to either light limitation or to the suspended sediment adsorbing some of the incoming orthophosphate rendering it unavailable to algae. However, if suspended sediment in some impoundments should act as a source of phosphate to algae it would mean that models using orthophosphate loading as the only input variable or incorporating the role of suspended sediment in the manner used by Walmsley and Butty (1979) above, (wherein increased sediment concentrations can only lead to decreased chlorophyll concentrations) could lead to incorrect predictions of mean chlorophyll concentrations in those impoundments. This is particularly relevant if it is taken into account that 33 of the 60 largest impoundments in South Africa are highly turbid and have mean Secchi depths of less than 0,7m (Bruwer and Grobler, 1980). The need has often been expressed for models to predict the levels of chlorophyll to be expected in impoundments (De Lucia, McBean and Harrington, 1978; Lee, Rast and Jones, 1978; Simonsen and Dahl-Madson, 1978; Uttormark and Hutchins, 1978). Therefore the former Department of Water Affairs (now the Department of Water Affairs, Forestry and Environmental Conservation) decided to investigate the usefulness of a number of these models on South African impoundments.

Information on the availability of phosphate adsorbed onto the sediment is needed for use in prediction models and this study was undertaken to determine the proportion of algal available phosphate adsorbed onto the sediments of 38 South African impoundments. An attempt was also made to establish whether useful relationships exist between algal available phosphate content and other easily measured sediment properties which might be incorporated into predictive models.

Materials and Methods

Sediment

Sediment samples were collected during the first part of 1979 from 38 South African impoundments (Figure 1). The impoundments differed from each other with respect to mean depths, Secchi depth (Walmsley and Bruwer, 1980) and geological characteristics of the catchments. Detailed information on the chemical quality of the water in these impoundments can be obtained from the Division of Hydrology of the Department of Water Affairs, Forestry and Environmental Conservation.

The collection and treatment of sediment samples were described earlier by Grobler and Davies (1979). Two bottom sediment samples were collected some distance apart in the main basin of each impoundment.

Bioassays and chemical analysis

The availability of sediment phosphate to algae (Algal P) was determined using a bioassay technique with *Selenastrum capricornutum* as test organism cultured in a nutrient medium deficient in phosphate only. Sediment was supplied as the only source of phosphate and algal biomass was measured after a 21 day incubation. Each bioassay was replicated 5 times (Grobler and Davies, 1979).

The sediment samples were analysed for total phosphate (TP) (extraction with 1 mol/ℓ HCl after ashing at 600°C); inorganic phosphate (IP) (extraction with, 1 mol/ℓ HCl without ashing); organic phosphate (OP), (difference between TP and IP); Bray-reagent extractable phosphate (Bray-2-P); nitrilotriacetic acid (NTA); extractable phosphate (NTA-P);

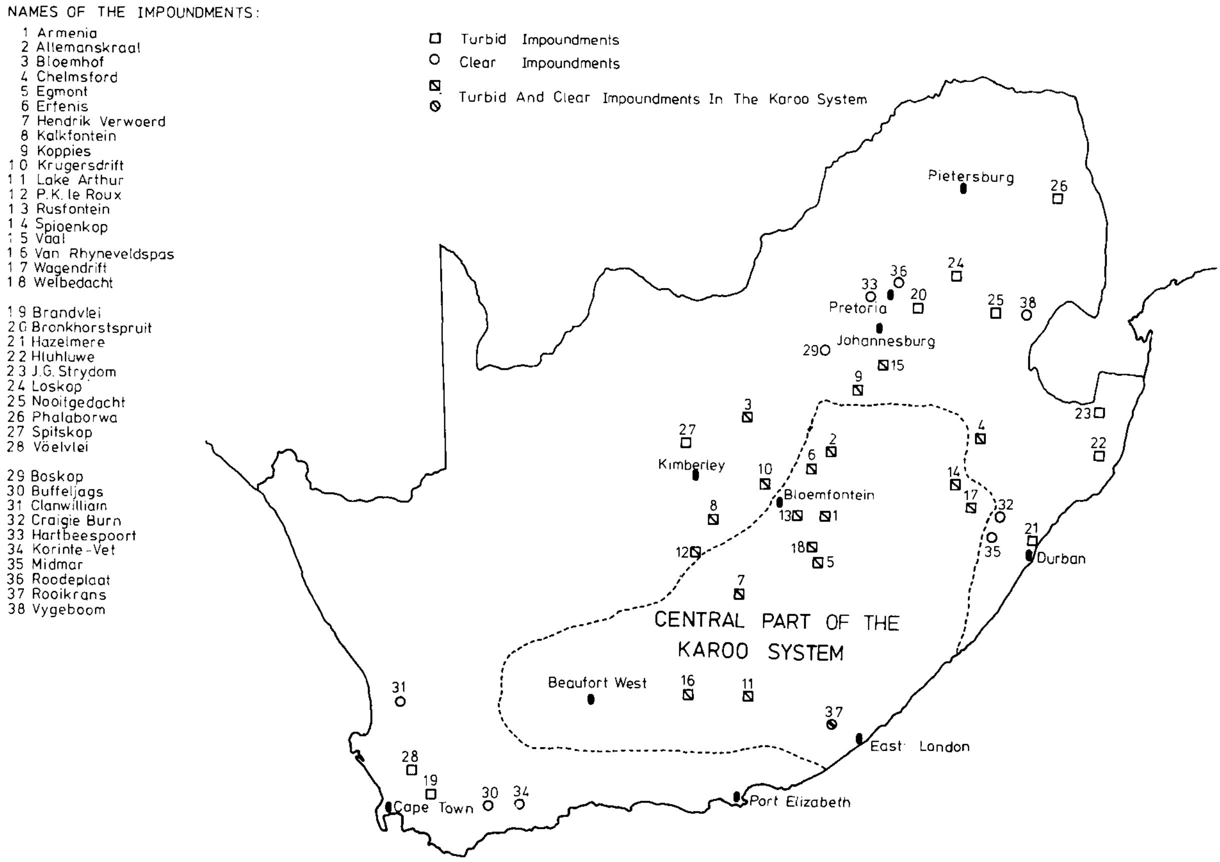

Figure 1
A map of South Africa showing the distribution of the impoundments sampled. The broken line encloses the area referred to as the "Central part of the Karoo System"

and organic carbon (OC) content (Grobler and Davies, 1979). The pH of the sediment samples was measured with a pH meter in a mixture of 1 part sediment to 2,5 parts distilled water. All the results reported are the means of the two sediment samples obtained from each impoundment.

Statistical methods

Multiple linear regressions were calculated with the aid of the computer program P/REGPAC (Galpin, 1979). Confidence limits about the estimates obtained from the regression were calculated from the formulae given by Draper and Smith (1966).

Results

Description of impoundments

Included in Table 1 are mean Secchi depths according to Walmsley and Bruwer (1980) and the mean depths of the impoundments. The impoundments were arbitrarily classified as turbid (mean Secchi depths less than 0,85 m) and clear (mean Secchi depths greater than 0,85 m). In the last column of Table 1 a further distinction was made between impoundments on the basis of the geology of their catchments. Impoundments with catchments lying within the area classified as the Molteno, Red Beds and Gave Sandstone Stages of the Stormberg Series and the Beaufort Series both of the Karoo System (indicated in Figure 1) on the 1970 edition of the Geological Map of the Republic of South Africa, were grouped together and classified in Table 1 as impoundments with catchments lying within the central part of the Karoo System.

The mean Secchi depths of the impoundments varied between 0,13 m (Hluhluwe Dam) and 2,97 m (Roodeplaat Dam). Buffeljags Dam with a mean Secchi depth of 0,53 m is grouped in the last column of Table 1 with the clear impoundments (mean Secchi depth of more than 0,85 m) because the low mean Secchi depth in this case is due to a brown colouration of the water caused by a high content of humic substances in the water. This observation was confirmed by the fact that Buffeljags Dam sediments had the highest OC content. In the rest of the impoundments with low mean Secchi depths and therefore classified as turbid, the low mean Secchi depths were due to high concentrations of suspended sediment in the water column. The mean depths of the impoundments ranged from 18,25 m in Spioenkop Dam to 1,43 m in Craigie Burn Dam.

Chemical analyses of sediment

The chemical analyses of the sediments obtained from the 38 impoundments are given in Table 1. The TP content of the

TABLE 1

TOTAL PHOSPHATE (TP) AS P; INORGANIC PHOSPHATE (IP) AS P; ORGANIC PHOSPHATE (OP) AS P; NITRILOTRIACETIC ACID EXTRACTABLE PHOSPHATE (NTA-P) AS P; PHOSPHATE EXTRACTABLE BY BRAY-REAGENT (BRAY-2-P) AS P; ALGAL AVAILABLE PHOSPHATE (AP) AS P; ORGANIC CARBON (OC) AND pH-VALUES OF THE SEDIMENT SAMPLES USED IN THE ALGAL BIOASSAYS. THE MEAN SECCHI DEPTH AND MEAN DEPTH OF THE IMPOUNDMENTS ARE GIVEN. THE IMPOUNDMENTS ARE CLASSIFIED AS CLEAR ○ AND TURBID □. IMPOUNDMENTS WITH CATCHMENTS ORIGINATING IN THE CENTRAL PART OF THE KAROO SYSTEM ARE INDICATED BY ⊘ AND ⧄

No.	Dam No.	Name of Impoundment	TP	IP	OP	NTA-P	Bray-2-P	AP	OC	pH	Mean Secchi depth	Mean depth	Classification
			mg.kg^{-1}						%		m		
1	D2R02	Armenia	467	347	119	96	48	409	1,25	7,04	0,21	33,81	⧄
2	C4R01	Allemanskraal	266	171	95	48	33	146	0,76	7,22	0,20	6,87	⧄
3	C9R02	Bloemhof	330	245	85	53	28	192	0,68	7,27	0,66	5,60	⧄
4	V3R01	Chelmsford	281	154	127	18	6	63	0,84	5,43	0,16	4,10	⧄
5	D2R01	Egmont	271	160	111	30	28	126	0,65	7,32	0,20	5,25	⧄
6	C4R02	Erfenis	299	180	119	54	32	187	0,84	7,31	0,18	6,73	⧄
7	D3R02	Hendrik Verwoerd	294	158	136	18	18	65	1,36	7,92	0,37	16,33	⧄
8	C5R02	Kalkfontein	476	365	111	62	11	288	1,10	7,93	0,49	7,06	⧄
9	C7R01	Koppies	263	205	58	36	12	142	0,83	6,65	0,30	3,48	⧄
10	C5R04	Krugersdrift	425	324	101	97	67	311	1,15	7,92	0,42	3,90	⧄
11	Q4R01	Lake Arthur	558	415	144	86	7	407	0,91	8,13	0,16	5,22	⧄
12	D3R03	P.K. le Roux	369	226	143	36	19	165	0,63	7,78	0,48	13,88	⧄
13	C5R03	Rusfontein	430	297	113	96	35	329	0,94	7,63	0,27	6,44	⧄
14	V1R01	Spioenkop	253	111	143	15	15	18	1,64	7,08	0,45	18,25	⧄
15	C1R01	Vaal	150	80	70	23	18	62	0,84	6,50	0,19	8,10	⧄
16	N1R01	Van Rhyneveldspas	539	461	78	66	15	398	0,81	8,29	0,30	7,40	⧄
17	V7R01	Wagendrift	280	133	148	6	3	47	1,52	6,22	0,59	11,75	⧄
18	D2R04	Welbedacht	313	156	157	11	10	141	1,65	7,29	0,59	—	⧄
19	H1R01	Brandvlei	187	77	110	8	16	84	1,42	5,70	0,25	4,04	□
20	B2R01	Bronkhorstspruit	424	252	172	4	1	73	2,01	5,74	0,31	6,91	□
21	U3R01	Hazelmere	311	125	185	9	8	100	0,68	5,91	0,80	13,24	□
22	W3R01	Hluhluwe	220	74	146	14	25	7	2,11	6,64	0,13	8,56	□
23	W4R01	J.G. Strydom	257	124	134	12	33	44	1,56	6,39	0,15	18,83	□
24	B3R02	Loskop	361	206	155	25	7	194	2,54	7,25	0,79	10,75	□
25	X1R01	Nooitgedacht	428	248	180	42	16	94	1,62	6,29	0,33	10,58	□
26	B7R02	Phalaborwa	244	117	127	15	0	117	1,10	8,25	0,40	4,58	□
27	C3R02	Spitskop	608	504	104	128	5	283	1,30	7,75	0,84	2,80	□
28	C1R01	Voëlvlei	382	245	137	12	35	70	0,99	6,33	0,70	10,60	□
29	C2R01	Boskop	261	148	113	17	2	106	1,04	7,94	1,87	5,49	□
30	H7R01	Buffeljags	234	95	139	9	28	77	3,96	5,16	0,53	4,00	○
31	E1R02	Clanwilliam	707	387	320	9	21	179	3,51	4,90	1,88	6,75	○
32	V2R01	Craigie Burn	462	288	174	36	19	78	1,90	4,99	1,92	1,43	○
33	A2R01	Hartbeespoort	978	956	22	170	9	364	3,12	7,54	0,99	6,75	○
34	H9R01	Kortine-Vet	284	117	168	24	37	141	2,99	5,11	1,03	8,06	○
35	U2R01	Midmar	464	276	190	45	16	88	1,97	5,17	1,12	11,36	○
36	A2R09	Roodeplaat	715	569	146	76	35	302	2,14	7,30	2,97	10,59	○
37	R2R02	Rooikrans	424	254	169	86	15	89	1,88	5,26	2,40	5,42	⊘
38	X1R03	Vygeboom	320	166	154	0	1	5	2,01	5,27	2,60	11,90	○

TABLE 2

THE INTERRELATIONSHIP BETWEEN SEDIMENT PROPERTIES OF ALL IMPOUNDMENTS, REPRESENTED BY A CORRELATION MATRIX (INORGANIC PHOSPHATE (IP), ORGANIC PHOSPHATE (OP), TOTAL PHOSPHATE (TP), NTA-EXTRACTABLE PHOSPHATE (NTA-P), BRAY-2-EXTRACTABLE PHOSPHATE (BRAY-2-P), ORGANIC CARBON (OC), pH AND ALGAL AVAILABLE PHOSPHATE (AP)

	TP	IP	OP	NTA-P	Bray-2-P	OC	pH
IP	0,96**						
OP	0,07	−0,21					
NTA-P	0,71**	0,82**	−0,43				
Bray-2-P	0,00	0,02	−0,07	0,24			
OC	0,33*	0,21	0,42**	−0,04	−0,01		
pH	0,14	0,29	−0,54**	0,43**	0,10	0,51**	
AP	0,66**	0,73**	−0,30	0,79**	0,27	−0,11	0,57**

**Indicates that the correlation coefficients are significant at the 1% test level.
* Indicates significance at the 5% level.

sediments varied between 150 mg/kg for Vaal Dam and 978 mg/kg for Hartbeespoort Dam. The IP content had the lowest value in Hluhluwe Dam (74 mg/kg) and the highest value was recorded for Hartbeespoort Dam (956 mg/kg). The OP content of the sediment samples varied between 22 mg/kg (Hartbeespoort Dam) and 320 mg/kg (Clanwilliam Dam). The NTA-P ranged from 0 (Vygeboom Dam) to 170 mg/kg (Hartbeespoort Dam). Bray-2-P ranged from 1 mg/kg for the sediments obtained from Bronkhorstspruit and Vygeboom Dam sediments to 67 mg/kg for the sediments of Krugersdrift Dam. The AP content, measured by means of bioassays, ranged from 5 mg/kg for Vygeboom Dam sediments to 364 mg/kg for Hartbeespoort Dam sediments. The OC content of the sediment samples varied between 0,63% (P.K. le Roux Dam) and 3,96% (Buffeljags Dam). The pH values of sediments varied between 4,90 (Clanwilliam Dam) and 8,29 (Van Rhyneveldspas Dam).

Regression analysis

It was decided to consider only correlation coefficients of ≥0,7 as meaningful because a regression based on that relationship would explain 50% (r^2 = 0,49) and more of the variation of the dependent variable.

The correlation matrix in Table 2 summarises the interrelationships between the sediment properties as given in Table 1. Meaningful correlations were observed between TP and IP (r = 0,96) and NTA-P (r = 0,71). IP was meaningfully correlated with NTA-P (r = 0,82) and AP (r = 0,73). Meaningful correlation (r = 0,79) was also observed between NTA-P and AP: The general lack of significant correlation between Bray-2-P and the rest of the phosphate fractions including AP is notable.

Multiple linear regression analyses were applied to predict the AP content from the sediment properties. NTA-P was the only independent variable selected by the program and explained only 62% of the variance in AP. Grobler and Davies (1979) previously found that if sediments, originating from different catchments were grouped together, better correlations were obtained and therefore grouping of the impoundments according to geological characteristics of the catchment was attempted.

The first 18 impoundments in Table 1 are those with the major part of their catchments lying within the central part of the Karoo System as defined earlier. Rooikrans Dam (number 35 in Figure 1) is within this area but is regarded as an exception and is therefore excluded from this group because of its very small, forested catchment which is not at all typical of this area. The sediments from these impoundments were grouped together on the basis that they originated from geologically similar catchments. In Table 3 the interrelationships between the sediment properties from these 18 impoundments are given.

TABLE 3
THE INTERRELATIONSHIP BETWEEN SEDIMENT PROPERTIES OF IMPOUNDMENTS WITH CATCHMENT LYING WITHIN THE CENTRAL PART OF THE KAROO SYSTEM (INORGANIC PHOSPHATE (IP), ORGANIC PHOSPHATE (OP), TOTAL PHOSPHATE (TP), NTA-EXTRACTABLE PHOSPHATE (NTA-P), BRAY-2-EXTRACTABLE PHOSPHATE (BRAY-2-P), ORGANIC CARBON (OC), pH AND ALGAL AVAILABLE PHOSPHATE (AP)

	TP	IP	OP	NTA-P	Bray-2-P	OC	pH
IP	0,97**						
OP	0,14	−0,12					
NTA-P	0,76**	0,81**	−0,18				
Bray-2-P	0,16	0,22	−0,22	0,65**			
OC	-0,06	−0,20	0,55*	−0,27	−0,13		
pH	0,66**	0,65	0,05	0,53*	0,28	−0,07	
AP	0,92**	0,95**	−0,11	0,91	0,40	−0.21	0,61**

**Indicates that the correlation coefficients are significant at the 1% level.
* Indicates significance at the 5% level.

TABLE 4
THE INTERRELATIONSHIP BETWEEN SEDIMENT PROPERTIES OF ALL IMPOUNDMENTS NOT LYING WITHIN THE CENTRAL PART OF THE KAROO SYSTEM (INORGANIC PHOSPHATE (IP), ORGANIC PHOSPHATE (OP), TOTAL PHOSPHATE (TP), NTA-EXTRACTABLE PHOSPHATE (NTA-P), BRAY-2-EXTRACTABLE PHOSPHATE (BRAY-2-P, ORGANIC CARBON (OC), pH AND ALGAL AVAILABLE PHOSPHATE (AP)

	TP	IP	OP	NTA-P	Bray-2-P	OC	pH
IP	0,97**						
OP	-0,05	-0,31					
NTA-P	0,77**	0,86**	−0,50*				
Bray-2-P	−0,03	−0,07	0,16	−0,10			
OC	0,33	0,26	0,20	0,12	0,30		
pH	0,16	0,30	−0,60	0,37	−0,33	−0,37	
AP	0,81**	0,85**	−0,30	0,79**	−0,05	0,26	0,48*

**Indicates that the correlation coefficients are significant at the 1% test level.
* Indicates significance at the 5% level.

The same general meaningful interrelations existed for all the impoundments but a marked increase in the respective correlation coefficients was noticed. The correlations between AP and TP increased from r = 0,66 to r = 0,91, from r = 0,73 to r = 0,95 between AP and IP and from r = 0,79 to r = 0,91 between AP and NTA-P. In multiple linear regression analyses the program selected only IP as the independent variable which explained 90% (r^2 = 0,90) of the variance in AP (the dependent variable) in the 18 sediments considered. In Figure 2 AP is plotted against the IP content of the sediment samples. The regression equation and the regression line are given. The 95% confidence band about the regression is also given. There is a close agreement between a similar regression equation reported by Grobler and Davies (1979) for sediments collected from Bloemhof Dam and Vaalharts Weir and the equation found in this study:-

Algal-P	= 1,02 IP − 72	(Grobler and Davies, 1979)
AP	= 1,12 IP − 67	(This study)

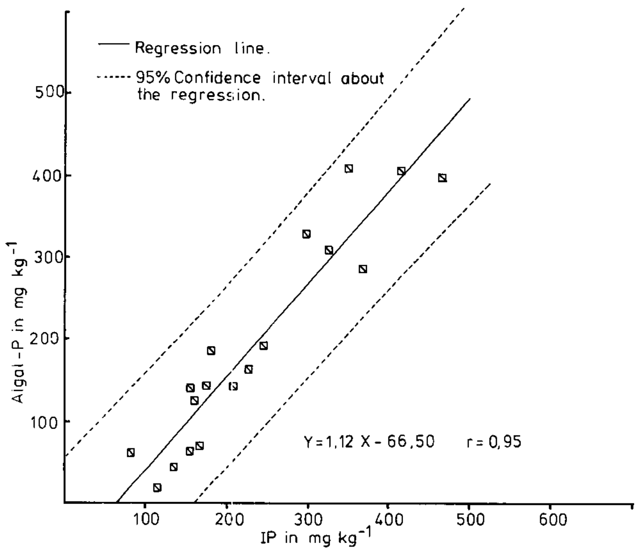

Figure 2
Relationship between algal available phosphate (Algal-P) and inorganic phosphate (IP) in sediment samples of turbid impoundments with catchments lying within the Karoo System

It was not possible to group the rest of the impoundments (20 in number) according to the geology of their catchments. Nevertheless they were considered as a group for the purpose of this study. The correlation matrix is given in Table 4. Surprisingly some of the correlation coefficients in this case were also markedly higher than those (Table 2) found when all the impoundments were considered. The correlation between AP and TP increased from r = 0,66 to r = 0,81 and between AP and IP from r = 0,73 to r = 0,85. The correlation coefficient between AP and NTA-P remained the same at r = 0,79. In multiple linear regression analysis only IP was selected by the program as the independent variable and it explained 72% (r^2 = 0,72) of the variance of the dependent variable (AP).

In Figure 3 the actual values for the impoundments other than those of the Karoo System are plotted and the regression equation, regression line and 95% confidence band about the regression are given. The slope of 0,38 in the regression equation for these impoundments is much lower than the slope of 1,12 in the regression equation for the impoundments with catchments lying within the central part of the Karoo System. Grobler and Davies (1979) found the same tendency with sediment samples from Spitskop Dam (outside this area) when these were compared to samples from Bloemhof Dam (within this area).

Discussion

The results of this study, based on analysis of sediment samples collected from 38 impoundments with widely differing properties, demonstrated conclusively that bottom sediments can act as an important source of phosphate to algae in laboratory cultures thus supporting the results obtained by Golterman (1976). The measurement of AP using bioassays is a time consuming method in which only a limited number of samples can be analysed at a time. Therefore, use has been made by various workers of chemical extractions to determine the so called "available" phosphate fraction from the sediment, often without correlating it with values obtained from actual bioassays (Porcella, Kumagai and Middlebrooks, 1970; Golterman, 1976). None of the chemical extractions of phosphate used in this study appeared to be a satisfactory and also a generally applicable measure on all impoundments of the AP content of the sediments. The best one, NTA-P, could explain only 62% of the variance in AP. IP, however, proved to be a relatively accurate measure of AP, explaining 90% of the variance in bottom sediments obtained from impoundments with the major part of their catchments lying within the central part of the Karoo system. The reason for this being so is obscure and any attempt at finding it would require the fractionation of the phosphate in the bottom sediments into all the different chemical and mineralogical forms. This, however, is not a prerequisite for the practical application of the relationships found and was therefore not undertaken in the scope of this study.

The potential for practical application of these relationships is enhanced by the fact that simple criteria is used for grouping the impoundments according to whether or not a major part of the catchments lie within the central part of the Karoo System. Only a geological map of the Republic of South Africa is required. Once this has been done, the AP content of the bottom sediments of impoundments with catchments in the Karoo system can be predicted using the equation:
AP = 1,2 IP − 67. If it is assumed that the bottom sediments of an impoundment can be considered to be representative of the suspended sediments, a rough estimate of the potentially available phosphate adsorbed onto the suspended sediment can be made.

For the rest of the impoundments, that is with catchments lying outside the previously defined part of the Karoo System, the IP content explained 72% of the variance in the AP content of the sediments. This is an increase of 19% on the variance explained by NTA-P when all impoundments were considered. The fact that the IP content explained only 72% of the variance in AP in this case is to be expected considering the great variation in the geology of the catchments of these impoundments. The IP content of the sediments can be used to predict the AP content of the suspended sediments in these impoundments, on the same basis as shown above although with less confidence by

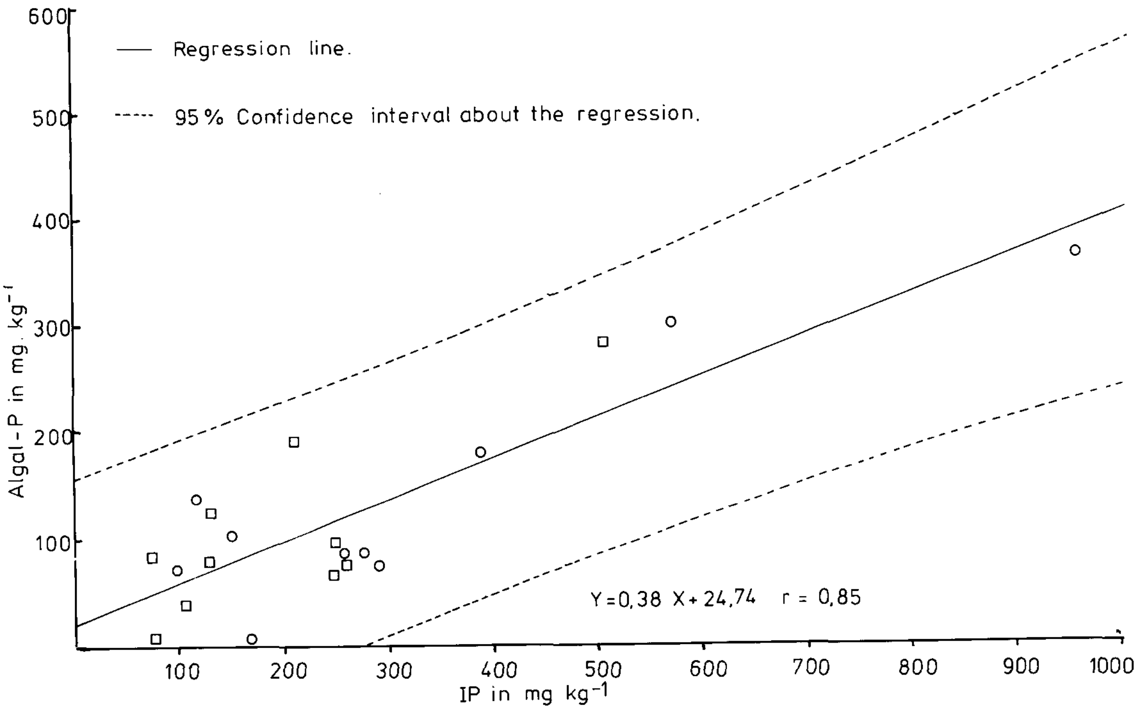

Figure 3
Relationship between algal available phosphate (Algal-P) and inorganic phosphate (IP) in sediment samples of all impoundments (turbid and clear), not considered as part of the Karoo System

using the equation: AP = 0,38 IP + 25.

The slope of the regression line indicates that about 38% of the IP can be available to algae. This is in same order of magnitude as the 20% of TP minus soluble PO_r-P being available to algae as reported by Lee, Rast and Jones (1978). This study indicated that the Bray-2-P is not a suitable measure of AP. The TP, OP, OC content and pH value of the sediment, did not make a significant contribution to explaining the variance in AP content of the sediments. Therefore, the measurement of any of these sediment properties other than IP content might be unnecessary if estimates of the AP contents of the sediments are needed.

In the bottom sediments, from impoundments with catchments within the central part of the Karoo System, a much greater fraction of the IP fraction is available to algae (slope of the regression = 1,12), than in the sediments from the rest of the impoundments (slope of the regression = 0,38).

The same group of impoundments are also usually turbid and shallow (Table 1, Figure 1). The high turbidity in these impoundments is caused by the geological characteristics of their catchments which result in soils with distinct dispersive properties and therefore soils that are highly erodable. Rooseboom (1978) reported the highest sediment yields in South Africa for catchments in this area. Also in turbid impoundments the sediment suspended in the water column might act as a direct source of phosphate to algae, whereas in shallow impoundments the possibility exists that the bottom sediments can be resuspended in the water column to act as a potential phosphate source to algae. This combination of a high proportion of AP, turbidity and shallowness might be a possible explanation of some of the massive algal blooms often noticed in some of these impoundments (reports received from water control officers and unpublished data from regular surveys) of which the catchments are sparsely populated with very little urban and industrial development (the usual causes of eutrophication).

It should be stressed that in this study the only real evidence of sediment phosphate being available to algae have been obtained from laboratory experiments. Before these results can be extrapolated with confidence to natural systems verification thereof in these systems is needed. The extension of this work will be directed at verification of the relationships found in natural systems.

Conclusions and Recommendations

1. The phosphate adsorbed onto bottom sediments can be an important source of phosphate to algae based on evidence obtained in laboratory experiments.

2. The algal available phosphate content of bottom sediments can be predicted using the inorganic phosphate content of those sediments. For impoundments with catchments lying within the central part of the Karoo System the following regression equation can be used:

$$AP = 1{,}12\,IP - 67 \qquad (r^2 = 0{,}90),\ n = 18.$$

The algal available phosphate content for impoundments with catchments outside this area can be predicted from the regression equation:

$$AP = 0{,}38\,IP + 25 \qquad (r^2 = 0{,}72),\ n = 20.$$

3. It is recommended that consideration be given to include the role of bottom and suspended sediment as a potential source of phosphate, specifically in turbid and shallow impoundments, in any model designed to predict the algal productivity in South African impoundments especially those with catchments lying within the central part of the Karoo System.

4. It is also suggested that the findings of this study be considered in the management of eutrophication. In the choice of sensitive catchments in South Africa in which a phosphate standard of 1 mg/ℓ will be enforced to limit the effects of eutrophication, it must be recognized that, if such a catchment lies in the central part of the Karoo System, the enforcement of this standard might be ineffectual due to the fact that the bottom and suspended sediment may act as the major source of phosphate.

Acknowledgements

This paper is published with the permission of the Department of Water Affairs, Forestry and Environmental Conservation.

References

BRUWER, C.A. and GROBLER, D.C. (1980) *A brief overview of the influence of sediments in South African impoundments.* In: Proceedings of the workshop on techniques for determination of mass movement of sediment in impoundments. South African National Scientific Programmes.

COWEN, W.F. and LEE, G.F. (1976) *Algal nutrient availability and limitation in Lake Ontario during IFYGL. Part 1. Available phosphorus in urban runoff and Lake Ontario tributary waters.* Ecological Research Series. EPA-600/3-76-094a. October 1976.

DRAPER, N. and SMITH, H. (1966) *Applied Regression Analyses.* John Wiley and Sons, New York.

DE LUCIA, R. McBEAN, E. and HARRINGTON, J. (1978) A water quality planning model with multiple time, pollutant and source capabilities. *Wat. Resour. Res.* 14(1) 9–14.

GALPIN, J.S. (1979) *Regression package REGPAC.* Technical Report SW15K9, 65 p. National Research Institute for Mathematical Sciences, CSIR, Pretoria, RSA.

GOLTERMAN, H.L. (1976) *Sediments as a source of phosphate for algal growth.* In: Interactions between sediments and fresh water. Proceedings of an international symposium held at Amsterdam, The Netherlands, September 6–10.

GROBLER, D.C. and DAVIES, E. (1979) The availability of sediment phosphate to algae. *Water S.A.* 5(3) 114–122.

LEE, G.F., RAST, W. and JONES, R.E. (1978) Eutrophication of water bodies. Insight for an age-old problem. *Environ. Sci. and Technol.* 12 900–908.

PORCELLA, D.B., KUMAGAI, J.S. and MIDDLEBROOKS, E.J. (1970) Biological effects of sediment-water nutrient interchange. *J. sanit. Engng. Div. Am. Soc. civ. Engrs.* **96** (SA4) 911–926.

ROOSEBOOM, A. (1978) Sedimentafvoer in Suider-Afrikaanse riviere. *Water SA* 4(1) 14–17.

SAGHER, A., HARRIS, R.F. and ARMSTRONG, D.E. (1975) *Availability of sediment phosphorus to microorganisms.* Water Resources Centre Technical Report W15 WRC 75-01. University of Wisconsin.

SIMONSEN, J.F. and DAHL-MADSEN, K.I. (1978) Eutrophication models for lakes. *Nordic Hydrology,* 9 131–142.

UTTORMARK, P.D. and HUTCHINS, M.L. (1978) *Input/output models as decision criteria for lake restoration.* Technical completion Report, Project C-7232, Water Resources Center, University of Wisconsin, Madison, Wisconsin.

WALMSLEY, R.D. and BUTTY, M. (1979) *Eutrophication of rivers and dams. Part 6. An investigation of chlorophyll-nutrient relationship for 21 South African impoundments.* Contract Report, Water Research Commission, Pretoria, R.S.A.

WALMSLEY, R.D. and BRUWER, C.A. (1980) Water transparency of South African impoundments (In preparation).