

## Obtaining the parameters required to model labile phosphorus for South African soils

M. van der Laan<sup>1</sup>, J.G. Annandale<sup>1\*</sup>, C.C. du Preez<sup>2</sup> and S.A. Lorentz<sup>3</sup>

<sup>1</sup> Department of Plant Production and Soil Science, University of Pretoria, Pretoria 0002, South Africa

<sup>2</sup> Department of Soil, Crop and Climate Sciences, University of the Free State, Bloemfontein 9300, South Africa

<sup>3</sup> School of Bioresources Engineering and Environmental Hydrology, University of KwaZulu-Natal, Pietermaritzburg 3209, South Africa

Accepted 31 July 2009

Modelling phosphorus (P) in the environment can increase our understanding of potential transfer pathways into receiving water bodies as well as the plant availability of this nutrient in soil. Many current models make use of algorithms originally developed for the EPIC model over two decades ago. These algorithms were developed primarily using continental USA soils. Obtaining the required input parameters can therefore be challenging when applying this approach to soils not classified according to the USA system, and for soils for which similar parameters are not available. In this paper, new equations for the estimation of labile P from Ambic P, Bray 2 P and the modified ISFEI method are proposed. Guidelines for the classification of South African soils as calcareous, slightly weathered and highly weathered are further suggested, and we propose that only topsoil properties be used for this purpose. Depending on the amount of soil information available, this classification can be achieved using the clay fraction SiO<sub>2</sub>:Al<sub>2</sub>O<sub>3</sub> molecular ratio, the sum of exchangeable Ca, Mg, K and Na, or a newly proposed categorization system for South African soil forms. It is clear that the above approaches should be thoroughly tested and relevant local research carried out to improve our ability to model P in South African soils.

**Keywords:** Modelling, phosphorus, soil parameters, SWB-Sci

\*To whom correspondence should be addressed (E-mail: john.annandale@up.ac.za)

### Introduction

Loss of phosphorus (P) from agricultural land to waterways is a major concern, as P is often the limiting factor for eutrophication. Increased P fertilizer prices, deficient levels of plant available P in many sub-Saharan African soils and the recognition of P as a finite resource globally, further necessitates the careful management of this nutrient (Buresh *et al.*, 1997; Mengel, 1997). In soils, P exists as organic P associated with soil organic matter and residues, and inorganically, as mineral P with varying degrees of solubility. Plant P uptake occurs in the form of soluble and weakly adsorbed phosphates (HPO<sub>4</sub><sup>2-</sup>, H<sub>2</sub>PO<sub>4</sub><sup>-</sup>). Sequential chemical extraction is often used to divide total soil P into different organic P and inorganic P fractions (Chang and Jackson, 1957; Buehler *et al.*, 2002). These fractions are not discrete entities, however, as intergrades and dynamic transformations continuously occur towards maintaining steady state conditions.

Models can be utilized to improve our understanding of P dynamics in the environment, identify zones within a catchment with high P export potential, and explore mitigation measures. Although models used to predict P export from land include process-based models, export coefficient models and statistical or empirical models (Sharpley, 2007), only process-based models are the subject of this paper. These models often have technical guidelines for estimating hydrology and sediment parameters, but similar technical notes for selecting P parameters are mostly absent (Radcliffe & Cabrera, 2007). A drawback of process-based P models is the difficult-to-obtain inputs required to run the model (Karpinets *et al.*, 2004), especially at catchment scale when limited soil information is available and model inputs must often be estimated. Acquiring the required parameters can

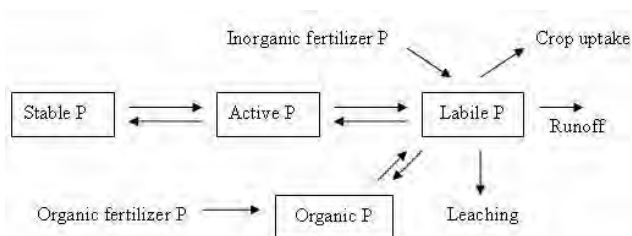
also be challenging for soils different to those from which the original modelling algorithms were developed. The objective of this paper is to guide the user through the parameterization of a P model for South African soils. New equations were required to estimate *Labile P* from soil P tests commonly used in South Africa and are presented here. Additionally, the approach to categorize soils as slightly weathered, highly weathered or calcareous is reviewed. A newly developed approach to categorize soil forms into one of these three groups using information available in land type maps is further proposed to facilitate P modelling at the catchment scale.

### Review of inorganic phosphorus modelling

A wide range of models are currently available to model phosphorus in soil-crop systems. To the best of our knowledge, P modelling is practised on a limited scale in South Africa, and models that are currently being used include SWAT (Soil Water Assessment Tool) (Arnold *et al.*, 1998), APSIM (Agricultural Production Systems Simulator) (Keating *et al.*, 2003), ACRU-NP (Campbell *et al.*, 2001) and the newly developed SWB-Sci model. ACRU-NP and SWAT have simple crop routines and were developed to be run at the catchment scale, while SWB-Sci and APSIM were developed to be run on the field scale and are more reflective of management practice interventions. The P modelling routines of all four these models can be traced back to work done by Jones *et al.* (1984) and Sharpley *et al.* (1984) to develop the model EPIC (Erosion Productivity Impact Calculator) (Williams *et al.*, 1983).

In the EPIC approach three inorganic P pools are simulated, namely, *Labile P*, *Active P* and *Stable P* (Figure 1). The *Labile P* pool refers to a pool from which plants are able to

take up P from the soil, and consists of both soluble P and weakly sorbed P. Phosphorus which is increasingly more strongly adsorbed and not immediately available to the plant is represented by the *Active P* followed by the *Stable P* pools. Phosphorus flux can occur between the *Labile P* and *Active P* pools, and between the *Active P* and *Stable P* pools. For all models, the various P pools are subject to a rate-defined equilibrium. Typically, no attempt is made to equate the *Active* and *Stable P* pools to the soil P fractions obtained through sequential chemical extraction (Probert, 2003). Instead, these three pools are used to represent the fast sorption, slower sorption and very slow precipitation processes which P undergoes in soils (McGechan & Lewis, 2002). Phosphorus is also transferred between the *Labile P* and *Organic P* pools as a result of mineralization and immobilization processes occurring in the soil. The size of the *Labile P* pool is further used to determine the concentration of P in runoff and drainage water.



**Figure 1** Structural diagram of the various P pools simulated using the EPIC approach

Originally, Jones *et al.* (1984) and Sharpley *et al.* (1984) used 78 continental USA and Puerto Rican soils to develop their plant and soil P model. Calcareous and non-calcareous soils which have undergone different degrees of weathering can be expected to undergo greatly differing soil-P reactions (Sharpley *et al.*, 1989), and Sharpley *et al.* (1984) observed that the most accurate estimation of Labile P, was achieved when soils were divided into calcareous, slightly weathered or highly weathered groups based on the presence of  $\text{CaCO}_3$  and degree of weathering. Strict definitions of these soil groups were not provided, however, making this a challenging exercise. The discussion below is provided to inform model users of the issues involved in categorizing a soil into one of these three groups.

### Calcareous, slightly weathered and highly weathered soils

Sharpley *et al.* (1984) defined calcareous soils as soils with free  $\text{CaCO}_3$ , and according to Thomas (1996), soils with pH ( $\text{H}_2\text{O}$ ) values of 7.6 to 8.3 are normally found to be calcareous. According to the South African taxonomic classification system, soils containing sufficient free calcium carbonate or calcium magnesium carbonate to effervesce visibly when exposed to a cold 10% HCl solution are considered to be calcareous (Soil Classification Working Group, 1991).

The degree of weathering that a non-calcareous soil has undergone can be judged by the presence of specific minerals

associated with weathering stages (Jackson & Sherman, 1953). Early weathering stages are associated with the presence of gypsum, calcite, olivine-hornblende, biotite and albite; intermediate weathering stages by quartz, muscovite, 2:1 layer silicates and montmorillonite; and advanced weathering stages by kaolinite, gibbsite, hematite and anatase. Sharpley *et al.* (1984) defined highly weathered USA soils as Oxisols, Ultisols, Quartzipsamments, Ultic subgroups of Alfisols and acidic Ochrepts, while all other soils fell into the slightly weathered group. Not all soils containing < 10 % clay – the definition for Quartzipsamments – should automatically be considered highly weathered, however. In a later study representing eight major soil orders from all regions of the United States, Puerto Rico, Indonesia, Malaysia, Papua New Guinea, Philippines and Sudan, Quartzipsamments were not considered as highly weathered (Sharpley *et al.*, 1987). According to the Soil Classification Working Group (1991), highly weathered or ‘ferrallitic’ soils are characterized by a clay fraction  $\text{SiO}_2:\text{Al}_2\text{O}_3$  molecular ratio of less than 1.3, whereas slightly weathered or ‘ferrisol’ soils have a ratio of between 1.3 and 2 and a base saturation of less than 50%. In South Africa, some non-calcareous soil forms are divided into eutrophic, mesotrophic and dystrophic soil families based on the degree of leaching which is an indication of the weathering status; and classification is determined by the sum of exchangeable Ca, Mg, K and Na expressed as  $\text{cmol}(+) \text{kg}^{-1}$  clay (Soil Classification Working Group, 1991). Dystrophic soils (highly weathered) have a value of less than 5, mesotrophic soils (moderately weathered) have a value between 5 and 15, and eutrophic soils (slightly weathered) have a value greater than 15  $\text{cmol}(+) \text{kg}^{-1}$  clay in their B1 horizons.

Sharpley *et al.* (1984) originally used weathering and soil taxonomic information to group soils, and although the United States Department of Agriculture mostly uses subsoil parameters to determine classification, for South African soils we suggest that the properties of the top horizon only should be considered for categorization as this is the diagnostic horizon used in the South African Classification system (Soil Classification Working Group, 1991). Furthermore, only surface samples (0-10 cm) were used by Jones *et al.* (1984) and Sharpley *et al.* (1984) to develop the various algorithms used.

Grouping of South African soils in the abovementioned groups when only soil form and series (MacVicar *et al.*, 1977) are known from the land-type survey (Land Type Survey Staff, 2001), as is often the case when modelling at the catchment scale, is discussed later in this paper.

### Estimation of inorganic P pool sizes

#### Labile P

The *Labile P* pool is measured using an anion exchange resin, but this is a time consuming and expensive procedure. In order to estimate the size of inorganic P pools, APSIM and SWAT require a direct input of a labile P value ( $\text{mg kg}^{-1}$ ). ACRU-NP and SWB-Sci require a soil test P (STP) result, for which algorithms have been developed to quantify the *Labile P* pool. This approach is based on work by Sharpley *et al.* (1984) to relate labile P to Bray 1 P (BP1), Olsen P (OP) and Mehlich-1 P (MP1) for slightly weathered, highly weathered and calcareous soils. Sharpley *et al.* (1989) later added addi-

tional equations using BP1 and OP for highly basic calcareous soils (free  $\text{CaCO}_3 > 50 \text{ g kg}^{-1}$ ), and additional BP1, OP, Colwell P (CoP), Truog P (TP) and Mehlich-3 P (MP3) soil P test values for highly weathered acid tropical soils (Al saturation  $> 30\%$ ). Sharpley *et al.* (1989) caution that the

application of these equations is limited to soils having physical and chemical properties within the range covered by the regression analyses. A summary of soil properties for the soils tested is provided in Table 1.

**Table 1** Ranges of soil properties for five soil groups tested by Sharpley *et al.* (1984) and Sharpley *et al.* (1989)

Soil group	pH ( $\text{H}_2\text{O}$ )	Sand (%)	Silt (%)	Clay (%)	$\text{CaCO}_3$ (%)	Base sat. (%)	CEC (cmol $\text{kg}^{-1}$ )	Org C (%)	Bray P ( $\mu\text{gP g}^{-1}$ )	Olsen P ( $\mu\text{gP g}^{-1}$ )	Labile P* ( $\mu\text{gP g}^{-1}$ )
<b>Calcareous (N=20)</b>											
Mean	7.7	35	41	24	9.1	100	20	1.4	20	13	17
Median	7.7	35	42	23	0.8	100	17	1.4	11	9	13
Range	7.1-8.4	4-71	17-62	10-67	0.5-54	100	8-55	0.4-3.2	1-77	3-38	6-56
<b>Slightly weathered (N=35)</b>											
Mean	6.4	27	51	22	-	89	17	1.7	24	13	19
Median	6.3	18	53	22	-	95	16	1.7	21	12	16
Range	5.2-8.3	1-87	6-85	6-62	-	40-100	5-43	0.2-3.5	4-79	3-42	4-53
<b>Highly weathered (N=23)</b>											
Mean	5.6	55	30	5	-	58	8.2	1.6	66	20	13
Median	5.6	59	28	10	-	77	7.6	1.4	47	19	11
Range	4.4-6.8	6-96	1-76	0.4-76	-	11-100	1.3-20.5	0.4-3.8	3-222	2-50	3-43
<b>Highly basic calcareous (N=23)</b>											
Mean	8.2	-	-	27.1	34	-	17.6	0.81	2.5	5.7	6.2
Median	8.1	-	-	26.1	22	-	13.4	0.36	0.2	4.9	6.2
Range	7.4-9.1	-	-	2.8-56.3	6-74	-	1.3-34.6	0.04-4.66	0.1-18.1	0.9-15.6	0.6-14.8
<b>Highly weathered acid tropical (N=32)</b>											
Mean	4.6	-	-	28.7	68	-	13.8	3.2	17.7	-	12.8
Median	4.6	-	-	15.2	74	-	11.1	2.54	9.4	-	10.6
Range	3.9-5.2	-	-	7.0-76.3	30-96	-	4.4-36.8	1.07-7.77	3.1-72.8	-	3.9-35.9

The most commonly used extraction methods in South Africa are BP1 (Fertilizer industry) and Ambic 1 (AP) (ARC Institutions and Departments of Agriculture). However, in the Western Cape the Citric acid method (CiP) and in KwaZulu-Natal the TP method, are also used. The OP method is mainly restricted to the Free State Department of Agriculture and the University of the Free State. The Bray 2 P (BP2) is also sometimes used in South Africa. In addition, a modified version of the ISFEI (IP) method was used to determine the 'P status' of modal profiles during the compiling of land type maps (Land Type Survey Staff, 1985). Although much work has been done locally and internationally to compare various P

extraction methods, much of this work has been restricted to unpublished reports (Schmidt *et al.*, 2004).

Equations for the estimation of *Labile P* using the locally popular AP, BP2 and IP test results were not derived for the original work done by Sharpley *et al.* (1984) in the U.S., but are essential for modelling P dynamics in South African soils. After a study comparing BP1 and AP results from 12 localities in South Africa, Schmidt *et al.* (2004) reported the following relationship using linear regression analysis:

$$\text{BP1} = 1.23 \times \text{AP} + 3.82 \quad (1)$$

An  $r^2$ -value of 0.91 was obtained where clay contents of the soils ranged from 8.4 to 47%. Buys and Venter (1980) reviewed correlations between BP1 and BP2 from several studies done by the Fertilizer Society of South Africa and observed greater correlation for acid soils than for alkaline soils and soils treated with rock phosphate. The authors reported the following relationship between BP1 and BP2 for a wide range of South African soils ( $r^2$  not reported):

$$BP1 = 0.42 \times BP2 + 1.44 \quad (2)$$

Buys and Venter (1980) also reported the following relationship between BP1 and IP for a range of 36 South African soils for which an  $r^2$  of 0.95 was obtained:

$$IP = 1.49 \times BP1 + 1.07 \quad (3)$$

Using these correlations, the equations in Table 2 are developed for the estimation of *Labile P* in South African soils.

**Table 2** Current and suggested equations for the estimation of labile P pool size for South African soils\*

Soil Group	Number of observations	R <sup>2</sup>	Soil Group	Number of observations	R <sup>2</sup>
<b>Slightly weathered</b>	35		<b>Highly weathered acid tropical</b>		
$P_{lab} = 0.56BP1 + 5.1^{\S}$		0.79	(> 30% Al saturation)	32	
$= 1.07OP + 4.1^{\S}$		0.77	$P_{lab} = 0.41BP1 + 5.55^{\dagger}$		0.86
$= 0.13MP1 + 11.4^{\S}$		0.39	$= 0.20TP + 5.62^{\dagger}$		0.80
$= 0.69AP + 7.2$	n/a		$= 0.43CP + 4.21^{\dagger}$		0.84
$= 0.24BP2 + 5.9$	n/a		$= 0.64MP3 + 5.72^{\dagger}$		0.71
$= 0.38IP^* + 4.69$	n/a		$= 0.50AP + 7.12$	n/a	
			$= 0.17BP2 + 6.14$	n/a	
<b>Highly weathered</b>	20		$= 0.28IP + 5.25$	n/a	
$P_{lab} = 0.14BP1 + 4.2^{\S}$		0.83	<b>Highly basic calcareous</b>		
$= 0.55OP + 2.1^{\S}$		0.74	(> 50 g kg <sup>-1</sup> CaCO <sub>3</sub> )	23	
$= 0.24MP1 + 2.9^{\S}$		0.51	$P_{lab} = 0.69BP1 - 1.76^{\dagger}$		0.35
$= 0.17AP + 4.7$	n/a		$= 0.96OP - 0.19^{\dagger}$		0.90
$= 0.059BP2 + 4.4$	n/a				
$= 0.09IP + 4.1$	n/a				
<b>Calcareous</b>	23				
$P_{lab} = 0.55BP1 + 6.1^{\S}$		0.76			
$= 1.09OP + 3.2^{\S}$		0.61			
$= 0.10MP1 + 10.2^{\S}$		0.84			
$= 0.68AP + 8.2$	n/a				
$= 0.23BP2 + 6.89$	n/a				
$= 0.37IP + 5.70$	n/a				

\* All P tests on a mass basis (mg kg<sup>-1</sup>), except the IP test which is on a volume basis (mg l<sup>-1</sup>)

§ Sharpley *et al.* (1984)

† Sharpley *et al.* (1989)

Equations derived for South African soils

A disadvantage of using chemical extractants to determine available P is that these tests are not equally reliable over all soil types, and the relative extractants may dissolve non-labile P tightly bound to Al, Fe and Ca complexes (Myers *et al.*, 2005). The BP1, MP1 and MP3 tests were designed to extract P from non-calcareous soils dominated by Fe and Al-P complexes, while the OP test was designed to extract P from calcareous soils (Bray & Kurtz, 1945; Watanabe & Olsen, 1965; Mehlich, 1984; Myers *et al.*, 2005). This

is evident in the low  $r^2$  of 0.35 for BP1 for the highly basic calcareous soil group, while OP has an  $r^2$  of 0.90 for the same soil group. BP2 and AP conversions were therefore not done for the highly basic calcareous group. It should also be noted that at low STP levels the equations can give *Labile P* values higher than the STP value in some cases. Care should therefore be taken when estimating *Labile P* using very low STP values. A standardized extraction method using anion exchange resin membranes, which are more representative of

plant available soil P, is suggested by Myers *et al.* (2005) for widespread adoption.

### Active and Stable P pools

The P Availability Index (PAI) of a soil is used to determine the direction and magnitude of fluxes between the *Labile*, *Active* and *Stable P* pools. Additionally, the PAI also influences the amount of *Labile P* that is available for plant uptake as well as P runoff and leaching losses. Algorithms to estimate PAI were first suggested by Sharpley *et al.* (1984) and later modified by Sharpley and Williams (1990). For calcareous soils, the calcium carbonate (CaCO<sub>3</sub>) percentage is required to calculate the PAI (Eq. 4), for slightly weathered soils the base saturation percentage and soil pH(H<sub>2</sub>O) is required (Eq. 5), and for highly weathered soils the clay percentage is required (Eq. 6):

$$\text{Calcareous: PAI} = 0.58 - 0.0061 \times \text{CaCO}_3 \quad (4)$$

$$\text{Slightly weathered: PAI} = 0.0054 \times \text{BaseSat\%} + 0.116 \times \text{pH(H}_2\text{O)} - 0.73 \quad (5)$$

$$\text{Highly weathered: PAI} = 0.46 - 0.0916 \times \ln(\text{Clay\%}) \quad (6)$$

Depending on soil grouping, the abovementioned input parameters will therefore also be required to model inorganic P.

According to the approach of Jones *et al.* (1984), the initial size of the *Active P* pool is calculated using a P Availability Index (PAI), with equation (7):

$$\text{Active P} = \frac{\text{Labile P}}{\left[ \frac{\text{PAI}}{1 - \text{PAI}} \right]} \quad (7)$$

ACRU-NP and SWB-*Sci* are also able to estimate the size of the *Active* and *Stable P* pools by subtracting organic P and *Labile P* from total soil P, if these values have been provided by the user. Initial *Stable P* is assumed to be four times larger than *Active P*.

### Obtaining inputs at catchment scale

When large areas such as catchments are modelled it is often impractical to perform soil analyses for the entire area. At this scale, limited soil information also often means that input data needs to be aggregated. Land type maps are available for the whole of South Africa at a scale of 1:250 000. Each land type map is accompanied by a memoir, from which the soil forms and series of a specific area can be obtained. Profile descriptions of representative soils and analytical data for particle size distribution, water retentivity, modulus of rupture, air-water permeability ratio, mineralogy, cation exchange properties, soluble salts, acidity, CBD-extractable Fe, micronutrients, P status and P sorption are also given in the memoirs (Land Type Survey Staff, 1985).

In Table 3, related soil forms (MacVicar *et al.*, 1977) used for land type mapping are placed in four groups in a way that allows the formation of a guideline for each group to enable categorization.

**Table 3** Grouping of soil forms used for Land-type mapping to facilitate categorization as slightly weathered, highly weathered or calcareous

Soil form			
Group 1	Group 2	Group 3	Group 4
Kranskop	Arcadia	Katspruit	Champagne
Magwa	Inhoek	Fernwood	Nomanci
Inanda	Milkwood		Sterkspruit
Avalon	Mispah		Estcourt
Pinedene	Rensburg		Kroonstad
Glencoe	Willowbrook		Constantia
Griffin	Bonheim		Shepstone
Clovelly	Tambankulu		Houwhoek
Bainsvlei	Mayo		Lamotte
Hutton	Swartland		Cartref
Shortlands	Valsrivier		Wasbank
	Vilafontes		Longlands
	Oakleaf		Westleigh
	Glenrosa		Dundee

After identifying the group to which a specific soil form belongs, the following guidelines are suggested to categorize South African soils as slightly weathered, highly weathered or calcareous.

**Group 1:** Soil forms in this group are divided into calcareous,

eutrophic, mesotrophic or dystrophic soil series. For the purposes of P modelling, we propose that dystrophic soil series are regarded as 'highly weathered', meso- and eutrophic soil series as 'slightly weathered', and calcareous soil series as 'calcareous'.

**Group 2:** Soil forms in this group are divided into calcareous and non-calcareous soil series. We propose that non-calcareous soil series are regarded as 'slightly weathered' and calcareous soil series as 'calcareous'.

**Group 3:** Soil forms in this group are divided into acid, neutral or alkaline soil series. We propose that alkaline and neutral soil series are regarded as 'slightly weathered' and acid soil series as 'highly weathered'.

**Group 4:** Soil forms in this group are not divided into soil series that suit the above categorization procedure. We propose that these soil forms are therefore categorized according to mean annual precipitation, namely 500-750 mm being 'slightly weathered' and >750 mm being 'highly weathered'.

The nearest relevant modal profile to the area of interest should then be used to obtain clay content, 'P status' (IP), as well as pH, base saturation and CaCO<sub>3</sub> content of the soil. For the large catchment scale model, SWAT, the *Labile P* pool size is initialized at 25 mg kg<sup>-1</sup> for the plough layer in cultivated land, and at 5 mg kg<sup>-1</sup> for all other layers and uncultivated land (Cope *et al.*, 1981; Neitsch *et al.*, 2002). This is recommended for use when no other information is available.

## Discussion

The use of the MP, BP2 and the IP tests to accurately estimate *Labile P* using the equations presented in this paper is based on the assumption that good correlation exists for the equations to convert one of the tests mentioned above to Bray 1 P for the soil being simulated. Unfortunately the range of properties for the soils used to obtain the original conversion equations was not reported. The suitability of the equations to estimate the PAI of South African soils requires further investigation. Improved understanding of P reactions in different soils, possibly including the role of various ions in P precipitation as insoluble phosphates (Johnston *et al.*, 1991), is essential to improve our ability to model P solubility in soils. In weathered soils, Fe and Al oxides can reduce P solubility to extremely low levels, while in alkaline soils, especially calcareous ones, the precipitation of Ca and Mg as insoluble phosphates can also drastically reduce plant available P levels (Johnston *et al.*, 1991). Johnston *et al.* (1991) noted that highly weathered Oxisols and Ultisols which have high Fe and Al contents generally have much higher P fixation capabilities than soils with crystalline mineralogy, and it is generally observed that P fixation is proportionally related to the clay content of soils. Highly weathered soils can often contain larger amounts of Fe and Al than slightly weathered soils. Certain models, including the model ANIMO (Groenendijk & Kroes, 1999) utilize either Freundlich or Langmuir isotherms to determine P sorption. This approach is, however, often deemed too mechanistic, and inputs too difficult to obtain for inclusion in field to catchment scale models. Numerous studies have been done in South Africa on P sorption kinetics (Johnston *et al.*, 1991; Henry & Smith, 2003; Henry & Smith, 2004). This work can potentially be adapted for local modelling purposes. Local research, similar to the work done by Jones *et al.* (1984) is ultimately required to develop P modelling algorithms more suited to South African soils.

The approach proposed in this paper to categorize South African soils as 'slightly weathered', 'highly weathered' or

'calcareous' at the catchment scale is open to further discussion and debate. While it is acknowledged that topsoil characteristics such as sum of bases, presence of CaCO<sub>3</sub> and acidity can easily be modified through fertilizer or lime applications to cultivated land, in South Africa only 10% of land is under cultivation. In most cases, modal profiles were in native land and soil characteristics would not have been expected to be modified by past agricultural practices. An uncertainty using this approach is whether small cultivated areas with high soil P in a catchment contribute comparable pollutant loads to larger areas with lower soil P. Therefore although by no means a faultless suggestion, it is meant to be a pragmatic approach considering the lack of detailed soil information at catchment scale, and the urgent need to estimate the impacts of land use and management strategies on eutrophication of inland waterways and impoundments.

## Conclusions

Increased environmental and financial pressures associated with P require the careful management of this widely used agricultural nutrient. Modelling has a major role to play in improving our understanding of the various P processes and determining P management practices. P modelling still closely follows the approach developed over two decades ago by Jones *et al.* (1984) and Sharpley *et al.* (1984). It is crucial that these equations only be used to model soils with properties within the range of those used for the establishment of the original regression equations. The lack of detailed input information can often hamper P modelling at all scales. Several guidelines have been provided in this paper to simplify the application of these algorithms to South African soils. These guidelines are aimed at reducing the effort required to obtain the inputs to model P in South African soils, and should be subjected to ongoing testing and refinement. A lack of suitable and complete P datasets makes validation exercises very difficult. The use of soil analyses to determine modelling inputs such as resin extractable P and sorption isotherms will theoretically give the best results for P modelling. Experienced pedologists and soil mineralogists should be consulted whenever possible for assistance in obtaining soil parameters. It is also hoped that an ability to compare different STPs, and to estimate plant available P and the PAI of soils will facilitate dialogue between modellers, government institutions, consultants and farmers on the P status and optimal management practices for various soils.

## Acknowledgements

The authors would like to acknowledge the Water Research Commission and National Research Foundation for funding this research, and to thank Dr Piet le Roux and Prof Malcolm Hensley for guidance on technical issues.

## References

- ARNOLD, J.G., SRINIVASA, R., MUTTIAH, R.S. & WILLIAMS, J.R., 1998. Large area hydrological modeling and assessment Part 1: Model development. *J. Am. Water Resour. Assoc.* 34, 73-89.
- BUEHLER, S., OBERSON, A., RAO, I.M., FRIESEN, D.K. & FROSSARD, E., 2002. Sequential phosphorus extraction of a <sup>33</sup>P-labeled Oxisol under contrasting agricultural systems. *Soil Sci. Soc. Am. J.* 66, 868-877.
- BURESH, R.J., SMITHSON, P.C. & HELIUMS, D.T., 1997. Build-

- ing soil phosphorus capital in Africa. p.111. In: R.J. Buresh, P.A. Sanchez & F. Calhoun (eds.). Replenishing soil fertility in Africa. *SSSA Special Publication Number 51*.
- BRAY, R.H. & KURTZ, L.T., 1945. Determination of total, organic, and available forms of phosphorus in soils. *Soil Sci.* 59, 39-45.
- BUYS, A.J. & VENTER, G.C.H., 1980. Correlations between Bray 1, Bray 2 and ISFEI (Volume) soil-P extractants. *Fert. Soc. S. Afr.* 1, 13-18.
- CAMPBELL, K.L., KIKER, G.A. & CLARK, D.J., 2001. Development and testing of a nitrogen and phosphorus process model for Southern African water quality issues. ASAE Annual International meeting. *Paper No. 012085*, St. Joseph, MI.: ASAE.
- CHANG, S.C. & JACKSON, M.L., 1957. Fractionation of soil phosphorus. *Soil Sci.*, 84, 133-144.
- COPE, J.T., EVANS, C.E. & WILLIAMS, H.C., 1981. Soil test fertility recommendations for Alabama crops. Alabama Agric. *Station Circular No. 251*.
- GROENENDIJK, P. & KROES, J.G., 1999. Modelling the nitrogen and phosphorus leaching to groundwater and surface water; ANIMO 3.5. *Report 144*. DLO Winand Staring Centre, Wageningen.
- HENRY, P.C. & SMITH, M.F., 2003. The relationship between phosphorus requirement and some phosphorus characteristics of selected soils of the South African tobacco industry. *S. Afr. J. Plant Soil* 20, 18-24.
- HENRY, P.C. & SMITH, M.F., 2004. An improved phosphorus desorption index for the routine determination of the Ambic 2 phosphorus requirement factor for South African soils. *S. Afr. J. Plant Soil* 21, 13-20.
- JACKSON, M.L. & SHERMAN, G.D., 1953. Chemical weathering of minerals in soils. *Advances in Agron.* 5, 219-318.
- JOHNSTON, M.A., MILES, N. & THIBAUD, G.R., 1991. Quantities of phosphorus fertilizer required to raise the soil test value. *S. Afr. J. Plant Soil* 8, 17-21.
- JONES, C.A., COLE, C.V., SHARPLEY, A.N. & WILLIAMS, J.R., 1984. A simplified soil and plant phosphorus model: I. Documentation. *Soil Sci. Soc. Am. J.*, 48, 800-805.
- KARPINETS, T.V., GREENWOOD, D.J. & AMMONS, J.T., 2004. Predictive mechanistic model of soil phosphorus dynamics with readily available inputs. *Soil Sci. Soc. Am. J.* 68, 644-653.
- KEATING, B.A., CARBERRY, P.S., HAMMER, G.L., PROBERT, M.E., ROBERTSON, M.J., HOLZWORTH, D., HUTH, N.I., HARGREAVES, J.N.G., MEINKE, H., HOCHMAN, Z., MCLEAN, G., VERBURG, K., SNOW, V., DIMES, J.P., SILBURN, M., WANG, E., BROWN, S., BRISTOW, K.L., ASSENG, S., CHAPMAN, S., MCCOWN, R.L., FREEBAIRN, D.M. & SMITH, C.J., 2003. An overview of APSIM, a model designed for farming systems simulation. *Eur. J. Agron.* 18, 267-288.
- LAND TYPE SURVEY STAFF, 1985. Land types of South Africa. ARC-Institute for Soil, Climate and Water, Pretoria.
- MACVICAR, C.N., DE VILLIERS, J.M., LOXTON, R.F., VESTER, E., LAMBRECHTS, J.J.N., MERRYWEATHER, F.R., LE ROUX, J., VAN ROOYEN, T.H. & HARMSE, H.J., 1977. Soil Classification. A binomial system for South Africa. *Sci. Bull.* 390. Dept. Agric. Tech. Serv., RSA, Pretoria.
- MCGECHAN, M.B. & LEWIS, D.R., 2002. Sorption of phosphorus by soil, Part 1: Principles, Equations and Models. *Bios. Eng.* 82, 1-24.
- MEHLICH, A., 1984. Mehlich 3 soil test extractant: A modification of Mehlich 2 extractant. *Commun. Soil Sci. Plant Anal.* 15, 1409-1416.
- MENGEL, K., 1997. Agronomic measures for better utilization of soil and fertilizer phosphates. *Eur. J. Agron.* 7, 221-233.
- MYERS, R.G., SHARPLEY, A.N., THIEN, S.J. & PIERZYNSKI, G.M., 2005. Ion-sink phosphorus extraction methods applied on 24 soils from the continental USA. *Soil Sci. Soc. Am. J.*, 69, 511-521.
- NEITSCH, S.L., ARNOLD, J.G., KINIRY, J.R., WILLIAMS, J.R. & KING, K.W., 2002. Soil Water Assessment Tool Theoretical Documentation. Grassland, Soil and Water Research Laboratory, Temple, Texas. *GSWRL Report* 02-01.
- PROBERT, M.E., 2004. A capability in APSIM to model phosphorus responses in crops. p. 92-100. In: R.J. Delle & M.E. Probert (eds.) *Modelling Nutrient Management in Tropical Cropping Systems*. Australian Centre for International Agricultural Research (ACIAR) Proceedings no. 114.
- RADCLIFFE, D.E. & CABRERA, M.L., 2007. Suggestions to improve modeling of phosphorus. p. 405-415. In: D.E. Radcliffe & M.L. Cabrera (eds.). *Modeling phosphorus in the environment*. CRC Press, New York, USA.
- SCHMIDT, C.J.J., ADRIAANSE, F.G. & DU PREEZ, C.C., 2004. Relationships between Ambic 1 and Bray 1 extractable phosphorus in some South African soil. *S. Afr. J. Plant Soil* 21 71-79.
- SHARPLEY, A.N., 2007. Modeling phosphorus movement from agriculture to surface waters. p. 3-19. In: D.E. Radcliffe & M.L. Cabrera (eds.). *Modeling phosphorus in the environment*. CRC Press, New York, USA.
- SHARPLEY, A.N., JONES, C.A., GRAY, C. & COLE, C.V., 1984. A simplified soil and plant phosphorus model. II Prediction of labile, organic and sorbed phosphorus. *Soil Sci. Soc. Am. J.* 48, 805-809.
- SHARPLEY, A.N., KLEINMAN, P.J.A., MCDOWELL, R.W., GITAU, M. & BRYANT, R.B., 2002. Modeling phosphorus transport in agricultural watersheds: Processes and Possibilities. *J. Soil Water Conserv.* 57, 425-439.
- SHARPLEY, A.N., SINGH, U., UEHARA, G. & KIMBLE, J., 1989. Modeling soil and plant phosphorus dynamics in calcareous and highly weathered soils. *Soil Sci. Soc. Am. J.* 53, 153-158.
- SHARPLEY, A.N., TIESSEN, H. & COLE, C.V., 1987. Soil phosphorus forms extracted by soil tests as a function of pedogenesis. *Soil Sci. Soc. Am. J.* 51, 362-365.
- SHARPLEY, A.N. & WILLIAMS, J.R. (eds.), 1990. EPIC-Erosion/Productivity Impact Calculator: 1. Model Documentation. U.S. Department of Agriculture, Agricultural Research Service, *Technical Bulletin No.1 768*.
- SOIL CLASSIFICATION WORKING GROUP, 1991. Soil Classification – a Taxonomic System for South Africa. *Memoirs on the Agricultural Natural Resources of South Africa No. 15*. Department of Agricultural Development, Pretoria.
- THOMAS, G.W., 1996. Soil pH and soil Acidity. p. 475-490. In: D.L. Sparks, A.L. Page, P.A. Helmke, R.H. Loeppert, P.N. Soltanpour, M.A. Tabatabai, C.T. Johnston & M.E. Summer (eds.). *Method of soil analysis. Part 3. Chemical methods. SSSA Book Ser. 5*. SSSA, Madison, WI.
- VADAS, P.A., KROGSTAD, T. & SHARPLEY, A.N., 2006. Modeling phosphorus transfer between labile and nonlabile soil pools: Updating the EPIC model. *Soil Sci. Soc. Am. J.* 70, 736-743.
- WATANABE, F.S. & OLSEN, S.R., 1965. Test of an ascorbic acid method for determining phosphorus in water and NaHCO<sub>3</sub> extracts from soil. *Soil Sci. Soc. Am. J.* 29, 677-678.
- WILLIAMS, J.R., RENARD, K.G. & DYKE, P.T., 1983. EPIC Erosion Productivity Impact Calculator: A new method for assessing erosion's effect on soil productivity. *J. Soil Water Conserv.* 38, 381-383.