

Environmentally sound phosphorus management for sugarcane soils

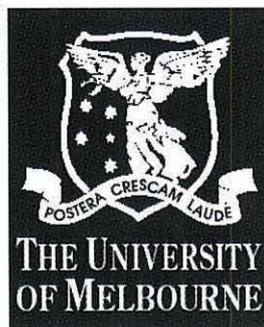
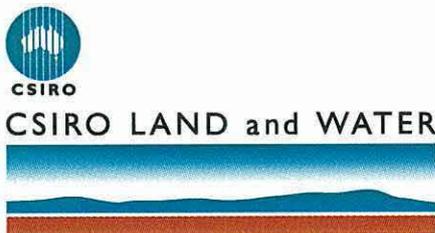
Final report on SRDC Project No. CSS3S
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Summary

A field and laboratory-based survey of the behaviour of phosphorus (P) was carried out on the soils of the lower Herbert River catchment, and sediments derived from them. The aim was to explore the factors governing P sorption or desorption in Herbert soils, and in suspended sediments in associated riverine and estuarine waters, so that the extent of any problem associated with sugarcane and soil-derived inputs to streamwaters could be defined. With this information, advice on the development of best management practices for P fertilizer could be provided to the sugar industry.

The results of the study of P behaviour in Herbert soils suggests that there is scope for refining the management of P fertilizer in the sugar industry based on a knowledge of particular soil properties and the behaviour of P in specific soils. Sorption of P in soils was found to be closely correlated with soil particle size, organic matter content and oxalate-extractable aluminium (Al). The results of this part of the project suggest that:

- in refining P fertilizer management, both for more efficient crop production and improved environmental stewardship, the utility of oxalate-extractable aluminium (Al_{ox}) as a predictor of P fertilizer requirement should be investigated; and
- clustering soils with similar physical and chemical properties is useful as a basis for identifying soils of similar potential P sorption/desorption characteristics so that, when coupled with a knowledge of the soil P content measured using normal soil testing procedures, they may also form a basis for delivery of improved fertilizer advice.

Further research is therefore warranted on both of these issues with a view to the development of specific guidelines for best-practice P fertilizer management.

A laboratory study investigated the potential for P release from suspended river sediments into riverine and estuarine waters assuming that these sediments were derived from the sugarcane soils studied in the early part of the project. It was found that a good correlation exists between the equilibrium phosphate concentration (EPC) - the P concentration at which neither sorption nor desorption occurs - when measured in soils, and the EPC when determined for suspended sediment in simulated river waters. In view of this correlation, and also the close relationship between P sorption in soils and selected soil properties, it was possible to estimate P desorption from suspended sediments on the basis of the properties of the soils from which the sediments were derived. Using this approach, classes of "P desorption risk" were derived and the soils studied were assigned to a desorption risk class. Using the same criteria, and data available from the 1:5,000 CSR survey of Herbert sugarcane soils (data from over 400 soil profiles), it was possible to assign the soils of the lower Herbert to a P desorption risk class. This part of the study suggested that sandier soils (which have relatively low capacities to retain P) that are also subject to intense surface runoff and erosion, require particular care with respect to P management; sandy soils were also identified in the first part of the study as being those on which the requirement of sugarcane for P fertilizer is likely to be relatively low.

The laboratory study also identified that desorption of P is much less in high salt (ie estuarine) waters compared to low salt (ie river) freshwaters. This finding suggests that any environmental degradation arising from the downstream export of fertilizer-derived P from Herbert canelands is likely to be concentrated in freshwater areas and not in the marine/estuarine environment. Furthermore, the finding that soil P chemistry in lower Herbert soils appears to be closely associated with aluminium oxides, as opposed to iron oxide-dominated minerals, is significant because it suggests that the induction of anoxic conditions in sediment porewaters following settling out of the sediment may not promote P desorption from Herbert sediments on deposition. When coupled with the outcomes of a preliminary assessment of runoff risk in the lower Herbert, the results

suggest that, any environmental and/or water quality monitoring targeted at possible environmental consequences of P fertilizer use in the lower Herbert would be best focussed in the area downstream of the mouth of the Stone River and in creeks and drains which drain clayey soils under cane, especially those in the Ripple Creek/Hawkins Creek region which are most subject to runoff.

This research has also enabled identification of areas in which additional work would contribute significantly to the further development of best-practice management for P fertilizer in the Australian sugar industry. In addition to the areas identified above, further work is warranted as follows:

- Research targeted at assessment of soil erosion risk as opposed to runoff susceptibility would promote a more exact understanding of the risk of certain soils being sediment sources, and therefore the extent to which they are contributors of P to riverine ecosystems.
- Complimentary to this erosion work and also that described in this report, spatial analysis of the assessment on P desorption risk based on digital maps of the CSR soil survey would enable more precise guidelines for better P management to be derived.
- Research aimed at assessing the comparative P sorption behaviour of riverine sediments in freshwater and estuarine waters in a range of catchments in which cane production is a major land use would corroborate one of the conclusions of this report, namely that any environmental degradation arising from sub-optimal P management is likely to be concentrated in the freshwater zone.
- Similarly, assessment of the relative roles of aluminium and iron-dominated minerals in controlling P sorption behaviour in caneland soils throughout Queensland would promote an ability to extrapolate the results of this study to other areas.
- Finally, our conclusions that freshwaters are at greater risk than estuarine waters, and that the area of the Herbert which lies downstream of the mouth of the Stone River ought to be focus of any subsequent water quality research, coupled with the existing dearth of information on the possible ecotoxicological impacts of P fertilizer use, suggests that a research program targeted at such impacts could usefully build on the knowledge derived in this work. Such a program could most usefully be located in the suggested part of the lower Herbert.

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1.0 Background

Population growth, and the associated competition between urban, rural, domestic, industrial and recreational land uses has put increasing pressure on Australia's coastal and near-shore zone. As a consequence, the need for better management of natural resources in coastal areas has become paramount. In north Queensland, recent policy initiatives such as Landcare and Integrated Catchment Management (ICM), together with concerns relating to possible degradation of the Great Barrier Reef due to inappropriate land management, have increased the demand for information to assist with land resource decision making. Of particular concern is the ability to minimise any environmental degradation which might arise as a result of agricultural production. This requires a detailed knowledge of the off-site effects of rural land use, and strategies to minimise the movement of nutrients and other contaminants off-farm (Bramley *et al.*, 1996).

The lower part of the Herbert River catchment, centred on Ingham in north Queensland, is a major sugarcane-producing area characterised by low-angle slopes and imperfectly drained duplex soils. Aside from sugarcane production, beef production on improved and unimproved pastures and forestry, both plantation and native, are significant land uses; there are also large areas of World Heritage-listed tropical wilderness in the catchment. In September 1992, and as part of its Coastal Zone Program (CZP), CSIRO began assessing the effects of these different forms of rural land use on water quality with a view to producing a computer-based decision support system to assist natural resource managers assess the downstream implications of changes in land use (Walker *et al.*, 1995). In the period between the start of this project and late 1994, it was established that:

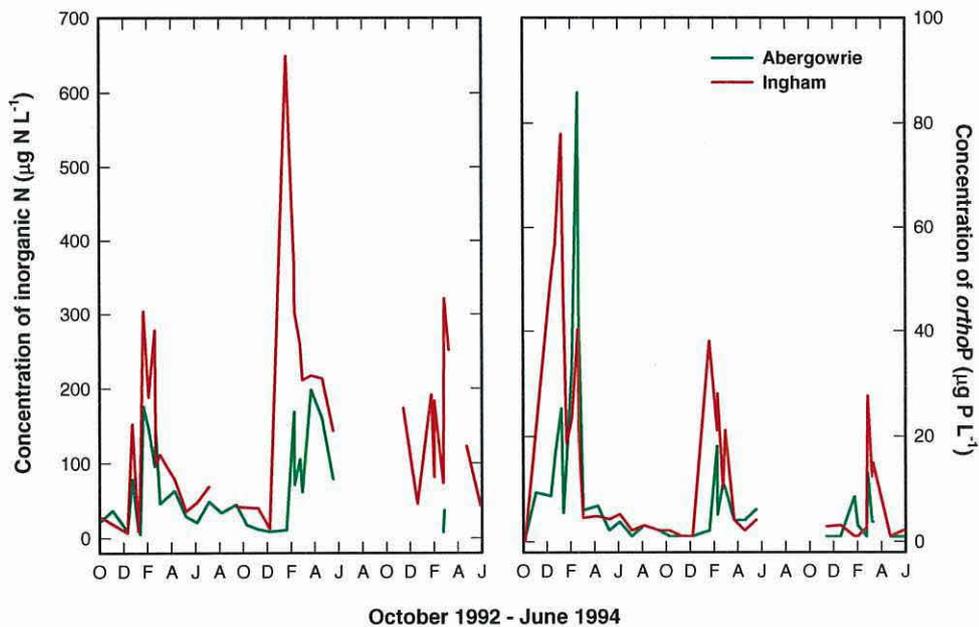


Figure 1. Concentrations of inorganic N and P at Ingham and 32 km upstream at Abergowrie (Data of Bramley *et al.*, 1994).

- nutrient (N and P) concentrations in the Herbert River at Ingham tend to be greater than at Abergowrie, 32 km upstream (Figure 1; Bramley *et al.*, 1994; Mitchell *et al.*, 1997), indicating an export of nutrients from land draining into the Herbert between these points;
- the concentration of nutrients in streams draining land under cane tend to be greater than in streams draining other land uses, but otherwise fall within acceptable levels (ANZECC, 1992) except during peak wet season events (Figure 2; Bramley and Johnson, 1996);
- peak wet season events dominate the annual riverine export of nutrients and sediments (Figures 3 and 4; Bramley and Johnson, 1996; Mitchell and Bramley, 1997; Mitchell *et al.*, 1996, 1997); and
- exports of phosphorus from catchments in which sugarcane production is the major land use during peak events such as Tropical Cyclone Sadie (January 1994), may be very significant (65 T in total over a 6 ½ day period; approximately 9 T of which was soluble *orthophosphate* (Mitchell *et al.*, 1997)).

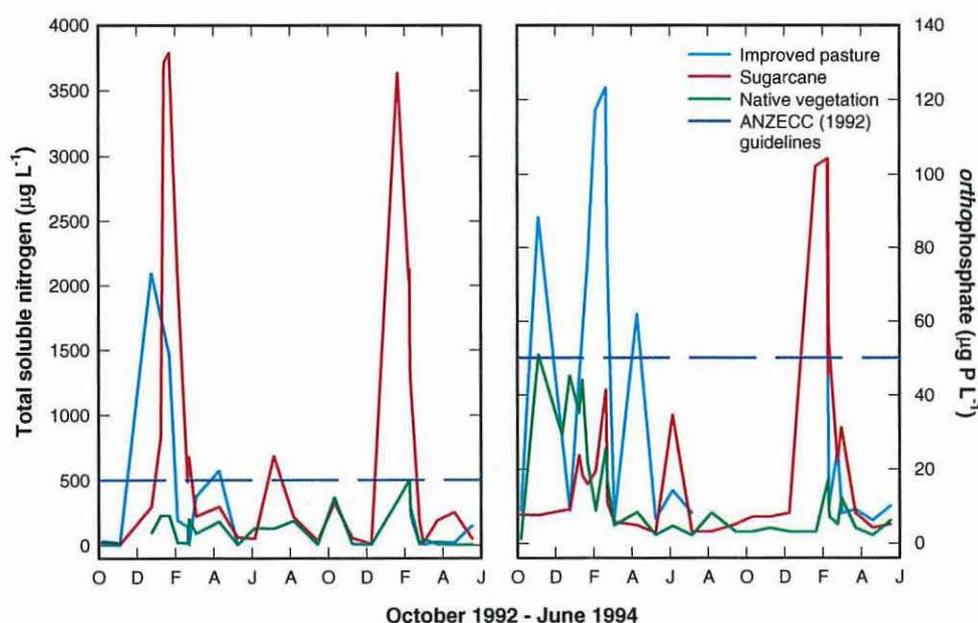


Figure 2. Concentrations of inorganic N and P in some lower Herbert streams draining different land uses (Data of Bramley and Johnson, 1996).

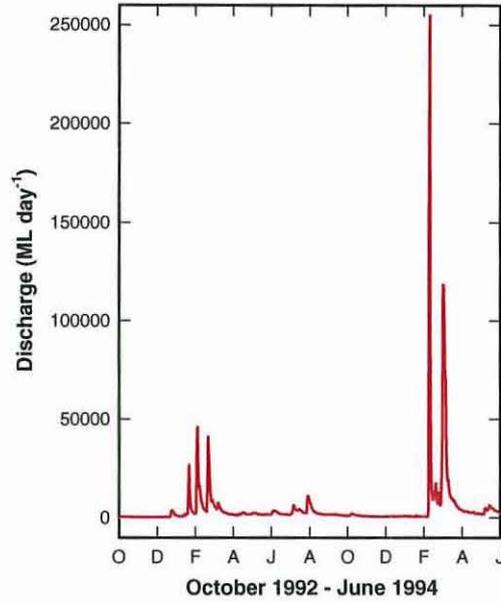


Figure 3. Herbert River discharge at the John Row Bridge, Ingham

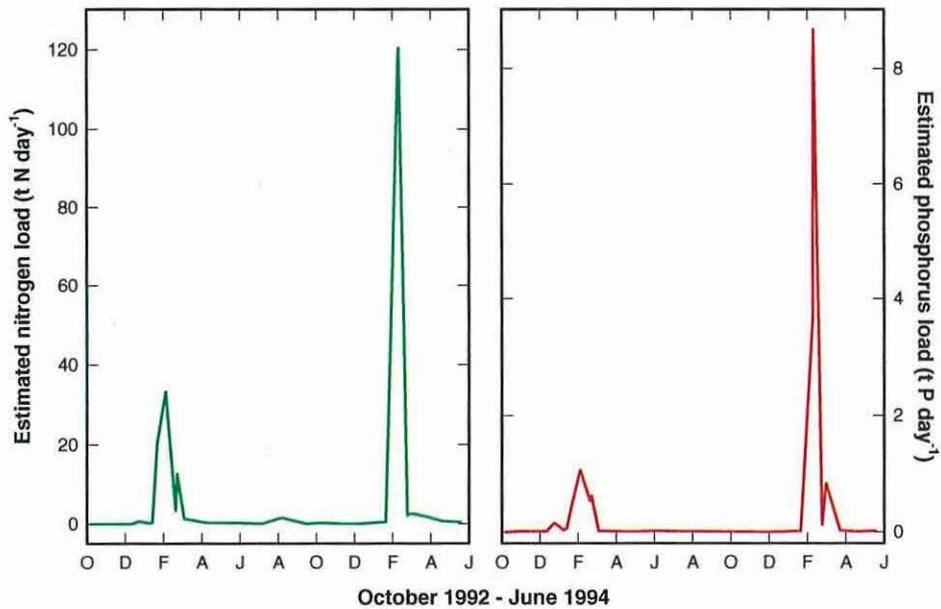


Figure 4. Estimated export of soluble N and *orthophosphate* from land draining into the Herbert River between Ingham and Abergowrie (Data of Bramley and Johnson, 1996).

The sugar industry has traditionally been a heavy user of P fertilizer (approximately \$27M spent annually). Application rates are high for agricultural land in Australia, ranging from about 25 kg P ha⁻¹ y⁻¹ for ratoon crops to about 50 kg P ha⁻¹ y⁻¹ for plant cane (Pulsford, 1991) and as our water quality research has indicated, the potential for P-enriched soil material to be eroded into rivers draining into environmentally sensitive coastal waters is high. Current industry recommendations for P fertilizer management are essentially made independently of consideration of key soil properties. Yet in a preliminary study, we have shown that different soils do have differing P sorption characteristics, and that as a consequence, the P requirements, and response to P, of cane grown on such contrasting soils may also differ (Figure 5; Bramley and Wood, 1996; Bramley *et al.*, 1995).

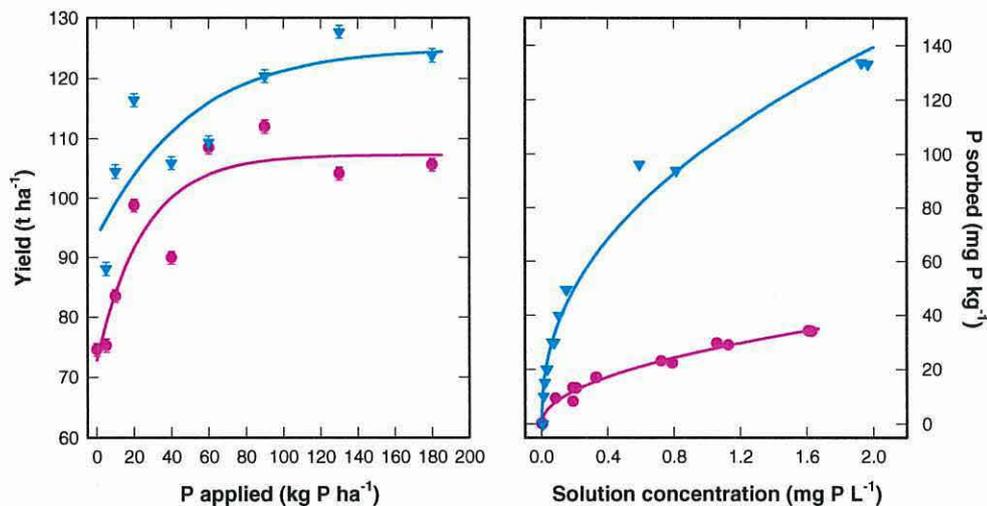


Figure 5. Response of plant cane to P at sites near Hamleigh (▼) and Upper Stone (●) in the lower Herbert and the P sorption characteristics of the soils at these sites. Data of Bramley *et al.*, 1995; Bramley and Wood, 1996).

Sustainable sugar production requires, amongst other things, that the impact of P inputs from cane lands be minimal. To achieve this, the industry needs to know the extent of the P loss problem, the conditions which govern whether eroded soil materials act as P sources or sinks in riverine or estuarine waters, and the extent to which the behaviour of P in different soils under sugarcane differs to the extent that investigation of the merits of differing P fertilizer management across a range of soils is warranted. Limited research has been done on the magnitude of the problem of P losses from cane land and the extent to which soil-derived sediments act as sources or sinks for inorganic P. Studies by Pailles and Moody (1992) in the Johnstone River catchment, which is dominated by soils with a high capacity for P retention, indicated that mid-channel sediments, under aerobic conditions, were predominantly sinks for P in solution. But the behaviour of such sediments under the anoxic conditions that often occur in estuaries is unknown. Further, Pailles and Moody's data for solution P concentrations in the Johnstone suggested that suspended sediments must be rich in sorbed P relative to the bed sediments that they sampled, but the P retention and release characteristics of these suspended sediments was unknown.

2.0 Objectives

Against the background outlined above, there appeared to be great merit in investigating P fertilizer management in the Herbert River Sugar Industry and the fate of P derived from land under cane.

This project therefore aimed to explore the factors governing P sorption or desorption in Herbert soils, and in suspended sediments in riverine and estuarine waters, so that the extent of any problem associated with sugarcane culture and soil-derived P inputs to the river systems could be defined with a view to promoting the development of best practice for P management.

3.0 Project design

Based on existing knowledge, our working assumptions throughout this study were that:

- P is generally strongly held (sorbed) by soil particles. As a consequence,
- notwithstanding the existence of an equilibrium between sorbed P and P in solution phases, movement of P off-site is dominated by the process of soil erosion followed by sediment removal in surface run-off, rather than by leaching or otherwise in solution;
- P sorption in soil is predominantly a clay fraction process;
- suspended sediments in-stream are predominantly clay-sized particles;
- fine suspended sediments, as opposed to coarser (bedload) sediments, are therefore expected to be the main conduits for P movement in-stream; and
- suspended river sediments in the lower Herbert are derived from the soils drained by the Herbert River.

With these assumptions and the objectives outlined above in mind, and with the endorsement of the panel which reviewed the project in 1997, the following were identified as the key tasks facing the project team:

1. A field and laboratory survey of the P sorption characteristics of the soils of the lower Herbert, and of related soil properties;
2. A laboratory study of P release from sediments derived from these soils under a range of simulated riverine and estuarine conditions;
3. Integration of the results of 1 and 2 with other relevant biophysical information available for the study area using GIS; and
4. Extension of the results obtained during each of the above to project stakeholders.

In other words, we needed to know how P behaves in the soils of the Herbert, assess the implications of this behaviour when these soils become suspended river sediments, and integrate this information so that advice could be provided to the sugar industry that assists in the development of best practice for management of P fertilizers.

4.0 A field and laboratory survey of the P sorption characteristics of the soils of the lower Herbert and related soil properties

4.1 *Methods and materials*

4.1.1 *Sampling strategy*

Our objective in this phase of the work was to assess the sorption characteristics of P in the soils of the Herbert, ensuring that the full range of variation in P behaviour was taken into consideration. In the lower Herbert, the sampling strategy was guided by the 1:5,000 survey of soils under sugarcane conducted by CSR (Wood and Bramley, 1996), although some lower Herbert soils not under sugarcane were also sampled. Our aim was to cover both the range of soil types identified in the CSR survey and also the different locations in which these soils occur. Fifty five sites in the lower Herbert catchment were sampled during November 1995, and a further 11 lower Herbert sites were sampled during December 1996. Ten sites in the upper Herbert were also sampled in June 1996; three of these included spoil and tailings from the discarded tin mines near Mt Garnet. Thus, a total of 76 sites were sampled^a.

The location of the lower Herbert sampling sites is given in Figure 6 which also indicates their distribution amongst four broadly defined "subcatchments". The Ripple Creek/Hawkins Creek subcatchment (21 sites) was an area of focus because this region is also the location of related research contributing to the CSIRO Coastal Zone Program, and because it was considered to be characteristic of much of the lower Herbert; the Stone River (24 sites) was intensively sampled due to the importance of the Stone as the main tributary of the Herbert and a relative predominance of sandy soils compared to the rest of the lower Herbert; the "floodplain group" (9 sites) were chosen to reflect sites in the area over which floodwaters tend to move when the Herbert River is in flood; and the Abergowrie group (12 sites) were chosen to contrast with sites sampled downstream as they are typically deeper, freer draining soils than those in the Ripple Ck or floodplain group.

The precise location of all sites, the land cover at the time sampling, and the soil type name assigned in the CSR soil survey is given in Appendix 1. Note that some sites were outside the area that has thus far been surveyed by CSR. At some of these, it was nevertheless possible to assign them to one of the soil types identified in the CSR survey.

4.1.2 *Sample analysis - basic soil properties*

The samples were air dried and sieved (< 2 mm), and were stored at 4 °C prior to analysis. A number of analyses were carried out for the purpose of simple characterisation, and also with a view to being able to relate P sorption characteristics (see below) to more commonly measured soil properties. The properties measured were:

- Particle size distribution (Mikhail and Briner, 1978);
- Soil-test resin P (Saggar *et al.*, 1990);
- Total P;
- pH (1:5 soil:water);
- Organic carbon (Heanes wet oxidation); and
- Oxalate, dithionite, and pyrophosphate-extractable iron (Fe) and aluminium (Al).

^a Note that since the three spoil/tailings samples were found to have P sorption properties and clay mineralogies that were markedly different from the rest of the samples, they were excluded from much of the analysis which forms the basis of this report.

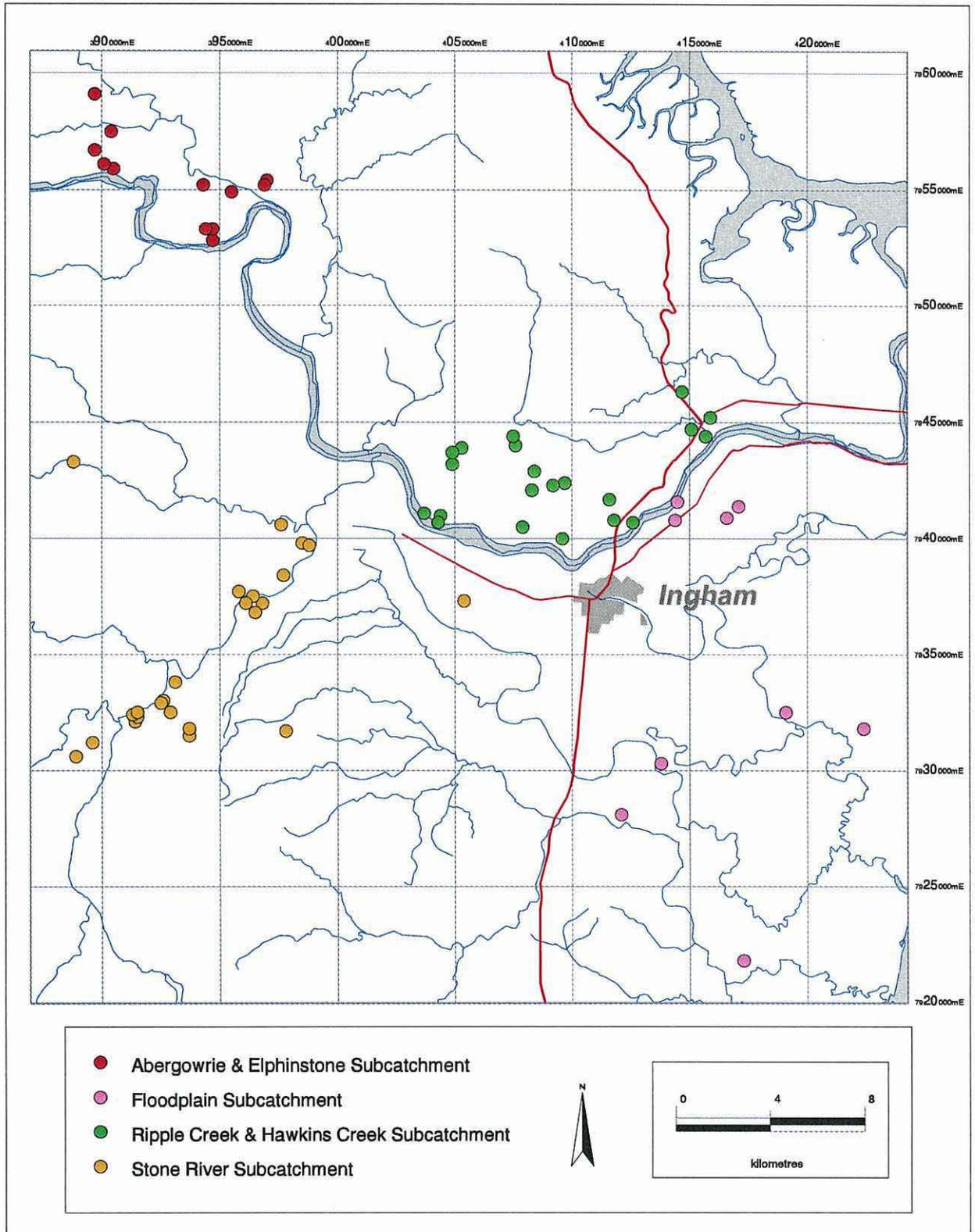


Figure 6. Location of lower Herbert soil sampling sites used for the survey of P sorption characteristics.

Unless otherwise indicated, the methodologies used for these analyses were as detailed by Rayment and Higginson (1992). The results of the physico-chemical analyses are detailed in Appendix 2.

Semi-quantitative mineralogical analysis (Taylor, 1991) using X-ray diffraction followed by Rietveld analysis using the commercial package SIROQUANT, available from Sietronics Pty Ltd, was also carried out on a number of samples which were selected to be representative of the whole set. The results of these analyses are detailed in Appendix 3.

4.1.3 Sorption of P by soil

Batch experiments were used to study the sorption of P by soil. Soil samples were suspended at a soil:solution ratio of 1:30 in solutions which were 0.01M with respect to CaCl₂, and which contained P at concentrations ranging from 0.04 - 18 mg P L⁻¹. The suspensions were shaken end over end for 17 hours at 23 °C, after which they were filtered (Whatman 42), and the concentration of P remaining in solution was measured using the spectrophotometric molybdate-blue method of Murphy and Riley (1962). The amount of P sorbed (or desorbed), denoted by ΔP , was calculated from the difference between the P concentration in solution at the beginning and end of the shaking period. ΔP was then plotted against C , the concentration of P in solution at the end of the shaking period. Sorption curves were then produced by fitting the data with the Freundlich equation (eg. Barrow, 1978)

$$\Delta P = KC^b - Q \quad 1$$

where Q is the amount of initially adsorbed P, and K and b are constants describing the slope and curvature of sorption curve. Estimation of Q for soils which have received additions of fertilizer P is problematic for a number of reasons, not the least being that Q is correlated with b (Barrow *et al.*, 1978). We therefore set the value of Q to be equal to the value obtained from the resin soil P test (Appendix 2). This is justified since the use of resins in this test is designed to mimic the action of plant roots in inducing desorption of P from soil by sequestering it from the soil solution. That is, the resin test gives a measure of the readily desorbable (ie. plant-available) P which, for practical purposes, can be assumed to be equivalent to the amount already sorbed. The data were fitted with equation 1 using the least squares optimisation functions available in SigmaPlot® v3 (Jandel Scientific, 1995).

4.2 Results and discussion

Figure 7 illustrates the sorption curves obtained by fitting equation 1 to the laboratory data obtained for five soils with differing values of K , b and Q (resin P; Table 1). The parameter b was found to be normally distributed and fairly constant for the whole suite of 73 samples (mean=0.34, se=0.007). This result is consistent with those of Barrow and Shaw (1975) and Barrow (1980) for soils sampled from restricted geographical regions, and allowed us to simplify equation 1, using the mean value of b for the whole dataset, to

$$\Delta P = KC^{0.34} - Q_R \quad 2$$

where Q_R denotes resin P. This is useful since it means that only one parameter, K , has to be estimated through curve fitting. In the following, this value of K is denoted by K_{soil} ; estimates of K_{soil} are given in Appendix 2.

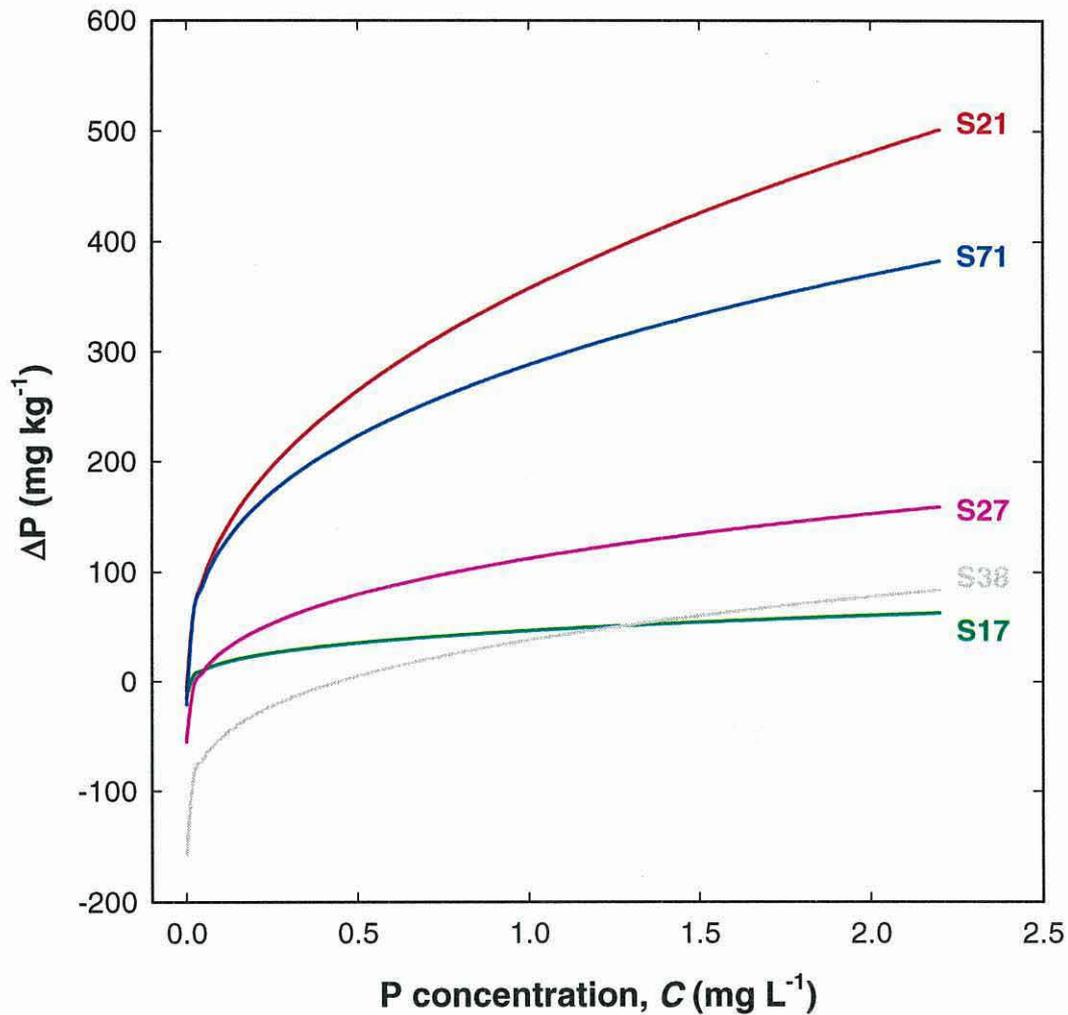


Figure 7. Sorption curves for five of the soils tested. These cover the range of subcatchment locations and variability in P sorption characteristics of the soils used in this study. Further details of these soils are given in Table 1. Note that positive values of ΔP indicate sorption whilst negative values indicate desorption.

Table 1. Sample location and equation 1 parameters for the soils shown in Figure 7

| Soil | Soil type name | Sub-catchment | Resin P | K | b |
|------|-------------------|---------------|---------|-------|-------|
| S17 | Coarse sandy loam | Stone River | 13.6 | 60.4 | 0.298 |
| S21 | Clay | Ripple Creek | 8.9 | 366.0 | 0.421 |
| S27 | River overflow | Abergowrie | 54.9 | 167.0 | 0.313 |
| S38 | Terrace silt | Floodplain | 157.0 | 195.0 | 0.267 |
| S71 | Silty clay | Ripple Creek | 21.0 | 309.0 | 0.339 |

4.2.1 Relationships between K_{soil} and other soil properties

Simple two variable correlation tests were used as an initial means of exploring relationships between soil properties and K_{soil} . It was found that K_{soil} correlated well with clay %, organic carbon (OC), kaolin and oxalate-extractable Al (Al_{ox}). The other extractions of Al also correlated well with K_{soil} . Iron, in any of the extractions, did not correlate well with K_{soil} and neither did the ratio of oxalate- to dithionite-extractable Fe, which is sometimes used to characterise P sorption (Rayment and Higginson, 1992). This is an important finding, the implications of which we discuss in section 5.2.4. The kaolin content was strongly related to clay % which suggests that the clay fraction of Herbert soil is dominated by this mineral.

Regression analysis indicated that Al_{ox} ($\mu\text{g g}^{-1}$) was the best single predictor of K_{soil} (L kg^{-1}), and little improvement in the prediction of K_{soil} was achieved by inclusion of other properties in the regression equation:

$$K_{soil} = 1115 Al_{ox} - 14.4 \quad r^2 (\text{adj}) = 0.79 \quad 3$$

$$K_{soil} = 943 Al_{ox} + 1.1 \text{ clay} + 1.16 \text{ silt} - 33.5 \quad r^2 (\text{adj}) = 0.82 \quad 4$$

The best prediction of K_{soil} , in terms of the proportion of variance accounted for, was obtained on the basis of Al_{ox} , clay and silt (equation 4).

Since the production of P sorption curves is a time-consuming procedure and one which is not routinely used by commercial soil testing laboratories, our objective here was to determine whether an index of P sorption could be obtained on the basis of more routinely obtained soil properties. The proportion of the variance in K_{soil} accounted for by equations 3 and 4 (79 and 82 %) for the 73 soil samples (ie the whole set of soil samples excluding those from the tin mines) suggests that this approach has merit. However, determination of Al_{ox} is not routinely used by a majority of commercial laboratories either (note however, that oxalate extractable Fe is used by a major fertilizer company in Western Australian as part of the suite of analyses used in making P fertilizer recommendations). Further, when Al_{ox} was excluded from the regression, K_{soil} was poorly predicted by the other soil properties that we measured; the best relationship, which accounted for only 62 % of the variation in K_{soil} , was on the basis of clay % and OC:

$$K_{soil} = 4.98 \text{ clay} + 45.5 \text{ OC} + 6 \quad r^2 (\text{adj}) = 0.62 \quad 5$$

Wood (1988) obtained a somewhat similar result.

These results suggest that, in any attempt at refining the basis of the current P fertilizer recommendations for sugarcane (Schroeder *et al.*, 1998), there may be merit investigating the utility of Al_{ox} as a predictor of P requirement and including it in the suite of analytes routinely tested by commercial laboratories for generating fertilizer recommendations.

4.2.2 Relationships between K_{soil} and soil type

Of the 73 soils analysed, 61 could be allocated to one of the 24 soil types identified in the CSR soil survey (Wood and Bramley, 1996); details are given in Appendix 1. As part of an on-going project (Bramley and Wood, unpublished data), we have been evaluating a clustering technique which groups the 24 soil types into a smaller number of "clusters" of similar soils based on the values of a

large database of associated physico-chemical soil properties. Using the data for over 450 soil profiles, it was found that using either the chemical or physical properties separately, 4 clusters could be justified and when both chemical and physical properties were considered simultaneously, allocation of the 24 soil types amongst 5 clusters could be justified. The 61 soil samples used in this study which could be assigned to an identifiable soil type, could thus be allocated to a cluster^a; details are given in Appendix 4.

The mean values of K_{soil} for soils clustered on the basis of chemical data alone are given in Table 2. It should be noted that these values might not be applicable to the clusters as a whole, as the clusters have different average values for soil properties to those of the samples used here - presumably due to the unbalanced nature of the sampling scheme used in each case. Nevertheless, the order of the clusters is likely to hold.

Table 2. K_{soil} of soil type clusters on the basis of chemical data, using 61 samples. Cluster 1 is dominated by clays, cluster 2 by silts, cluster 4 by sands and cluster 3 by "loams" - which are presumably well-mixed.

| Cluster | 1 | 2 | 3 | 4 |
|--|------|------|-----|------|
| K_{soil} average (L kg ⁻¹) | 326 | 156 | 119 | 116 |
| Standard error of mean | 17.6 | 18.7 | 9.7 | 23.2 |
| Number of samples | 11 | 19 | 16 | 15 |

Using 61 samples, the value of K_{soil} for cluster 1 was significantly greater than for clusters 2, 3 and 4 ($P < 0.05$). The value of K_{soil} for cluster 2 was significantly greater than for cluster 3, but not for cluster 4 (due to the large variance of the cluster 4 estimate). A Red Sand (S67) was allocated to cluster 4. This sample had a very high value of K_{soil} (382 L kg⁻¹). The removal of that sample from the analysis led to K_{soil} of cluster 2 being significantly greater than that of cluster 4 (Note that S67 was from outside the area covered by the CSR survey and was allocated to the Red Sand soil type after sampling; thus, it may have been mis-allocated). In general, the clustering has been found to reflect soil texture irrespective of which properties (chemical, physical or both) are included in the analysis.

4.3 Conclusions

The survey of P sorption characteristics of Herbert river soils suggests that, in terms of the parameters describing sorption (equation 1), most of the variation may be accounted for by differences in Q and K . Q , the amount of initially sorbed P, which we assumed to be well estimated by resin P, is essentially a function of fertilizer history, and we therefore regard K as a key parameter for the provision of advice on improved P fertilizer management. The differences in K , as estimated by K_{soil} , between different soils or clusters of soils, should allow identification of soils with different sorption characteristics within the catchment. When coupled with a knowledge of fertilizer history (Barrow *et al.*, 1998) and Q , which should preferably be estimated using a sensitive soil test (Bramley *et al.*, 1995) such as the resin test (Saggar *et al.*, 1990), as opposed to that currently used by the sugar industry (Kerr and Von Steiglitz, 1938), this should allow a refinement of estimated fertilizer requirements. For example, cane grown on soil types in clusters 3 and 4 are likely to require less

^a Note that the allocation of soils to clusters may change given that soil property values are now available for over 800 profiles in the lower Herbert. Further, our first attempt at using the clustering methodology used all available soil property data and not just those soil properties which discriminate between soil types. Thus, the information in Appendix 4 and the following discussion should be considered as indicative rather than definitive.

applied P than cane grown on soils in the other clusters, with soils in cluster 1 requiring the most P. This assertion is consistent with the results of Bramley *et al.* (1995) and Bramley and Wood (1996). This type of classification could usefully form the basis of refinements to the P fertilizer recommendations for the Herbert district. Further research on this issue is warranted.

5.0 Sorption/desorption of P in simulated river and estuary waters

5.1 Methods and materials

5.1.1 Sample selection

In view of the nature of desorption experiments, it was considered that we would gain a greater amount of useful information by conducting a thorough study of selected soils compared to a less rigorous analysis of the whole suite of soil samples. The survey of P sorption characteristics in soils (Section 4 above) indicated that K (equation 1) was a parameter which could be used to discriminate between soils. Much of the work conducted in the CSIRO Coastal Zone Program has been undertaken in the Ripple Creek subcatchment and we wished to focus on soils/sediments from that area in this study too, if this could be shown to be representative of the soils of the lower Herbert in general. Figure 8 suggests that the range of variation in values of K in the Ripple Creek subcatchment is similar to that for the whole district, and on that basis, we selected a subset of samples from Ripple Creek (10 samples). In addition, one sample was selected from the Stone River subcatchment in order to ensure adequate coverage of sandy soils. The samples selected for desorption experiments are identified in the appendices.

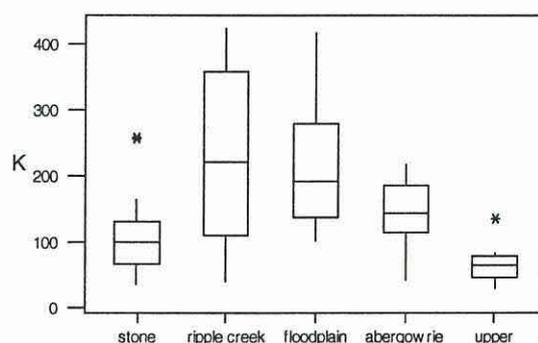


Figure 8. Boxplot showing variation in values of K (equation 1) across subcatchments.

5.1.2 Simulation of river and estuary waters

In order to enable proper simulation of riverine and estuarine conditions in the laboratory, a set of river water samples covering the length of the Herbert between the mouth at Dungeness and just below the gorge at Nash's Crossing, the most up-stream point in the study area, were taken and analysed for EC, pH and chemical composition using inductively coupled plasma atomic emission spectroscopy (ICP-AES). On the basis of the results obtained (Appendix 5), the background matrix in which the desorption experiments were conducted was: for river waters, approximately (mg L^{-1}) Na 4.6, Ca 2.8 and Cl 11.9; and for estuarine waters, approximately (mg L^{-1}) Na 6680, Ca 284, Mg 760, K 292, SO_4^{2-} -S 522 and Cl 11590.

The appropriate level of pH and EC buffering of the background matrices was determined by varying the amount (0-0.5 mL) of 0.05N NaOH added to 1:30 soil:water suspensions with and

without the presence of anion exchange resin (AER). AER was the principal means through which we induced P desorption (see below); the methodology used is essentially the same as the resin P soil test (Saggar *et al.*, 1990) which was used to determine Q (see section 4 above). The suspensions were shaken end-over-end for 17 hours, after which the EC and pH were measured. The amount of base required for pH 6.0 at the end of the shaking period was estimated for different amounts of resin. The required amount of simulated river water for EC of $\sim 60 \mu\text{S cm}^{-1}$ was also estimated for different amounts of AER.

5.1.3 Sorption/desorption curves

Suspensions comprising 1 g soil and 30 mL solution (containing required base and varying amounts of AER and P solution) were prepared in triplicate with varying amounts of added P or AER as follows:

5 $\mu\text{g P}$, no AER (some soils only)
 2 $\mu\text{g P}$, no AER
 0 P, no AER
 0 P, $\sim 25 \text{ mm}^2$ AER
 0 P, $\sim 75 \text{ mm}^2$ AER
 0 P, $\sim 225 \text{ mm}^2$ AER
 0 P, $\sim 1600 \text{ mm}^2$ AER
 0 P, $\sim 4800 \text{ mm}^2$ AER

These treatments were designed to induce either a small amount of sorption (no AER with P) or varying amounts of desorption; note that AER acts as a sink for desorbable P and therefore the greater the surface area of AER, the greater the size of the sink for P. The suspensions were shaken end over end (30 rpm) for 17 hours at 23 °C, then centrifuged at 3500 rpm and filtered (0.45 μm , 15 mL). The pieces of AER were removed after centrifugation, and the P stripped from them with 0.5M NaCl. The P content of suspension solution and resin extract were analysed using the molybdate blue method as before (section 4.1.3).

5.2 Results and discussion

There are three major differences in the conditions under which the soil and simulated river water experiments were collected. The river water desorption experiments were conducted at a higher pH; a lower ionic strength; and with a monovalent cation (Na) dominating the background matrix. In the case of variable charged materials, the effect of increased pH would be to decrease the amount of positive charge at the surface, and thereby decrease the sorption of P. However, changing the pH of the solution also impacts on the speciation of P and the solubility of P-complexes, effects which tend to offset the impact of pH on surface charge and therefore net sorption. The effect of ionic strength is also not straight-forward in a mixed system of permanent and variable charge surfaces. Increased salt leads to lower absolute surface potential, which gives rise to more absolute charge and consequently more sorption. Overall, we expected that under the simulated riverine conditions, desorption of P would be enhanced whereas in the simulated estuarine conditions, we expected sorption to be enhanced.

Plots of the relationship between P sorption/desorption and solution P concentration were prepared for the 11 soils (which we now refer to as sediments) and analysed using the same approach as for soil (section 4.2; Figure 7). An example is given in Figure 9 which, for sediment S17, shows data points for sorption and/or desorption in simulated riverine and estuarine waters, in addition to the curve derived for soil in 0.01M CaCl₂ (section 4).

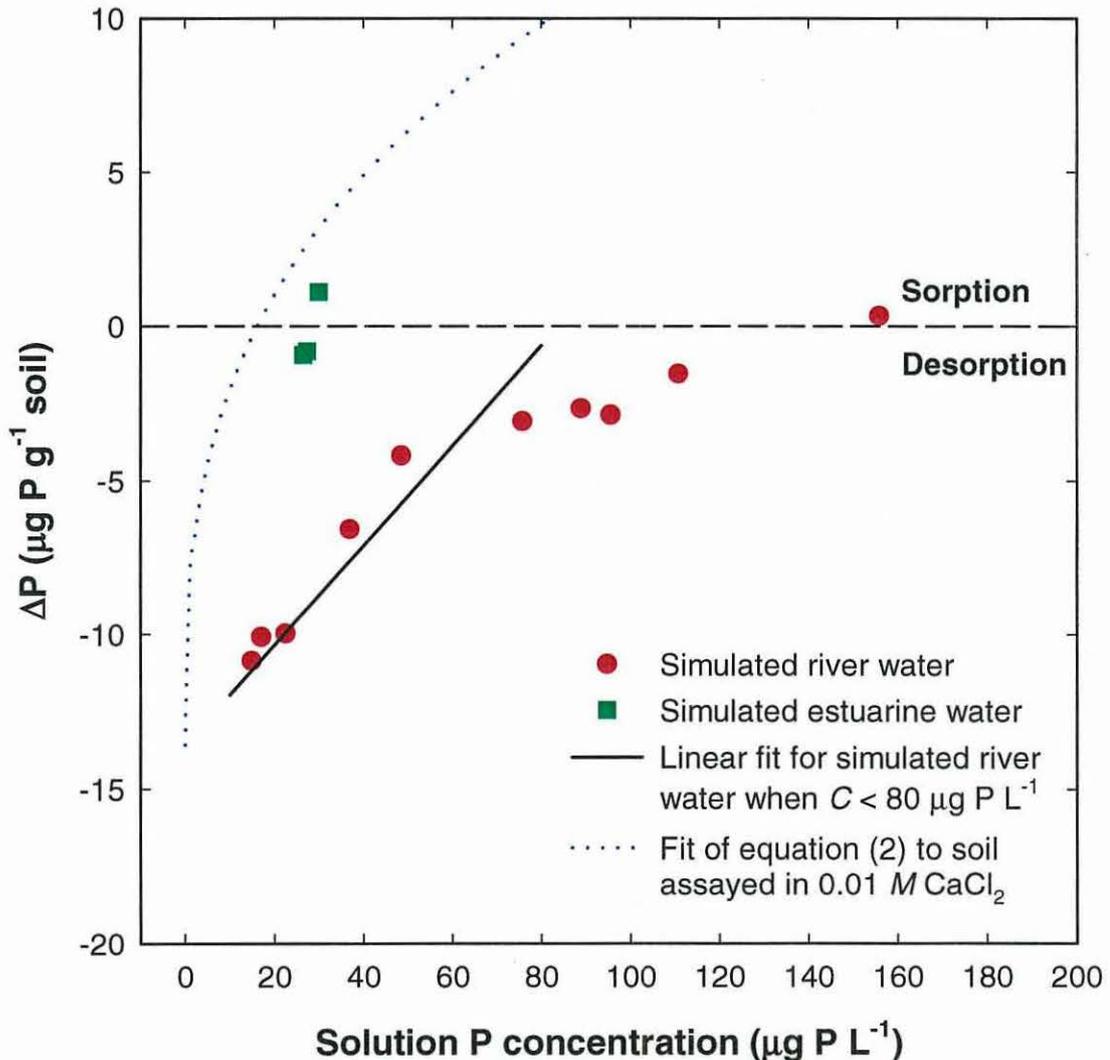


Figure 9. Sorption/desorption data (ΔP) for sediment S17 in simulated riverine and estuarine waters and comparison with the curve obtained for the same sample as part of the survey of soil P characteristics (See text for further explanation).

5.2.1 Equilibrium P concentration (EPC) in simulated river water

From the plots of ΔP against the concentration of P in solution at the end of the 17 hour equilibration period, estimates of equilibrium P concentration (EPC) can be made for each sediment. The EPC is the solution concentration at which P is neither sorbed nor desorbed; that is, EPC is the concentration at which $\Delta P = 0$. Thus, concentrations of P in solution less than the EPC will result in desorption (sediment acts as a P source) whilst at concentrations above the EPC, sorption will occur (sediment acts as a sink). Estimates of EPC can also be calculated from the data obtained in section 4 for soils and a solution matrix of 0.01M CaCl_2 . The EPC values for the simulated river water (sediment) and 0.01M CaCl_2 (soil) systems correlated quite well. For all the samples for which reliable estimates of EPC in simulated river water (EPC_{river}) were obtained (S17, S19, S20, S21, S22, S46, S71, S73, S74 and S76), the linear regression with EPC in 0.01M CaCl_2 (EPC_{soil}) was:

$$EPC_{river} = 16.92 EPC_{soil} + 38.82 \quad r^2 (\text{adj}) = 0.91 \quad 6$$

Therefore, from the set of 10 samples for which EPC_{river} was measured, the EPC_{river} of the full 73 samples could be estimated using EPC_{soil} obtained from the survey of P sorption characteristics in soil (Section 4). This tells us the concentration of P in the river at which a sediment derived from a particular soil will be a source of dissolved P. This is one way to identify soils that are potential contributors to dissolved P should they be eroded.

A river may be considered to be eutrophic if the concentration of P is above $50 \mu\text{g P L}^{-1}$, and hypertrophic above $100 \mu\text{g P L}^{-1}$ (Anon, 1996). An EPC_{river} class was therefore allocated to each soil according to:

$$\begin{aligned} EPC_{river} \text{ class 1: } & EPC_{river} < 50 \mu\text{g P L}^{-1} \\ EPC_{river} \text{ class 2: } & EPC_{river} 50\text{-}100 \mu\text{g P L}^{-1} \\ EPC_{river} \text{ class 3: } & EPC_{river} 100\text{-}200 \mu\text{g P L}^{-1} \\ EPC_{river} \text{ class 4: } & EPC_{river} 200\text{-}500 \mu\text{g P L}^{-1} \\ EPC_{river} \text{ class 5: } & EPC_{river} > 500 \mu\text{g P L}^{-1} \end{aligned}$$

Because estimation of EPC requires a value for Q (equation 1), the initially adsorbed P in the soil, equation 6 could not be used to expand the results to the clusters of soil type since resin P was not one of the analytes assayed as part of the CSR soil survey. The location of sampled soils whose sediments have high EPC_{river} values is shown in Figure 10.

5.2.2 Estimating desorption quantities in river water from soil properties

For solution P concentrations below about $80 \mu\text{g P L}^{-1}$ in the simulated river water experiments, ΔP appeared to be approximately linearly related to concentration. Using equation 1, with the b term set at 1 and the Q term set at the value of the soil test resin extraction, the optimised value of K in river water (K_{river}) was calculated for each sample using only data corresponding to P concentrations $< 80 \mu\text{g P L}^{-1}$. Thus, K_{river} is the slope of the straight line shown in Figure 9.

K_{river} was found to be well correlated with several soil properties; specifically, clay %, silt %, organic carbon (OC), kaolin, mica, and oxalate-extractable Al (Al_{ox}), as well as with K_{soil} . The regression equation that best fitted the observed data was

$$K_{river} = 5.4 \text{ clay} + 1.3 \text{ silt} - 122 \text{ pH} + 116 \text{ OC} - 845 \text{ Al}_{ox} + 601 \quad r^2 (\text{adj}) = 0.99 \quad 7$$

although good predictions of K_{river} were also obtained when Al_{ox} was omitted because there was a strong covariance between Al_{ox} and OC:

$$K_{river} = 2.6 \text{ clay} + 0.2 \text{ silt} - 122 \text{ pH} + 68.4 \text{ OC} + 609 \quad r^2 (\text{adj}) = 0.95 \quad 8$$

Using equation 7, the value of K_{river} could be estimated for the whole set of 73 soil samples. Since soil test resin P extractions were undertaken for all the samples, values of ΔP could also be estimated for river concentrations less than $80 \mu\text{g L}^{-1}$ using the linearised version of equation 1. The mesotrophic/eutrophic P concentration boundary is at $50 \mu\text{g L}^{-1}$. The amount of P that can be desorbed at this concentration by a sediment that has been eroded reflects the amount of P that can be rapidly supplied to riverine organisms. Therefore the soils were grouped according to the amount of P that would desorb if sediments derived from them were suspended in the river, and if the river

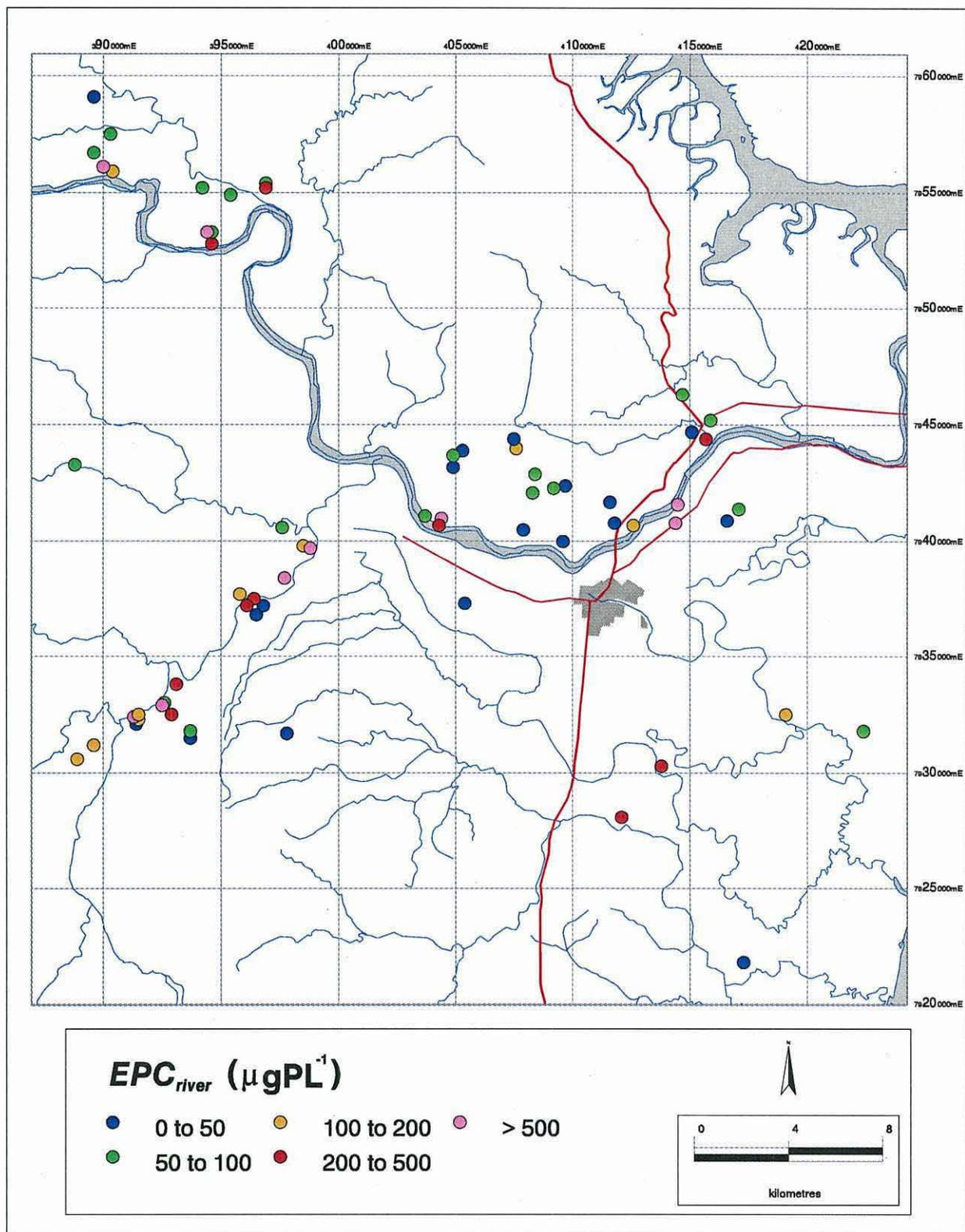


Figure 10 Map of lower Herbert catchment showing the EPC_{river} classes of the soils sampled.

water P concentration was $50 \mu\text{g L}^{-1}$. This grouping of soils can be taken to indicate their P “desorption risk”. The samples were allocated to 5 classes of “P desorption risk” on the basis of the amount of P desorbed at $50 \mu\text{g P L}^{-1}$:

1. Minimal: no desorption at $50 \mu\text{g L}^{-1}$
2. Small: desorption at $50 \mu\text{g L}^{-1}$ between 0 and $5 \mu\text{g P g}^{-1}$
3. Moderate: desorption at $50 \mu\text{g L}^{-1}$ between 5 and $10 \mu\text{g P g}^{-1}$
4. Moderately large: desorption at $50 \mu\text{g L}^{-1}$ between 10 and $50 \mu\text{g P g}^{-1}$
5. Large: desorption at $50 \mu\text{g L}^{-1} > 50 \mu\text{g P g}^{-1}$

Using either equation 7 or 8 together with the linearised version of equation 2 (Figure 9), the calculated values of ΔP at $50 \mu\text{g P L}^{-1}$ for the samples used for sediment studies were generally close to the observed value (Table 3). All 73 soils sampled were then allocated to classes of “P desorption risk”. The location of samples and their risk class are shown in Figure 11. When considered together with a knowledge of the soils of the district, Figure 11 indicates that with the exception of the heavier clays, the majority of lower Herbert soils have a desorption risk of class 3 or greater.

Table 3 Observed and calculated amounts of desorption at $50 \mu\text{g P L}^{-1}$ in simulated river water. Negative values indicate sorption; that is, the sediment would act as a sink for P.

| Sample | P desorption @ $50 \mu\text{g P L}^{-1}$ ($\mu\text{g P g}^{-1}$) | | |
|--------|---|----------------------|----------------------|
| | Observed | Calculated from eq 7 | Calculated from eq 8 |
| S17 | 5.0 | 5.5 | 5.4 |
| S19 | 3.0 | 2.5 | 2.0 |
| S20 | 8.0 | 9.0 | 10.0 |
| S21 | -5.0 | -10.0 | -10.0 |
| S22 | -2.0 | -4.0 | -3.0 |
| S42 | 13.5 | 12.5 | 13.0 |
| S46 | 6.0 | 6.0 | 5.0 |
| S71 | 7.0 | 8.0 | 8.5 |
| S73 | -5.0 | 0.5 | 0 |
| S74 | -4.0 | -3.0 | -3.0 |
| S76 | ~35.0 | 32.5 | 32.5 |

It is not appropriate to estimate EPC values using this approach, as the EPC may occur at concentrations above $80 \mu\text{g P L}^{-1}$ and the assumption of linearity between sorption and solution concentration becomes dubious. The correlation between EPC_{river} and EPC_{soil} is likely to give a more reliable estimate of the EPC (equation 6).

5.2.3 K_{river} and soil type

In the absence of an estimate of the initially adsorbed P, no estimate of the mass of P that would be desorbed at $50 \mu\text{g L}^{-1}$ can be made. However, because commonly measured soil properties were good predictors of K_{river} , average values of K_{river} can be estimated for clusters of soil types. Using the data for the samples studied here, K_{river} was estimated for soils clustered on the basis of chemical properties (Table 4) using equation 8.

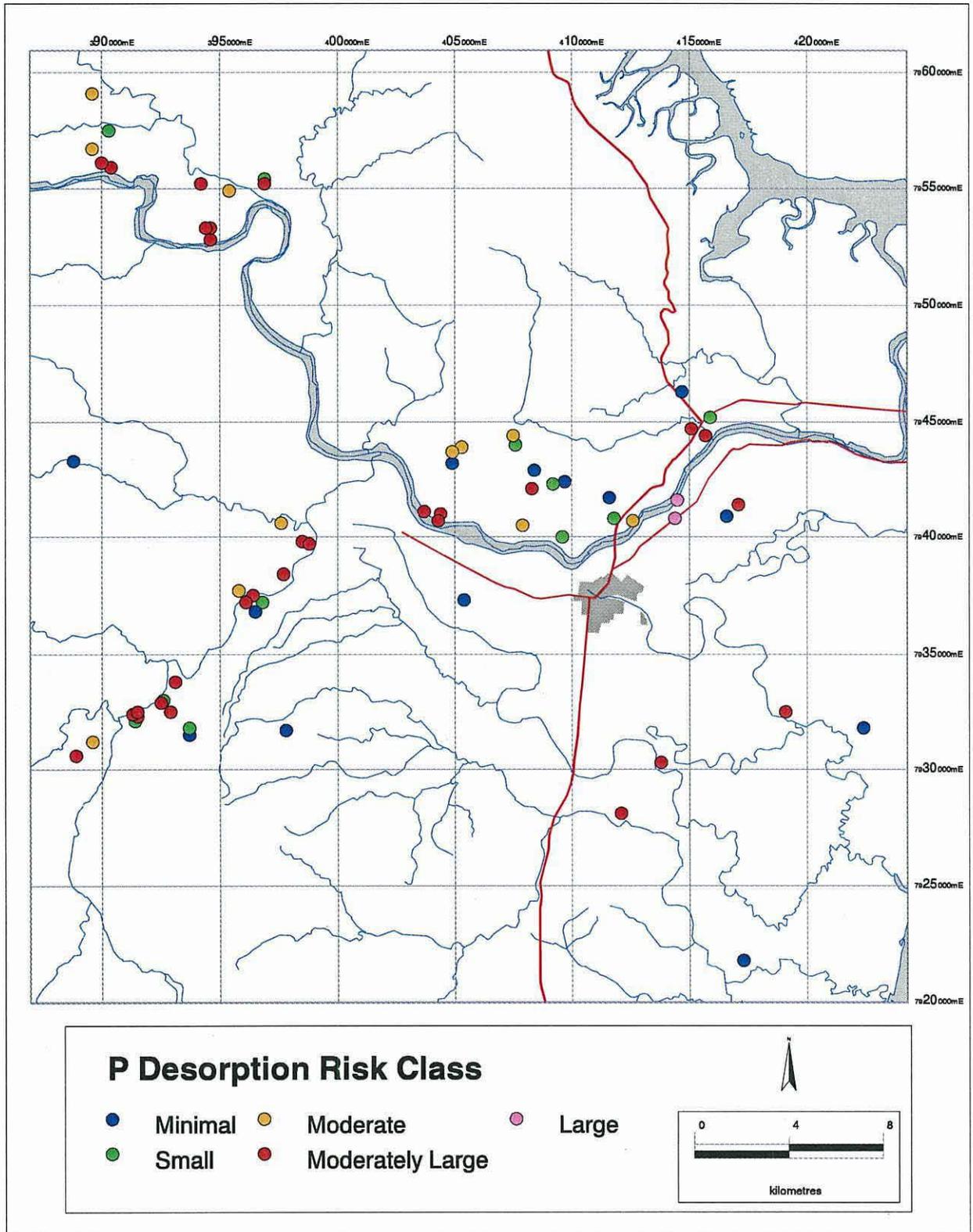


Figure 11 Map of lower Herbert catchment showing the “desorption risk” classes of the soils sampled.

Table 4. K_{river} of soils clustered on the basis of chemical data, using 61 samples. Cluster 1 is dominated by clays, cluster 2 by silts, cluster 4 by sands and cluster 3 by “loams” - which are presumably well-mixed.

| | Cluster 1 | Cluster 2 | Cluster 3 | Cluster 4 |
|---|-----------|-----------|-----------|-----------|
| K_{river} average (L kg ⁻¹) | 317 | 243 | 181 | 130 |
| Standard error of mean | 24.4 | 12.6 | 13.6 | 11.8 |
| Number of samples | 11 | 19 | 16 | 15 |

The average value of K_{river} of each cluster was significantly different to the average value of the other clusters ($p < 0.05$), in the order cluster 1 > cluster 2 > cluster 3 > cluster 4. Using values available from the database associated with the CSR soil survey for topsoil organic carbon, pH, clay and silt, K_{river} was estimated for a larger suite of soils using equation 8 and average values calculated for soils clustered on the basis of chemical properties (Table 5).

Table 5. K_{river} of soils clusters on the basis of chemical data, using 633 samples. Cluster 1 is dominated by clays, cluster 2 by silts, cluster 4 by sands and cluster 3 by “loams” - which are presumably well-mixed.

| | Cluster 1 | Cluster 2 | Cluster 3 | Cluster 4 |
|---|-----------|-----------|-----------|-----------|
| K_{river} average (L kg ⁻¹) | 186 | 139 | 131 | 92 |
| Standard error of mean | 7.8 | 3.8 | 4.1 | 4.0 |
| Number of samples | 80 | 202 | 157 | 199 |

For this larger suite of samples, the order of the values of K_{river} were ($p < 0.05$) cluster 1 > cluster 2 = cluster 3 > cluster 4. Since the results of this analysis are similar when either the 61 soils studied here, or 633 soils from the CSR survey database are used, it seems reasonable to map K_{river} on the basis of soil type. The practical implication of a soil having a low value of K_{river} is that greater desorption of P can be expected from suspended sediments derived from that soil, for the same amount of initially held P. Consequently, soils with low K_{river} values (predominantly the sandier soils of cluster 4), and which are at risk from erosion (see below), require special care with respect to P fertilizer management. Note however, that in general, sandy soils are often less subject to erosion than finer textured soils.

5.2.4 Effect of ionic strength on P adsorption-desorption

There was much less desorption in the simulated estuary water than in the river water (Figure 9) for all samples. A strong correlation was found between the estimated EPC_{soil} , and the EPC measured in the simulated estuary water ($EPC_{estuary}$), which is consistent with the observation that the measured data points for P sorption/desorption by sediments in simulated estuarine water matched the curves obtained when equation 2 was fitted to data obtained for soils suspended in 0.01 M CaCl₂ (section 2; Figure 9).

$$EPC_{estuary} = 1.97 EPC_{soil} + 1.8$$

$$r^2 \text{ (adj)} = 0.96$$

When this regression was applied to the whole suite of soils sampled, most samples were calculated to have $EPC_{estuary}$ values less than $25 \mu\text{g L}^{-1}$. Four classes of $EPC_{estuary}$ were selected:

- $EPC_{estuary}$ class 1: $0-25 \mu\text{g L}^{-1}$
- $EPC_{estuary}$ class 2: $25-50 \mu\text{g L}^{-1}$
- $EPC_{estuary}$ class 3: $50-100 \mu\text{g L}^{-1}$
- $EPC_{estuary}$ class 4: $> 100 \mu\text{g L}^{-1}$

The locations of samples belonging to each class are shown in Figure 12; note that only 9 samples fall into class 3 or 4.

Data points for sorption/desorption were only obtained for a very narrow range of solution concentrations in the simulated estuary water. This was because the AER was a poor scavenger of P in the high ionic strength solution. Therefore, no useful estimates of ΔP can be made for solution concentrations below the EPC concentration of the soil. However, the very low values of $EPC_{estuary}$ compared to EPC_{river} , suggest that desorption of P from suspended sediments derived from lower Herbert soils is likely to occur principally in the fresh water zone. Once the sediment reaches more saline zones, little further desorption is likely to occur, and some sediments can be expected to act as sinks for P in these saline waters. This is an important finding, especially given the strong relationship between P sorption, in both soils and the sediments derived from them, and oxalate-extractable Al, and the absence of a relationship between P sorption and extractable Fe.

The reason that this finding is considered important is that P is generally expected to be released from sediments upon settling, because the settling process tends to be associated with the occurrence of anoxic conditions (eg. House *et al.*, 1998). These in turn induce reduction of iron-oxide minerals which are often thought to dominate P sorption/desorption reactions. However, the fact that our results indicate that Fe minerals are relatively unimportant in controlling P sorption behaviour in Herbert soils and the sediments derived from them, also suggests that anoxia may not promote P desorption. Since we have also demonstrated that P in suspended Herbert sediments is more strongly held in the estuarine, compared to the freshwater zone, we conclude that any environmental threat posed by P loss associated with soil erosion and sediment loss in agricultural run-off, is likely to be more significant in freshwater, as opposed to marine ecosystems. Given the proximity of the Great Barrier Reef to the Herbert cane growing area, this conclusion may have important implications for environmental managers.

5.3 Conclusions

Phosphorus sorption behaviour in sediments was found to be broadly similar to that in the soils from which they were derived, to the extent that P behaviour in simulated riverine and estuarine conditions could be predicted on the basis of P behaviour in soils. At least for the Herbert soils studied here, it was apparent that P is much more strongly held in simulated marine conditions than in simulated river waters. This, together with the relative unimportance of iron minerals in controlling P sorption behaviour in these soils/sediments, suggests that any environmental threat posed by the off-site export of P attached to sediments lost from agricultural land in surface run-off is likely to be greatest in the freshwater, compared to the marine ecosystem.

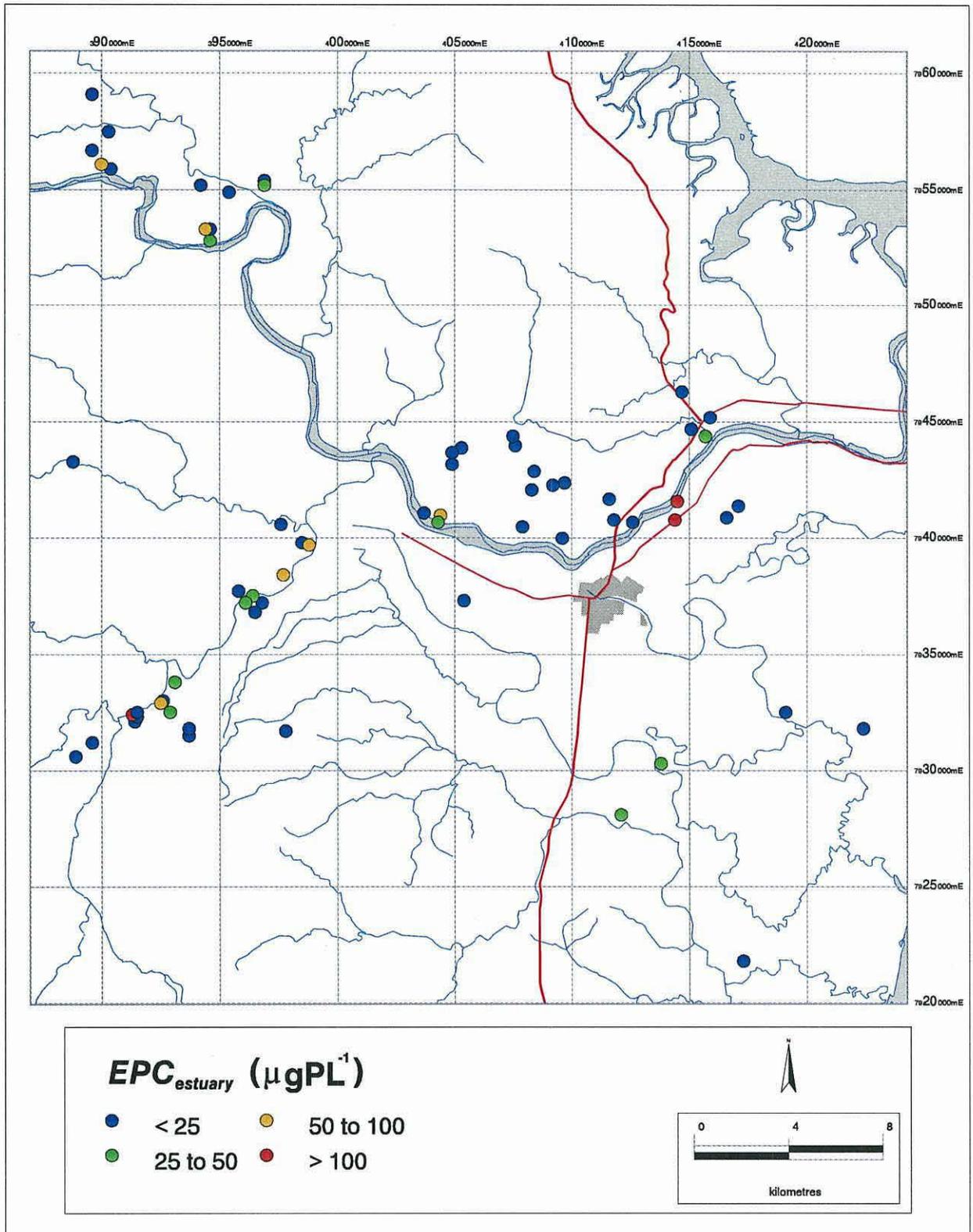


Figure 12 Map of the lower Herbert catchment showing the $EPC_{estuary}$ classes of the soils sampled.

6.0 Matching P desorption risk with the risk of soil erosion

The results obtained from the work discussed in sections 4 and 5 presumes that all soils in the lower Herbert, irrespective of their location, have an equal probability of being the source of suspended river sediments. This is unlikely to be the case for reasons which include:

- differences in the inherent erodibility of the soils;
- differences in the slopes on which different soils tend to occur; and
- differences in the distance between given sites characterised by particular soils and the Herbert River or its tributaries.

The extent to which P can be lost through sediment export not only depends on the amount of P sorbed to soil particles, but also the frequency and magnitude of runoff. Consequently, an assessment of the likelihood of runoff generation from soils in the Lower Herbert is an important step in evaluating the risk of P loss through sediment export. Such an assessment has been made for the lower Herbert by C.H Roth (CSIRO Land and Water, Townsville - pers. comm.) and is described in this section.

6.1 *Methods and materials*

A qualitative rating of Herbert soils was derived, based primarily on soil morphological data reported by Wilson and Baker (1990). The assessment of runoff generation was based on three basic criteria:

- Profile wetness - a combined index derived by rating the soil's intrinsic permeability and its drainage class;
- Annual rainfall; and
- Soil cover and texture - a surrogate for the degree of surface protection against crusting and water extraction.

The drainage class rating was taken directly from the ARCInfo soil coverage containing the original rating for each unique mapping area (UMA) of Wilson and Baker (1990). Three classes were identified:

- Very poorly to poorly drained - ie. alluvial flats with <1% slope and/or perched/shallow water tables (Class 1).
- Imperfectly to moderately drained and/or deep water tables (Class 2).
- Well drained to rapidly drained, ie. slope <5%, and/or moderately deep water tables (Class 3).

Permeability was also rated in three classes based on the profile morphological description. Uniform or gradational, sandy to loamy-sand soils were generally rated as highly permeable (class H = high; >50 cm d⁻¹), texture contrast soils, with no or few mottles and well structured B-horizons were rated as moderately permeable (class M = moderate; 5-50 cm d⁻¹), whilst texture contrast soils with the presence of mottles, concretions and a massive light to heavy clay were rated as slowly permeable (class L = low; <5cm d⁻¹).

Rainfall was arbitrarily assigned to three classes:

- <1500 mm y⁻¹
- 1500-2000 mm y⁻¹
- >2000 mm y⁻¹

Crusting susceptibility was assessed in two classes based on the texture classes assigned by Wilson and Baker (1990):

- High crusting susceptibility: soil bare and presence of a crust prone surface texture (LS, CS, SL, ZL, CLS, ZCL, L, SCL)^a;
- Low crusting susceptibility: soil covered (trash), or when unprotected, surface not crust prone (S, CL, IC, lmC, mC, mhC, hC).

Following the allocation of wetness and rainfall classes to each UMA, a rating matrix was established separately for each crusting class to assess the runoff generation hazard. Runoff generation hazard was rated in five classes:

- 0: no runoff
- 1: occasional runoff
- 2: moderately frequent runoff
- 3: frequent runoff
- 4: very frequent runoff

The rating matrices are presented in Tables 6 and 7.

Table 6. Rating matrix for runoff generation from protected soil, or when bare, with surface texture not crust prone

| Rainfall class | Drainage class 1 | | | Drainage class 2 | | | Drainage class 3 | | |
|------------------|------------------|---|---|------------------|---|---|------------------|---|---|
| | Permeability | | | Permeability | | | Permeability | | |
| | S | M | H | S | M | H | S | M | H |
| 1 <1500mm | 3 | 3 | 2 | 2 | 2 | 1 | 1 | 0 | 0 |
| 2 1500-2000mm | 3 | 3 | 3 | 2 | 2 | 2 | 2 | 1 | 1 |
| 3 >2000mm | 4 | 4 | 3 | 3 | 3 | 2 | 2 | 2 | 1 |

Table 7. Rating matrix for runoff generation from bare soil and crust prone surface texture.

| Rainfall class | Drainage class 1 | | | Drainage class 2 | | | Drainage class 3 | | |
|------------------|------------------|---|---|------------------|---|---|------------------|---|---|
| | Permeability | | | Permeability | | | Permeability | | |
| | S | M | H | S | M | H | S | M | H |
| 1 <1500mm | 3 | 3 | 2 | 2 | 2 | 2 | 2 | 1 | 1 |
| 2 1500-2000mm | 4 | 3 | 3 | 3 | 2 | 2 | 2 | 1 | 1 |
| 3 >2000mm | 4 | 4 | 3 | 3 | 3 | 2 | 3 | 2 | 2 |

^a S: sand; Z: silt; C: clay; L: loam; l: light; m: medium; lm: light to medium; h: heavy; mh: medium to heavy

To operationalise map production, an attribute table was generated in ARCInfo. The resulting maps are presented in Figure 13.

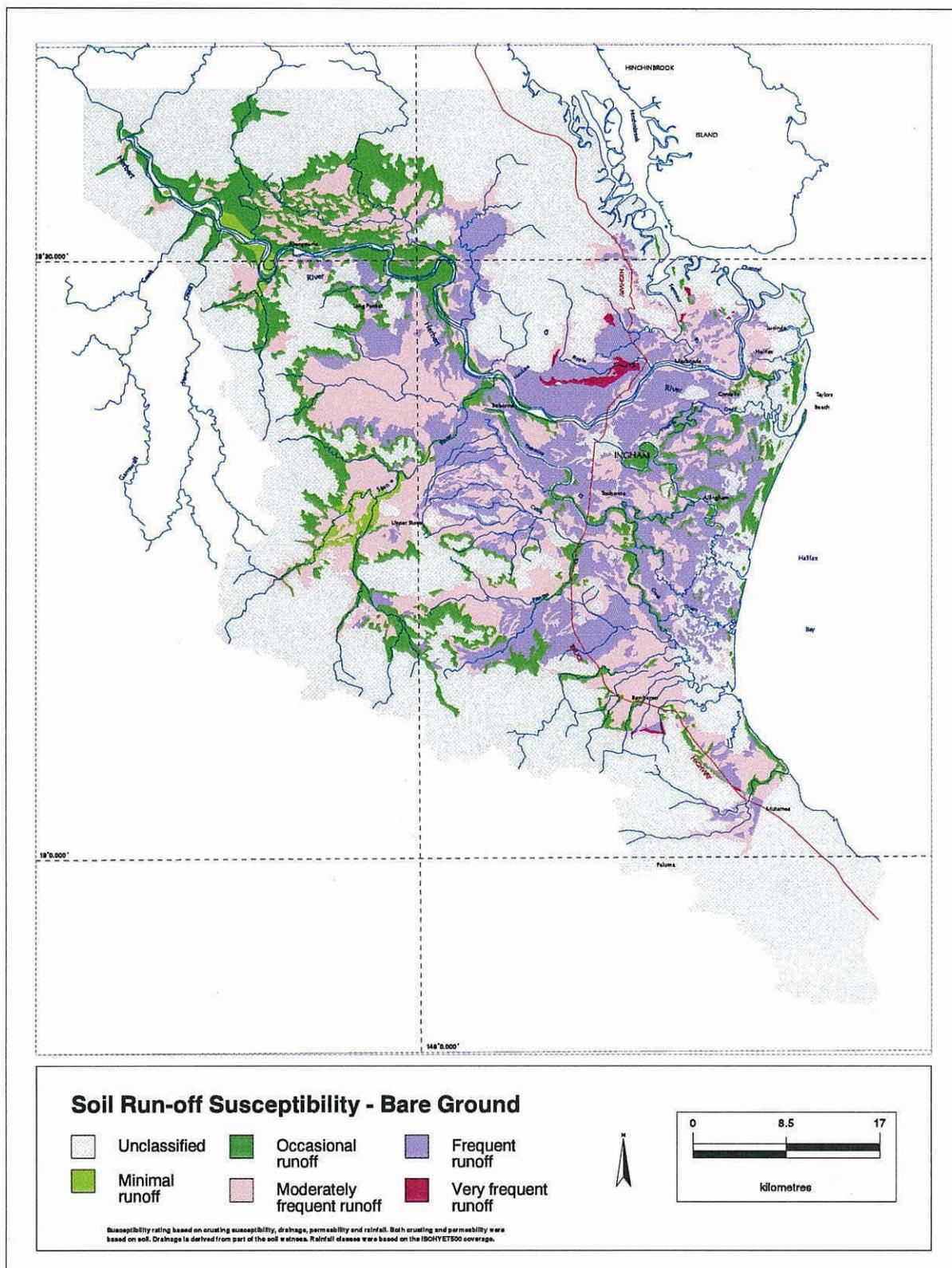


Figure 13a Run-off susceptibility assessment for the lower Herbert catchment for a bare ground scenario (C.H. Roth, CSIRO Land and Water, Townsville - pers. comm.).

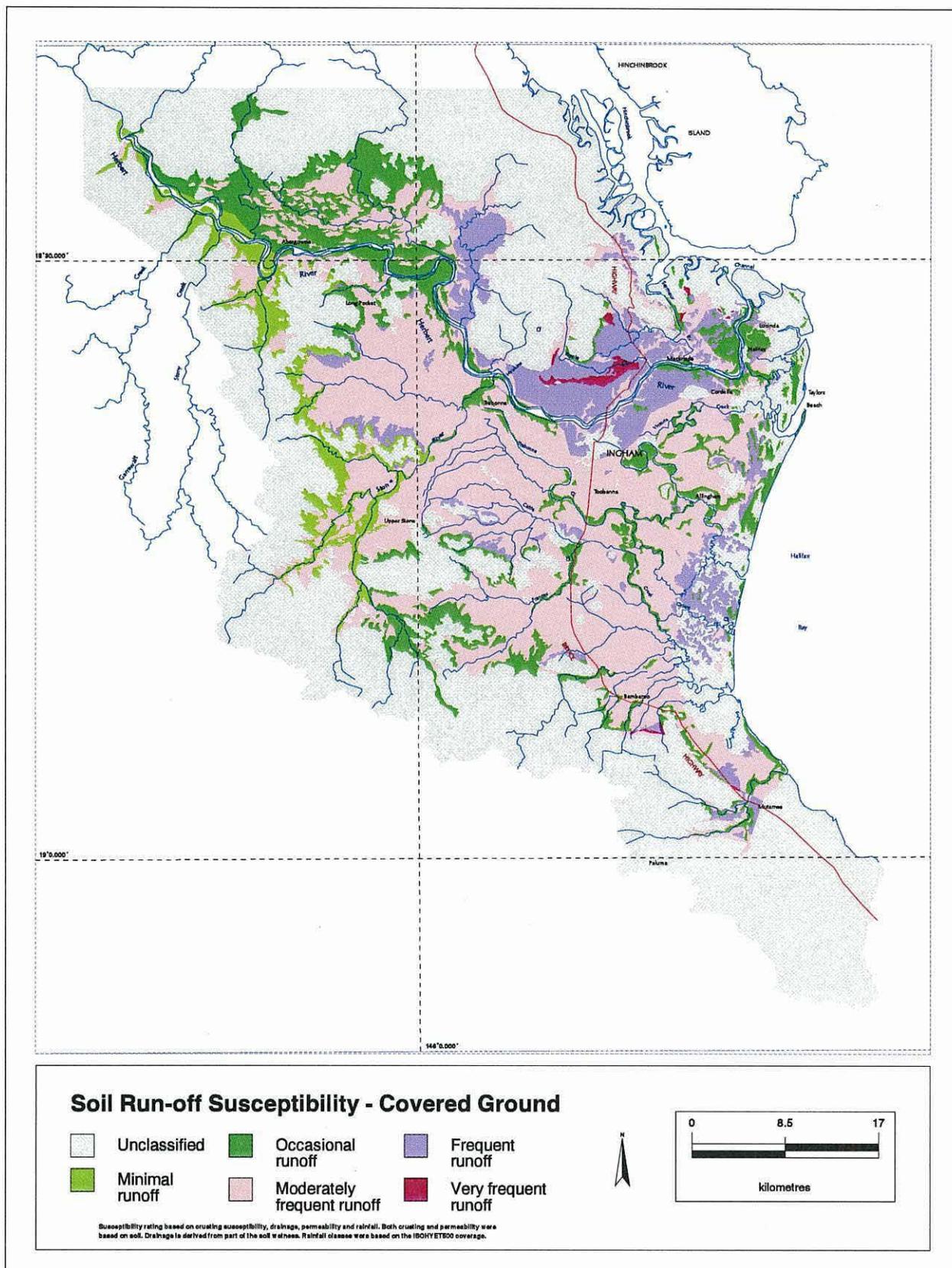


Figure 13b Run-off susceptibility assessment for the lower Herbert catchment for a covered ground scenario (C.H. Roth, CSIRO Land and Water, Townsville - pers. comm.).

6.2 Results and discussion

In general, the highest likelihood of runoff generation is expected to the north of the Herbert River in the Ripple Creek catchment, due to the considerably higher rainfall and generally poorly drained, low permeability soils. Conversely, some of the lower runoff incidence is to be expected on the well-drained levee.

Using GIS, it is possible to overlay the information presented in Figures 10-12 with that presented in Figure 13 with a view to identifying those soils which, where present in particular locations, pose the greatest threat in terms of being sources of riverine P, and which are therefore most deserving of improved management of P fertilizers. The results of such an analysis are presented in Figures 14-16 in which we have considered the worst case scenario of bare ground. It is unfortunate that digitising of the CSR soil survey is not yet sufficiently complete for the results of this study to be overlain with spatially arranged soils information, and it is to be hoped that SRDC will feel able to support a small project to complete the spatial analysis inferred in this discussion. Nevertheless, Figures 14-16, coupled with a knowledge of typical Herbert River P concentrations (eg Figure 2) indicate that the soils most deserving of careful/modified P fertilizer management aimed at minimizing the potential for environmental degradation downstream, are those in the lower part of the Stone River catchment and the clayey soils draining into creeks which in turn drain into the Herbert downstream of the mouth of the Stone River, especially those on the northern bank which tend to be more susceptible to the occurrence of run off. Since the values for $EPC_{estuary}$ suggest a much greater threat to the freshwater, compared to the estuarine or marine environments, the results also suggest that any water quality monitoring aimed at identifying environmental degradation of the waterway arising from P transfer off-farm, should be focussed in that stretch of the Herbert between the mouth of the Stone and the tidal zone. Drains and creeks, such as the Ripple Creek system, draining caneland on clayey soils also warrant attention. These would also most sensibly be the focus of any studies aimed at quantifying any downstream ecotoxicological impact (GE Rayment and RGV Bramley, CRC for Sustainable Sugar Production - pers. comm.) of sugarcane production.

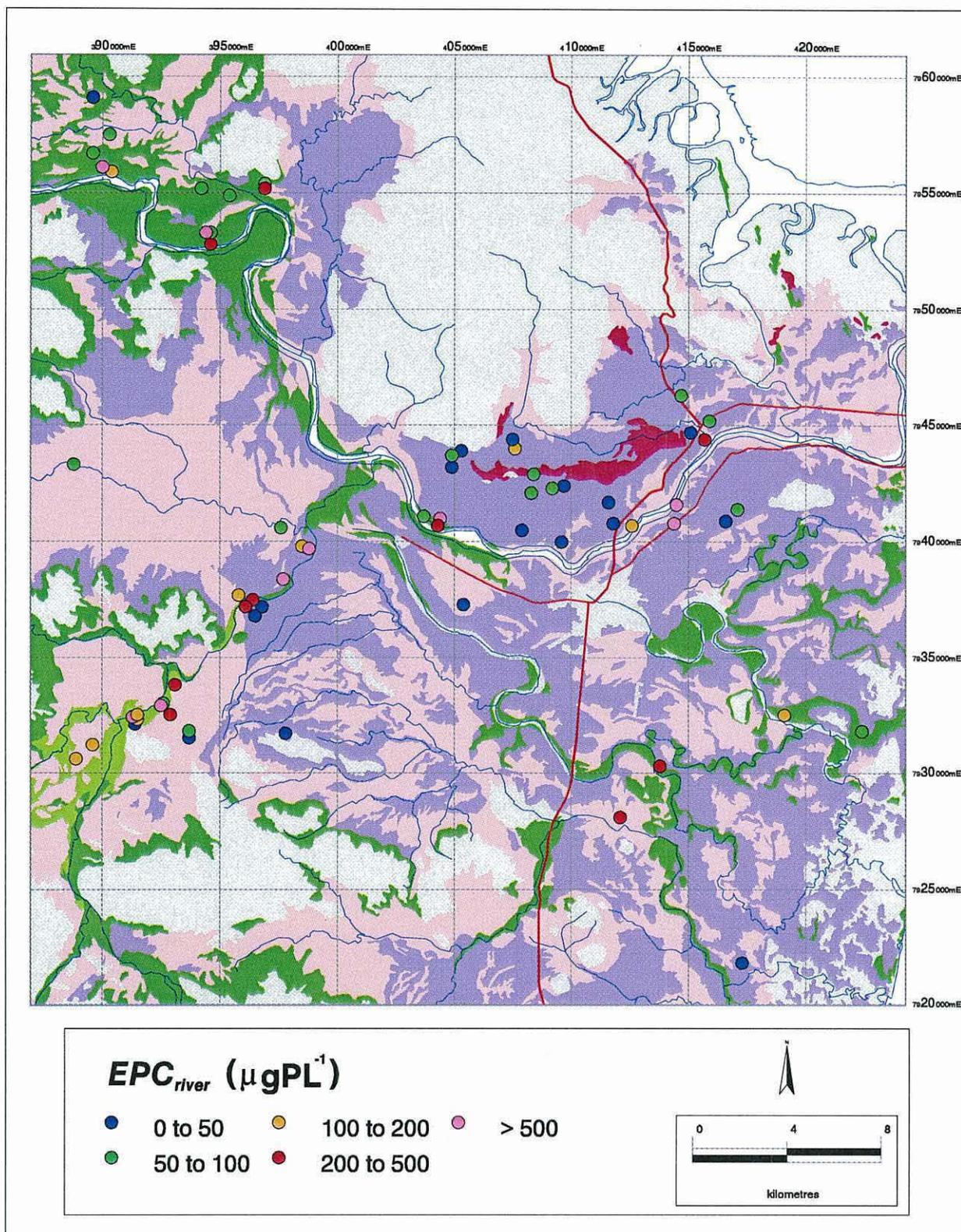


Figure 14. EPC_{river} classes (figure 10) and bare ground runoff susceptibility (figure 13b) for lower Herbert soils. Runoff susceptibility is indicated by the background colour, the legend for which is given in figure 13b.

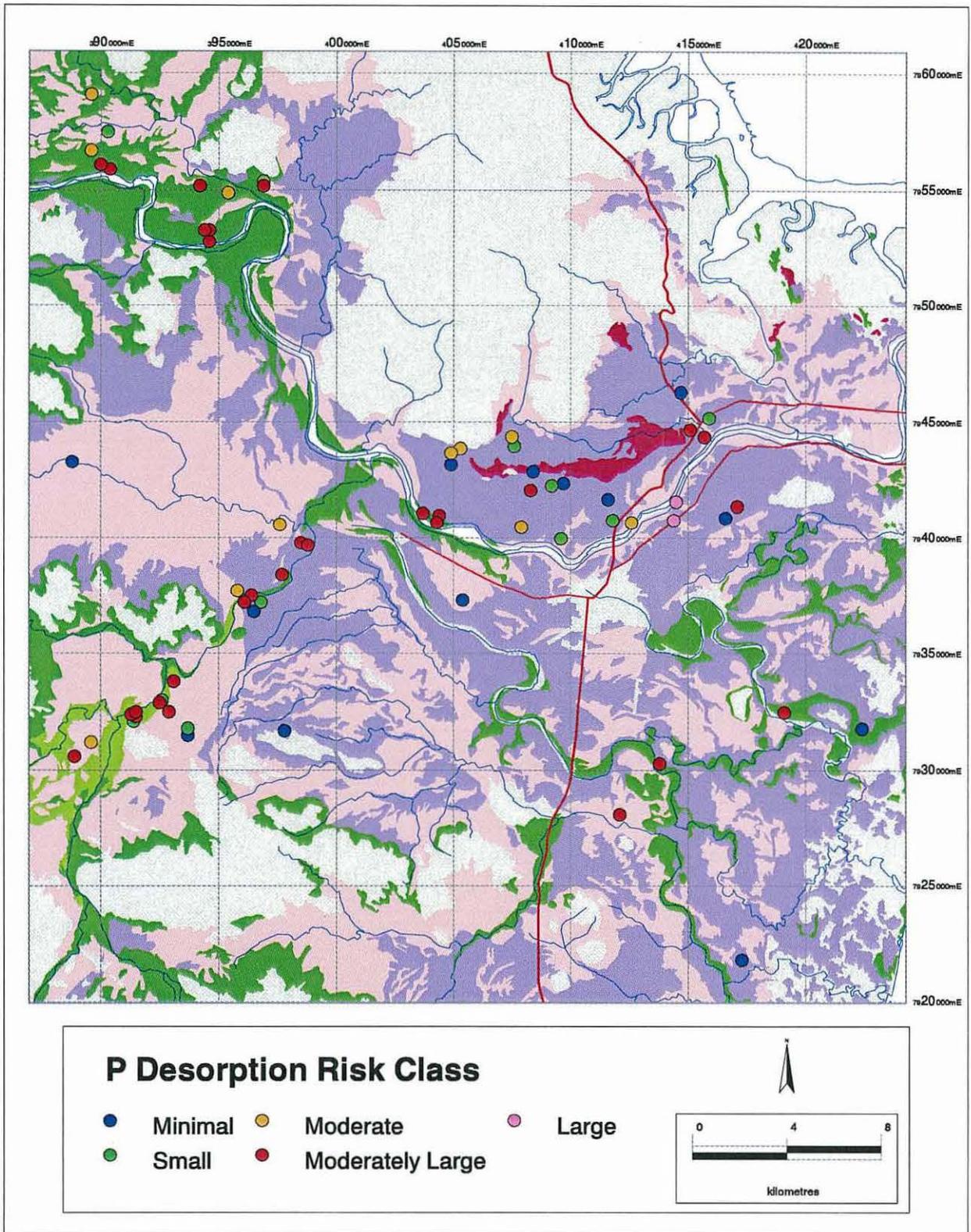


Figure 15. P desorption risk class (figure 11) and bare ground runoff susceptibility (figure 13b) for lower Herbert soils. Runoff susceptibility is indicated by the background colour, the legend for which is given in figure 13b.

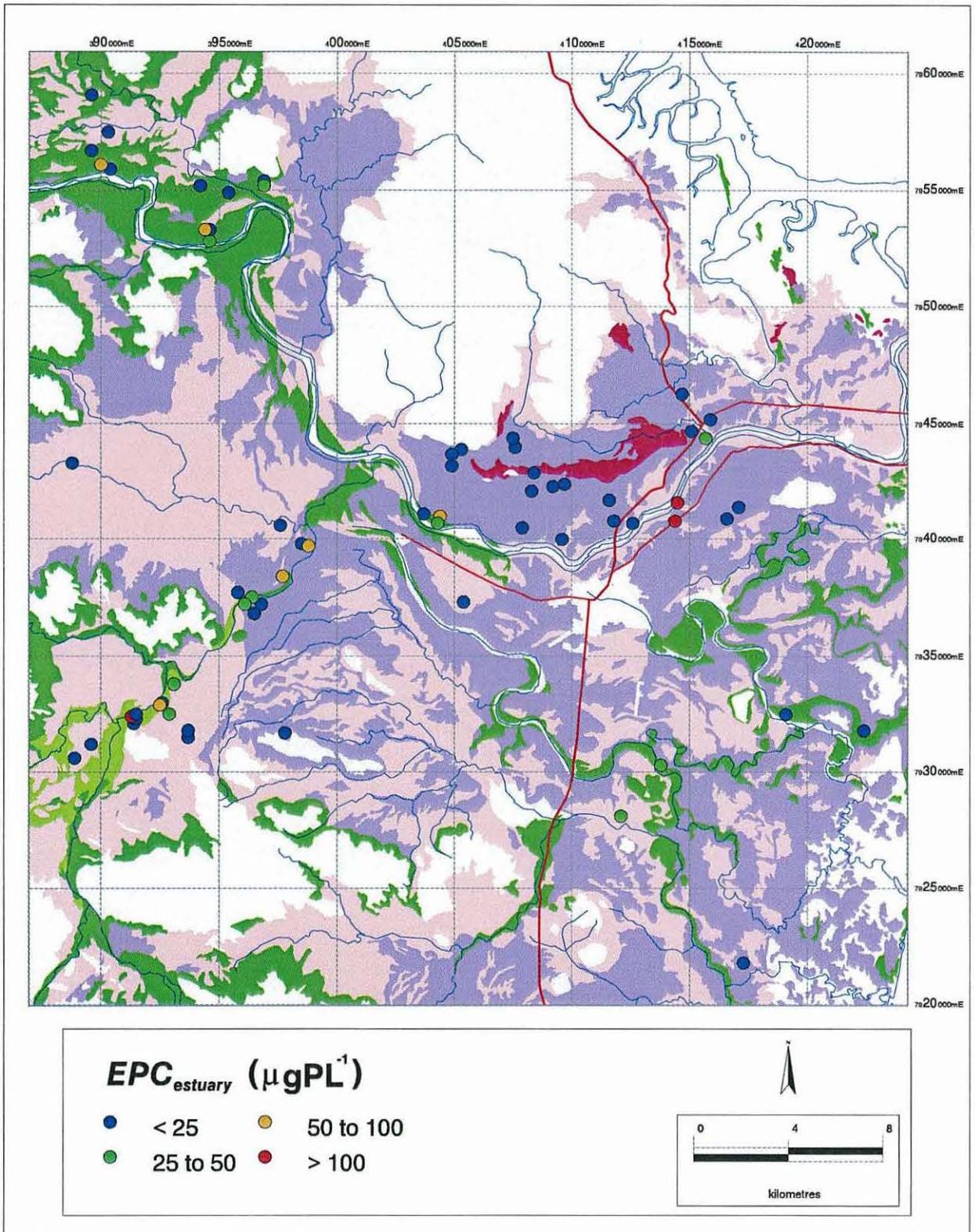


Figure 16. $EPC_{estuary}$ (figure 12) and bare ground runoff susceptibility (figure 13b) for lower Herbert soils. Runoff susceptibility is indicated by the background colour, the legend for which is given in figure 13b.

7.0 Conclusions and future research needs

The results of the study of P behaviour in Herbert soils suggest that there is scope for refining the management of P fertilizer in the sugar industry based on a knowledge of particular soil properties and the behaviour of P in specific soils. In particular, the results suggest that:

- in refining P fertilizer management, both for more efficient crop production and improved environmental stewardship, the utility of oxalate-extractable aluminium (Al_{ox}) as a predictor of P fertilizer requirement should be investigated; and
- clustering soils of similar physico-chemical properties is useful as a basis for identifying soils of similar potential P reaction so that, when coupled with a knowledge of existing P status, they may also form a basis for delivery of improved fertilizer advice. A large database already exists and this could be used to map areas requiring similar management.

Further research is warranted on both of these issues with a view to the development of more soil specific guidelines than those currently in place (Calcino, 1992). Such guidelines would be the basis of best-practice P fertilizer management in the sugar industry.

In the laboratory study of the potential for P release from suspended sediments into riverine and estuarine waters, it was found that a good correlation exists between the equilibrium phosphate concentration (EPC) - the P concentration at which neither sorption nor desorption occurs - when measured in soils, and the EPC when determined for suspended sediment in simulated river waters. This correlation, together with the close relationship between P sorption in soils and selected soil properties, enabled estimation of P desorption from suspended sediments on the basis of the properties of the soils from which the sediments were derived. Thus, classes of "P desorption risk" were derived and the soils assigned to a desorption risk class. Using the same criteria, and data available from the 1:5,000 CSR survey of Herbert sugarcane soils (data from over 400 soil profiles), it was possible to assign the mapped soils of the lower Herbert to a P desorption risk class. Soils that are subject to intense surface runoff and erosion require particular care with respect to P management; the early part of the study identified that differences in the P fertilizer requirement of cane grown on sandy soils is likely to be relatively low compared to that on clays. Further research aimed at assessing soil erosion risk, as opposed to runoff risk, would promote a more precise identification of those soils for which particular care is warranted with respect to P fertilizer management.

The current absence of Herbert soils data in digital format, together with the fact that the CSR survey remains incomplete, means that it is not currently possible to produce a definitive map of P desorption risk for the lower Herbert, nor to overlay this with a spatial representation of key soil properties, such as Al_{ox} , that might be valuable in providing a basis for the improved delivery of fertilizer advice. It would therefore be desirable for a subsequent project to be carried out with a view to producing the maps that extension staff could use in assisting growers to refine their P management - from both a crop production and environmental sustainability perspective.

The laboratory study of sediment-P interactions in simulated riverine and estuarine waters identified that desorption of P is much less in high salt (ie estuarine) waters compared to low salt (ie river) freshwaters - a finding which suggests that any environmental degradation arising from the downstream export of fertilizer-derived P from Herbert canelands is likely to be concentrated in freshwater areas and not in the marine/estuarine environment. This finding is likely to be generally applicable up and down the Queensland coast, although the sugar industry would be better able to respond to suggestions that its P fertilizer management was impacting on the marine environment if data were available for riverine and estuarine waters in other catchments. Again, appropriate research is warranted.

The finding that soil P chemistry in lower Herbert soils appears to be closely associated with aluminium oxide, as opposed to iron oxide-dominated minerals, is significant because it suggests that the induction of anoxic conditions in sediment porewaters following settling out of the sediment may not promote P desorption from Herbert sediments on deposition. However, this may not be the case in the wet tropics areas dominated by Ferrosols (Innisfail, Mareeba) and additional work in appropriate catchments is certainly warranted, as is some more detailed work on the effects of redox on Fe- and Al-P mineral complexes which would corroborate our conclusions.

As indicated, further work on a more robust estimation of the risk of soil erosion (as opposed to surface runoff risk) would be desirable. In the meantime, the present results suggest that, any environmental and/or water quality monitoring targeted at possible environmental consequences of P fertilizer use in the lower Herbert would be best targeted downstream of the mouth of the Stone River and in creeks and drains which drain clayey soils under cane, especially those in the Ripple Creek/Hawkins Creek region which are most subject to runoff.

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Appendix 1. Soil sampling locations

| Site ID | Subcatchment | Map name | Map sheet | Grid reference | Cover | Soil type CSR Survey |
|---------|--------------|----------------|-----------|----------------|------------|-------------------------|
| S1 | Stone | WALLAMAN FALLS | 8060 1 | CV937315 | ratoon | coarse sandy loam |
| S2 | Stone | WALLAMAN FALLS | 8060 1 | CV937318 | ratoon | coarse sandy loam |
| S3 | Stone | WALLAMAN FALLS | 8060 1 | CV929325 | plant | terrace silt |
| S4 | Stone | WALLAMAN FALLS | 8060 1 | CV926330 | ratoon | red loam |
| S5 | Stone | WALLAMAN FALLS | 8060 1 | CV925329 | ratoon | red loam |
| S6 | Stone | INGHAM | 8160 IV | CV968372 | ratoon | silty clay |
| S7 | Stone | INGHAM | 8160 IV | CV965368 | ratoon | terrace silt |
| S8 | Stone | INGHAM | 8160 IV | CV964375 | plant | river bank |
| S9 | Stone | INGHAM | 8160 IV | CV961372 | ratoon | river bank |
| S10 | Stone | INGHAM | 8160 IV | CV977384 | ratoon | silty clay |
| S11 | Stone | INGHAM | 8160 IV | CV985398 | ratoon | silty clay |
| S12 | Stone | WALLAMAN FALLS | 8060 1 | CV914321 | ratoon | red loam |
| S13 | Stone | WALLAMAN FALLS | 8060 1 | CV915323 | ratoon | red loam |
| S14 | Stone | WALLAMAN FALLS | 8060 1 | CV913324 | fallow | river bank |
| S15 | Stone | WALLAMAN FALLS | 8060 1 | CV915325 | ratoon | riverbank |
| S16 | Stone | WALLAMAN FALLS | 8060 1 | CV889306 | ratoon | silty clay |
| S17* | Stone | WALLAMAN FALLS | 8060 1 | CV896312 | ratoon | coarse sandy loam |
| S18 | Ripple creek | INGHAM | 8160 IV | DV147463 | ratoon | clay loam |
| S19* | Ripple creek | INGHAM | 8160 IV | DV159452 | plant | terrace silt |
| S20* | Ripple creek | INGHAM | 8160 IV | DV126407 | ratoon | riverbank |
| S21* | Ripple creek | INGHAM | 8160 IV | DV097424 | ratoon | clay |
| S22* | Ripple creek | INGHAM | 8160 IV | DV049432 | ratoon | silty clay |
| S23 | floodplain | INGHAM | 8160 IV | DV121281 | pasture | |
| S24 | floodplain | MOUNT SPEC | 8160 III | DV173218 | pasture | |
| S25 | floodplain | INGHAM | 8160 IV | DV138303 | ratoon | |
| S26 | Abergowrie | MOUNT GRAHAM | 8061 2 | CV904559 | rainforest | |
| S27 | Abergowrie | MOUNT GRAHAM | 8061 2 | CV900561 | ratoon | river overflow |
| S28 | Abergowrie | MOUNT GRAHAM | 8061 2 | CV896567 | ratoon | red loam |
| S29 | Abergowrie | MOUNT GRAHAM | 8061 2 | CV903575 | ratoon | silty clay |
| S30 | Abergowrie | MOUNT GRAHAM | 8061 2 | CV896591 | ratoon | coarse sandy loam |
| S31 | Abergowrie | INGHAM | 8160 IV | CV946528 | ratoon | riverbank |
| S32 | Abergowrie | INGHAM | 8160 IV | CV946533 | ratoon | river overflow |
| S33 | Stone | INGHAM | 8160 IV | CV976406 | ratoon | heavy clay |
| S34 | Stone | INGHAM | 8160 IV | CV988397 | ratoon | riverbank |
| S35 | Abergowrie | MOUNT GRAHAM | 8061 2 | CV942552 | ratoon | red loam |
| S36 | Abergowrie | CARDWELL | 8161 3 | CV954549 | ratoon | fine sandy loam |

Appendix 1. (contd) Soil sampling locations

| Site ID | Subcatchment | Map name | Map sheet | Grid reference | Cover | Soil type CSR Survey |
|---------|--------------|----------------|-----------|----------------|---------|-------------------------|
| S37 | Abergowrie | CARDWELL | 8161 3 | CV969554 | ratoon | red sand |
| S38 | Floodplain | INGHAM | 8160 IV | DV144408 | plant | terrace silt |
| S39 | Floodplain | INGHAM | 8160 IV | DV145416 | ratoon | riverbank |
| S40 | Floodplain | INGHAM | 8160 IV | DV166409 | ratoon | silty clay |
| S41 | Floodplain | INGHAM | 8160 IV | DV171414 | ratoon | clay |
| S42* | Ripple creek | INGHAM | 8160 IV | DV044410 | ratoon | river sand |
| S43 | Ripple creek | INGHAM | 8160 IV | DV043407 | ratoon | terrace silt |
| S44 | Ripple creek | INGHAM | 8160 IV | DV037411 | ratoon | red loam |
| S45 | Ripple creek | INGHAM | 8160 IV | DV053439 | ratoon | red sand |
| S46* | Ripple creek | INGHAM | 8160 IV | DV049437 | ratoon | grey sand |
| S47 | Floodplain | LUCINDA | 8160 I | DV224318 | pasture | terrace silt |
| S48 | Floodplain | INGHAM | 8160 IV | DV191325 | plant | terrace silt |
| S49 | Stone | INGHAM | 8160 IV | DV054373 | ratoon | heavy clay |
| S50 | Stone | INGHAM | 8160 IV | CV958377 | ratoon | sandy clay |
| S51 | Stone | WALLAMAN FALLS | 8060 1 | CV888433 | pasture | |
| S52 | Stone | INGHAM | 8160 IV | CV978317 | plant | |
| S53 | Stone | WALLAMAN FALLS | 8060 1 | CV931338 | ratoon | river bank |
| S54 | Abergowrie | CARDWELL | 8161 3 | CV969552 | ratoon | grey sand |
| S55 | Abergowrie | WALLAMAN FALLS | 8060 1 | CV944533 | plant | river overflow |
| S56 | Upper | Ravenshoe | | CA268141 | upper | |
| S57 | Upper | Ravenshoe | | CA180362 | upper | |
| S58 | Upper | Ravenshoe | | CA178367 | upper | |
| S59 | Upper | Ravenshoe | | CA155409 | upper | |
| S60 | Upper | Ravenshoe | | CA135399 | upper | |
| S65 | Upper | Ravenshoe | | CA026305 | ratoon | |
| S66 | Ripple creek | INGHAM | 8160 IV | DV076440 | ratoon | fine grey sand |
| S67 | Ripple creek | INGHAM | 8160 IV | DV075444 | ratoon | red sand |
| S68 | Ripple creek | INGHAM | 8160 IV | DV084429 | ratoon | clay |
| S69 | Ripple creek | INGHAM | 8160 IV | DV083421 | ratoon | clay |
| S70 | Ripple creek | INGHAM | 8160 IV | DV092423 | ratoon | clay |
| S71* | Ripple creek | INGHAM | 8160 IV | DV079405 | ratoon | silty clay |
| S72 | Ripple creek | INGHAM | 8160 IV | DV096400 | ratoon | terrace silt |
| S73* | Ripple creek | INGHAM | 8160 IV | DV118408 | ratoon | clay |
| S74* | Ripple creek | INGHAM | 8160 IV | DV116417 | ratoon | sandy clay |
| S75 | Ripple creek | INGHAM | 8160 IV | DV151447 | ratoon | clay loam |
| S76* | Ripple creek | INGHAM | 8160 IV | DV157444 | ratoon | silty loam |

*samples used for desorption in simulated river water

Appendix 2. Selected properties of the soils sampled at the 76 sites

| Site ID | Particle size | | org C % | pH | Oxalate extractable | | Dithionate extractable | | Pyrophosphate extractable | | Total P | Resin P | K_{soil} ($b=0.34$) L/kg |
|---------|---------------|-----------|------------|------|---------------------|------|------------------------|------|---------------------------|------|---------|---------|------------------------------------|
| | clay % | silt % | | | Fe | Al | Fe | Al | Fe | Al | | | |
| S1 | 7.5 | 13 | 0.44 | 4.63 | 0.30 | 0.04 | 0.42 | 0.06 | 0.07 | 0.11 | 84 | 3.5 | 34.2 |
| S2 | 6 | 6 | 0.20 | 4.66 | 0.29 | 0.06 | 0.33 | 0.06 | 0.01 | 0.05 | 51 | 3.9 | 40.3 |
| S3 | 11 | 21.5 | 0.88 | 4.02 | 0.38 | 0.07 | 0.50 | 0.08 | 0.17 | 0.17 | 302 | 25.1 | 82.3 |
| S4 | 9 | 14.5 | 0.48 | 4.03 | 0.62 | 0.09 | 0.66 | 0.09 | 0.10 | 0.09 | 161 | 8.8 | 69.7 |
| S5 | 9 | 10.5 | 0.44 | 3.73 | 0.39 | 0.09 | 0.48 | 0.09 | 0.09 | 0.14 | 191 | 22.8 | 62.4 |
| S6 | 25.5 | 30.5 | 0.92 | 4.75 | 0.69 | 0.16 | 1.01 | 0.12 | 0.31 | 0.40 | 255 | 9.4 | 112.0 |
| S7 | 21 | 31.5 | 0.72 | 3.87 | 0.63 | 0.11 | 0.84 | 0.10 | 0.34 | 0.47 | 243 | 11.1 | 165.0 |
| S8 | 15.5 | 18 | 1.23 | 4.11 | 0.47 | 0.17 | 0.76 | 0.16 | 0.25 | 0.28 | 477 | 27.8 | 116.0 |
| S9 | 10 | 11.5 | 0.97 | 3.95 | 0.36 | 0.14 | 0.52 | 0.13 | 0.13 | 0.18 | 385 | 38.6 | 127.0 |
| S10 | 14.5 | 26.5 | 1.33 | 4.86 | 0.56 | 0.08 | 0.71 | 0.08 | 0.24 | 0.19 | 333 | 43.7 | 119.0 |
| S11 | 12.5 | 16.5 | 0.61 | 3.88 | 0.48 | 0.10 | 0.62 | 0.10 | 0.22 | 0.21 | 283 | 21.9 | 116.0 |
| S12 | 17.5 | 10 | 0.36 | 4.12 | 0.37 | 0.15 | 0.71 | 0.12 | 0.14 | 0.28 | 182 | 10.1 | 128.0 |
| S13 | 11 | 10.5 | 0.45 | 4.12 | 0.34 | 0.11 | 0.49 | 0.10 | 0.13 | 0.26 | 201 | 21.4 | 94.6 |
| S14 | 9.5 | 9 | 0.60 | 3.74 | 0.40 | 0.13 | 0.46 | 0.10 | 0.09 | 0.21 | 221 | 35.9 | 88.0 |
| S15 | 21.5 | 23.5 | 1.30 | 4.21 | 0.56 | 0.21 | 1.06 | 0.17 | 0.28 | 0.34 | 417 | 27.0 | 178.0 |
| S16 | 20 | 19 | 0.38 | 4.14 | 0.49 | 0.15 | 1.20 | 0.18 | 0.25 | 0.48 | 335 | 24.1 | 120.0 |
| S17* | 7 | 10 | 0.20 | 3.93 | 0.18 | 0.04 | 0.24 | 0.05 | 0.04 | 0.15 | 151 | 13.6 | 55.2 |
| S18 | 40.5 | 37.5 | 1.50 | 4.28 | 0.88 | 0.27 | 2.04 | 0.26 | 0.67 | 0.95 | 444 | 9.0 | 298.0 |
| S19* | 14 | 19.5 | 1.06 | 4.00 | 0.74 | 0.14 | 1.04 | 0.14 | 0.24 | 0.22 | 303 | 13.5 | 132.0 |
| S20* | 12 | 13.5 | 0.93 | 4.21 | 0.34 | 0.08 | 0.72 | 0.10 | 0.17 | 0.13 | 316 | 19.3 | 108.0 |
| S21* | 54 | 25.5 | 1.70 | 3.97 | 0.50 | 0.30 | 0.81 | 0.19 | 0.69 | 2.02 | 295 | 8.9 | 366.0 |
| S22* | 22 | 26 | 0.90 | 4.45 | 0.22 | 0.13 | 0.27 | 0.09 | 0.12 | 0.30 | 155 | 6.5 | 96.5 |
| S23 | 42 | 23 | 2.87 | 4.23 | 0.66 | 0.35 | 1.17 | 0.27 | 0.59 | 0.75 | 709 | 30.4 | 385.0 |
| S24 | 22.5 | 19 | 2.54 | 4.12 | 0.28 | 0.14 | 0.44 | 0.10 | 0.28 | 0.50 | 219 | 5.2 | 206.0 |
| S25 | 20 | 28 | 1.14 | 4.15 | 0.37 | 0.12 | 1.31 | 0.18 | 0.41 | 0.38 | 384 | 27.2 | 123.0 |
| S26 | 6 | 4.5 | 1.22 | 6.06 | 0.52 | 0.08 | 0.73 | 0.07 | 0.06 | 0.04 | 253 | 13.7 | 51.2 |
| S27 | 27 | 31.5 | 2.38 | 4.52 | 0.65 | 0.17 | 1.53 | 0.17 | 0.56 | 0.48 | 832 | 54.9 | 158.0 |
| S28 | 19 | 19.5 | 1.97 | 4.52 | 0.54 | 0.21 | 1.02 | 0.18 | 0.25 | 0.25 | 299 | 18.2 | 120.0 |
| S29 | 19 | 28 | 0.73 | 4.02 | 0.58 | 0.11 | 1.20 | 0.14 | 0.38 | 0.48 | 267 | 13.0 | 149.0 |
| S30 | 18.5 | 17.5 | 0.65 | 4.18 | 0.31 | 0.20 | 0.77 | 0.19 | 0.13 | 0.30 | 192 | 14.8 | 161.0 |
| S31 | 16 | 17 | 1.95 | 5.10 | 0.49 | 0.20 | 0.94 | 0.17 | 0.31 | 0.20 | 658 | 36.1 | 146.0 |
| S32 | 23.5 | 26.5 | 1.25 | 3.93 | 0.55 | 0.22 | 1.18 | 0.21 | 0.41 | 0.45 | 517 | 29.4 | 207.0 |
| S33 | 36 | 28.5 | 2.40 | 4.40 | 0.64 | 0.19 | 2.05 | 0.26 | 0.65 | 0.83 | 476 | 28.4 | 263.0 |
| S34 | 10 | 12 | 1.69 | 3.89 | 0.59 | 0.14 | 0.62 | 0.11 | 0.14 | 0.11 | 294 | 33.1 | 86.7 |
| S35 | 19.5 | 14 | 0.78 | 4.78 | 0.34 | 0.20 | 0.88 | 0.16 | 0.20 | 0.43 | 254 | 20.4 | 140.0 |

Appendix 2. (Contd) Selected properties of the soils sampled at the 76 sites

| Site ID | Particle size | | org C % | pH | Oxalate extractable | | Dithionate extractable | | Pyrophosphate extractable | | Total P | Resin P | K_{soil} ($b=0.34$) L/kg |
|---------|---------------|-----------|------------|------|---------------------|------|------------------------|------|---------------------------|------|---------|---------|------------------------------------|
| | clay % | silt % | | | Fe | Al | Fe | Al | Fe | Al | | | |
| S36 | 14.5 | 10 | 0.53 | 3.99 | 0.34 | 0.15 | 0.59 | 0.12 | 0.11 | 0.27 | 172 | 12.9 | 116.0 |
| S37 | 11.5 | 13 | 0.45 | 4.39 | 0.74 | 0.13 | 1.34 | 0.17 | 0.13 | 0.20 | 182 | 8.2 | 96.4 |
| S38 | 23 | 28.5 | 2.02 | 4.19 | 0.55 | 0.21 | 1.13 | 0.22 | 0.38 | 0.43 | 847 | 157.0 | 170.0 |
| S39 | 13 | 13.5 | 1.59 | 3.89 | 0.43 | 0.15 | 0.83 | 0.15 | 0.23 | 0.22 | 641 | 115.7 | 128.0 |
| S40 | 23 | 34 | 1.16 | 4.03 | 0.78 | 0.20 | 1.67 | 0.22 | 0.43 | 0.50 | 348 | 12.1 | 202.0 |
| S41 | 43.5 | 32.5 | 1.98 | 3.86 | 0.49 | 0.29 | 0.81 | 0.21 | 0.64 | 1.29 | 562 | 37.5 | 364.0 |
| S42* | 5.5 | 4 | 0.41 | 4.59 | 0.30 | 0.03 | 0.42 | 0.05 | 0.04 | 0.05 | 151 | 17.4 | 42.7 |
| S43 | 10 | 11 | 0.90 | 3.64 | 0.41 | 0.11 | 0.62 | 0.11 | 0.16 | 0.14 | 437 | 33.1 | 117.0 |
| S44 | 15.5 | 13.5 | 1.24 | 3.86 | 0.47 | 0.26 | 0.82 | 0.21 | 0.29 | 0.48 | 396 | 31.7 | 214.0 |
| S45 | 16 | 10 | 0.84 | 4.01 | 0.29 | 0.21 | 0.74 | 0.18 | 0.14 | 0.25 | 203 | 13.2 | 167.0 |
| S46* | 10 | 12 | 0.72 | 4.67 | 0.40 | 0.10 | 0.52 | 0.10 | 0.08 | 0.11 | 161 | 11.0 | 77.9 |
| S47 | 16 | 19 | 2.05 | 4.60 | 0.41 | 0.09 | 0.49 | 0.10 | 0.18 | 0.11 | 293 | 12.0 | 106.0 |
| S48 | 20.5 | 25 | 1.11 | 4.03 | 0.49 | 0.15 | 1.00 | 0.17 | 0.34 | 0.39 | 132 | 26.4 | 160.0 |
| S49 | 39 | 32 | 2.00 | 3.82 | 0.45 | 0.19 | 0.71 | 0.15 | 0.51 | 0.94 | 640 | 14.0 | 269.0 |
| S50 | 10 | 19.5 | 0.80 | 3.94 | 0.35 | 0.08 | 0.54 | 0.10 | 0.17 | 0.16 | 142 | 20.6 | 89.9 |
| S51 | 10 | 15.5 | 1.59 | 4.93 | 0.29 | 0.07 | 0.45 | 0.09 | 0.07 | 0.06 | 141 | 5.3 | 64.3 |
| S52 | 6.5 | 10.5 | 0.38 | 4.70 | 0.28 | 0.05 | 0.56 | 0.09 | 0.07 | 0.09 | 68 | 1.8 | 38.4 |
| S53 | 13.5 | 20 | 0.54 | 3.76 | 0.45 | 0.12 | 0.84 | 0.15 | 0.20 | 0.28 | 293 | 21.9 | 97.8 |
| S54 | 7.5 | 11 | 0.51 | 4.15 | 0.21 | 0.06 | 0.32 | 0.08 | 0.07 | 0.11 | 131 | 32.8 | 99.1 |
| S55 | 29.5 | 40 | 1.78 | 4.22 | 0.68 | 0.23 | 1.38 | 0.24 | 0.42 | 0.41 | 627 | 63.2 | 218.0 |
| S56 | 26 | 10 | 1.72 | 4.89 | 0.39 | 0.21 | 1.70 | 0.24 | 0.21 | 0.40 | 142 | 2.7 | 148.0 |
| S57 | 51 | 30.5 | 1.44 | 5.05 | 0.17 | 0.17 | 0.52 | 0.13 | 0.34 | 1.35 | 145 | 5.8 | 86.4 |
| S58 | 29.5 | 45 | 0.98 | 4.91 | 0.29 | 0.09 | 0.58 | 0.09 | 0.28 | 0.68 | 215 | 13.1 | 85.4 |
| S59 | 19.5 | 5 | 0.18 | 5.25 | 0.34 | 0.08 | 1.45 | 0.09 | 0.01 | 0.11 | 192 | 28.0 | 60.1 |
| S60 | 10 | 7.5 | 0.38 | 5.75 | 0.45 | 0.00 | 1.35 | 0.10 | 0.03 | 0.07 | 151 | 2.0 | 31.6 |
| S65 | 9.5 | 13 | 0.47 | 4.38 | 0.14 | 0.04 | 0.48 | 0.08 | 0.05 | 0.19 | 82 | 1.1 | 43.0 |
| s66 | 10 | 20 | 1.59 | 4.77 | 0.19 | 0.12 | 0.35 | 0.11 | 0.07 | 0.18 | 161 | 10.3 | 115.0 |
| s67 | 11.5 | 8.5 | 1.14 | 5.18 | 0.21 | 0.31 | 0.65 | 0.27 | 0.16 | 0.32 | 82 | 3.2 | 382.0 |
| s68 | 41 | 26.5 | 2.05 | 4.51 | 0.39 | 0.29 | 0.59 | 0.19 | 0.43 | 1.42 | 258 | 12.7 | 323.0 |
| s69 | 34.5 | 25 | 2.39 | 4.62 | 0.38 | 0.36 | 0.53 | 0.22 | 0.31 | 0.89 | 339 | 27.0 | 364.0 |
| S70 | 27.5 | 31 | 1.51 | 4.28 | 0.74 | 0.23 | 1.89 | 0.25 | 0.47 | 0.73 | 325 | 17.2 | 311.0 |
| S71* | 32.5 | 35.5 | 1.72 | 4.61 | 0.47 | 0.23 | 0.66 | 0.18 | 0.41 | 0.84 | 399 | 21.0 | 309.0 |
| S72 | 22.5 | 29.5 | 1.33 | 4.96 | 0.63 | 0.15 | 0.84 | 0.13 | 0.32 | 0.36 | 254 | 10.4 | 224.0 |
| S73* | 38 | 39 | 1.62 | 4.75 | 0.64 | 0.27 | 1.16 | 0.21 | 0.54 | 0.99 | 320 | 12.6 | 422.0 |
| S74* | 22 | 23.5 | 0.82 | 4.79 | 0.45 | 0.14 | 0.98 | 0.14 | 0.28 | 0.52 | 162 | 4.3 | 211.0 |

Appendix 2. (Contd) Selected properties of the soils sampled at the 76 sites

| Site ID | Particle size | | org C % | pH | Oxalate extractable | | Dithionate extractable | | Pyrophosphate extractable | | Total P | Resin P | K_{soil} ($b=0.34$) L/kg |
|---------|---------------|-----------|------------|------|---------------------|------|------------------------|------|---------------------------|------|---------|---------|------------------------------------|
| | clay % | silt % | | | Fe | Al | Fe | Al | Fe | Al | | | |
| S75 | 36.5 | 40.5 | 1.99 | 4.59 | 0.91 | 0.26 | 1.50 | 0.22 | 0.66 | 1.02 | 596 | 26.6 | 376.0 |
| S76* | 22.5 | 32.5 | 2.05 | 4.72 | 0.72 | 0.22 | 1.31 | 0.22 | 0.50 | 0.48 | 703 | 44.6 | 227.0 |

* samples used for desorption in simulated river water.

Appendix 3. Mineralogy of selected samples, based on semi-quantitative XRD analysis of random powders of total sample.

| Site ID | Catchment | Quartz | | Orthoclase | | Albite | | Mica | | Kaolin | | Amphibole | | Smectite | | Vermiculite | |
|---------|--------------|--------|-------|------------|-------|--------|-------|------|-------|--------|-------|-----------|-------|----------|-------|-------------|-------|
| | | % | error | % | error | % | error | % | error | % | error | % | error | % | error | % | error |
| S2 | Stone | 62 | 2 | 36 | 2 | 1.1 | 2 | 0 | | 0 | | 0 | | 0 | | 0 | |
| S3 | Stone | 73 | 2 | 19 | 1 | 5 | 1 | 2 | 1 | 2 | 1 | 0.1 | | 0 | | 0 | |
| S4 | Stone | 68 | 2 | 23 | 1 | 7 | 1 | 0.1 | | 0.1 | | 0.1 | | 0 | | 0 | |
| S6 | Stone | 43 | 2 | 24 | 2 | 12 | 1 | 11 | 2 | 9 | 1 | 0.1 | | 0 | | 0 | |
| S9 | Stone | 60 | 2 | 21 | 1 | 11 | 1 | 1.5 | 2 | 4 | 1 | 1.3 | 8 | 0 | | 0 | |
| S10 | Stone | 44 | 1 | 28 | 1 | 12 | 1 | 3 | 1 | 12 | 1 | 1.1 | 5 | 0 | | 0 | |
| S12 | Stone | 66 | 2 | 14 | 1 | 10 | 1 | 4 | 1 | 5 | 1 | 0.1 | | 0 | | 0 | |
| S14 | Stone | 66 | 1 | 25 | 2 | 8 | 1 | 0.1 | | 0.1 | | 0.1 | | 0 | | 0 | |
| S15 | Stone | 35 | 1 | 32 | 2 | 3 | 1 | 5 | 1 | 13 | 2 | 6 | 1 | 6 | 1 | 0 | |
| S16 | Stone | 46 | 1 | 29 | 1 | 9 | 1 | 3 | 1 | 13 | 1 | 0.1 | | 0 | | 0 | |
| S17* | Stone | 72 | 2 | 24 | 1 | 2 | 1 | 0 | | 2 | 1 | 0 | | 0 | | 0 | |
| S18 | Ripple Creek | 40 | 1 | 5 | 1 | 4 | 1 | 4 | 1 | 40 | 2 | 0 | | 3 | 1 | 4 | 1 |
| S19* | Ripple Creek | 61 | 2 | 15 | 1 | 6 | 1 | 3 | 1 | 11 | 1 | 2 | 1 | 3 | 1 | 0 | |
| S20* | Ripple Creek | 49 | 1 | 27 | 1 | 3 | 1 | 5 | 1 | 13 | 1 | 0 | | 3 | 1 | 0 | |
| S21* | Ripple Creek | 34 | 1 | 2 | 1 | 0.1 | | 4 | 1 | 59 | 2 | 0 | | 0 | | 0 | |
| S22* | Ripple Creek | 60 | 2 | 21 | 1 | 2 | 1 | 0.1 | | 16 | 1 | 0 | | 0 | | 0 | |
| S27 | Abergowrie | 31 | 1 | 6 | 1 | 11 | 1 | 13 | 1 | 27 | 1 | 0.1 | | 7 | 1 | 5 | 1 |
| S28 | Abergowrie | 65 | 2 | 16 | 1 | 2 | 1 | 4 | 1 | 14 | 1 | 0 | | 0 | | 0 | |
| S29 | Abergowrie | 68 | 2 | 12 | 1 | 3 | 1 | 5 | 1 | 12 | 1 | 0 | | 0 | | 0 | |
| S30 | Abergowrie | 76 | 2 | 7 | 1 | 2 | 1 | 0.1 | | 14 | 1 | 0 | | 0 | | 0 | |
| S31 | Abergowrie | 60 | 2 | 12 | 1 | 13 | 1 | 4 | 1 | 7 | 1 | 0.1 | | 0 | | 3 | 1 |
| S33 | Stone | 39 | 1 | 6 | 1 | 13 | 1 | 9 | 1 | 34 | 2 | 0 | | 0 | | 0 | |
| S34 | Stone | 60 | 2 | 25 | 1 | 7 | 1 | 3 | 1 | 4 | 1 | 0.1 | | 0 | | 0 | |
| S42* | Ripple Creek | 68 | 2 | 14 | 1 | 14 | 1 | 0.1 | | 0.1 | | 0 | | 3 | 1 | 0 | |
| S44 | Ripple Creek | 65 | 2 | 19 | 1 | 13 | 1 | 0 | | 3 | 1 | 0 | | 0 | | 0 | |
| S45 | Ripple Creek | 64 | 2 | 16 | 1 | 7 | 1 | 8 | 1 | 5 | 1 | 0 | | 0 | | 0 | |
| S46* | Ripple Creek | 59 | 2 | 28 | 1 | 11 | 1 | 0 | | 3 | 1 | 0 | | 0 | | 0 | |
| S49 | Stone | 54 | 1 | 9 | 1 | 4 | 1 | 14 | 1 | 20 | 2 | 0 | | 0 | | 0 | |
| S51 | Stone | 67 | 2 | 20 | 1 | 11 | 1 | 0 | | 2 | 1 | 0 | | 0 | | 0 | |
| S52 | Stone | 90 | 3 | 8 | 1 | 2 | 1 | 0 | | 0 | | 0 | | 0 | | 0 | |
| S57 | Upper | 50 | 1 | 0.1 | | 0.1 | | 5 | 1 | 37 | 2 | 0 | | 6 | 1 | 0 | |
| S58 | Upper | 73 | 2 | 2 | 1 | 0.1 | | 6 | 1 | 18 | 1 | 0 | | 0 | | 0 | |
| S66 | Ripple Creek | 75 | 2 | 20 | 1 | 2 | 1 | 0 | | 4 | 1 | 0 | | 0 | | 0 | |
| S67 | Ripple Creek | 88 | 3 | 8 | 1 | 0.1 | | 0.1 | | 3 | 1 | 0.1 | | 0 | | 0 | |
| S68 | Ripple Creek | 45 | 1 | 10 | 1 | 3 | 1 | 4 | 1 | 37 | 2 | 0 | | 0 | | 0 | |
| S69 | Ripple Creek | 47 | 1 | 11 | 1 | 3 | 1 | 5 | 1 | 34 | 2 | 0 | | 0 | | 0.1 | |
| S70 | Ripple Creek | 45 | 1 | 12 | 1 | 15 | 1 | 0 | | 29 | 1 | 0 | | 0 | | 0 | |
| S71* | Ripple Creek | 40 | 1 | 14 | 1 | 5 | 1 | 0.1 | | 41 | 2 | 0 | | 0.2 | | 0 | |
| S72 | Ripple Creek | 44 | 1 | 10 | 1 | 14 | 1 | 1.1 | 4 | 28 | 1 | 0.1 | | 0 | | 0.1 | |
| S73* | Ripple Creek | 29 | 1 | 6 | 1 | 8 | 1 | 2 | 1 | 47 | 2 | 0.1 | | 4 | 1 | 4 | 1 |
| S74* | Ripple Creek | 66 | 1 | 8 | 1 | 7 | 1 | 0.1 | | 19 | 1 | 0 | | 0 | | 0 | |
| S76* | Ripple Creek | 37 | 1 | 12 | 1 | 16 | 1 | 2 | 1 | 26 | 1 | 0.1 | | 0 | | 3 | 1 |

Appendix 4. Allocation of soil samples to clusters (see section 4.2.2 for explanation)

| Site ID | Subcatchment | Soil type | Cluster No. | | |
|---------|--------------|-------------------|-------------|----------|----------|
| | | | CSR Survey | Chemical | Physical |
| S1 | Stone | coarse sandy loam | 4 | 3 | 3 |
| S2 | Stone | coarse sandy loam | 4 | 3 | 3 |
| S3 | Stone | terrace silt | 2 | 2 | 5 |
| S4 | Stone | red loam | 3 | 3 | 2 |
| S5 | Stone | red loam | 3 | 3 | 2 |
| S6 | Stone | silty clay | 2 | 2 | 5 |
| S7 | Stone | terrace silt | 2 | 2 | 5 |
| S8 | Stone | river bank | 3 | 4 | 2 |
| S9 | Stone | river bank | 3 | 4 | 2 |
| S10 | Stone | silty clay | 2 | 2 | 5 |
| S11 | Stone | silty clay | 2 | 2 | 5 |
| S12 | Stone | red loam | 3 | 3 | 2 |
| S13 | Stone | red loam | 3 | 3 | 2 |
| S14 | Stone | river bank | 3 | 4 | 2 |
| S15 | Stone | river bank | 3 | 4 | 2 |
| S16 | Stone | silty clay | 2 | 2 | 5 |
| S17* | Stone | coarse sandy loam | 4 | 3 | 3 |
| S18 | Ripple creek | clay loam | 1 | 1 | 1 |
| S19* | Ripple creek | terrace silt | 2 | 2 | 5 |
| S20* | Ripple creek | river bank | 3 | 4 | 2 |
| S21* | Ripple creek | clay | 1 | 1 | 1 |
| S22* | Ripple creek | silty clay | 2 | 2 | 5 |
| S27 | Abergowrie | river overflow | 2 | 2 | 5 |
| S28 | Abergowrie | red loam | 3 | 3 | 2 |
| S29 | Abergowrie | silty clay | 2 | 2 | 5 |
| S30 | Abergowrie | coarse sandy loam | 4 | 3 | 3 |
| S31 | Abergowrie | river bank | 3 | 4 | 2 |
| S32 | Abergowrie | river overflow | 2 | 2 | 5 |
| S33 | Stone | heavy clay | 1 | 1 | 1 |
| S34 | Stone | river bank | 3 | 4 | 2 |
| S35 | Abergowrie | red loam | 3 | 3 | 2 |
| S36 | Abergowrie | fine sandy loam | 4 | 3 | 3 |
| S37 | Abergowrie | red sand | 4 | 3 | 3 |
| S38 | Floodplain | terrace silt | 2 | 2 | 5 |
| S39 | Floodplain | river bank | 3 | 4 | 2 |
| S40 | Floodplain | silty clay | 2 | 2 | 5 |

Appendix 4 (Contd). Allocation of soil samples to clusters (see section 4.2.2 for explanation)

| Site ID | Subcatchment | Soil type | Cluster No. | | |
|---------|--------------|----------------|-------------|----------|----------|
| | | | CSR Survey | Chemical | Physical |
| S41 | Floodplain | clay | 1 | 1 | 1 |
| S42* | Ripple creek | river sand | 4 | 4 | 3 |
| S43 | Ripple creek | terrace silt | 2 | 2 | 5 |
| S44 | Ripple creek | red loam | 3 | 3 | 2 |
| S45 | Ripple creek | red sand | 4 | 3 | 3 |
| S46* | Ripple creek | grey sand | 4 | 4 | 3 |
| S47 | Floodplain | terrace silt | 2 | 2 | 5 |
| S48 | Floodplain | terrace silt | 2 | 2 | 5 |
| S49 | Stone | heavy clay | 1 | 1 | 1 |
| S50 | Stone | sandy clay | 4 | 3 | 3 |
| S53 | Stone | river bank | 3 | 4 | 2 |
| S54 | Abergcwrie | grey sand | 4 | 3 | 3 |
| S55 | Abergowrie | river overflow | 2 | 2 | 5 |
| S66 | Ripple creek | fine grey sand | 4 | 3 | 3 |
| S67 | Ripple creek | red sand | 4 | 3 | 3 |
| S68 | Ripple creek | clay | 1 | 1 | 1 |
| S69 | Ripple creek | clay | 1 | 1 | 1 |
| S70 | Ripple creek | clay | 1 | 1 | 1 |
| S71* | Ripple creek | silty clay | 2 | 2 | 5 |
| S72 | Ripple creek | terrace silt | 2 | 2 | 5 |
| S73* | Ripple creek | clay | 1 | 1 | 1 |
| S74* | Ripple creek | sandy clay | 4 | 3 | 3 |
| S75 | Ripple creek | clay loam | 1 | 1 | 1 |
| S76* | Ripple creek | silty loam | 1 | 1 | 1 |

*samples used for desorption in simulated river water

Soils S23, S24, S25, S26 (floodplain), S26 (Abergowrie), S14, S51, S52, S53 (Stone), S67 (Ripple) and S56-65 (Upper) were from outside the area covered by the CSR survey. However S14, S26, S53 and S67 could be allocated to CSR soil types as indicated.

Appendix 5. Chemical analysis of Herbert River waters, January 1998

| Site ^a | pH | EC μS/cm | Cl | B | Ca | Fe | K | Mg | Mn | Na | P | S | Zn |
|-------------------|------|-------------|-------|-------|-----|-----|-----|------|------|------|------|-----|-------|
| | | | | | | | | mg/L | | | | | |
| "Pristine Ck" | 6.50 | 43.8 | 7.0 | <0.02 | 0.7 | 0.1 | 1.2 | 0.5 | <0.1 | 7.9 | <0.1 | 0.3 | <0.02 |
| Nash's X'ing | 5.33 | 60.0 | 8.3 | <0.02 | 2.6 | 1.4 | 1.8 | 1.5 | <0.1 | 8.3 | <0.1 | 0.4 | 0.06 |
| Abergowrie Br | 5.62 | 61.0 | 7.8 | <0.02 | 2.6 | 1.1 | 1.7 | 1.5 | <0.1 | 7.8 | <0.1 | 0.3 | 0.04 |
| Stone River | 6.52 | 67.4 | 9.0 | <0.02 | 2.9 | 0.4 | 1.5 | 1.5 | <0.1 | 9.4 | <0.1 | 0.5 | <0.02 |
| John Row Br | 6.36 | 56.8 | 7.3 | <0.02 | 2.4 | 0.8 | 1.6 | 1.3 | <0.1 | 7.5 | <0.1 | 0.4 | <0.02 |
| Gairloch Br | 5.45 | 58.0 | 7.7 | <0.02 | 2.4 | 1.0 | 1.6 | 1.3 | <0.1 | 7.6 | <0.1 | 0.4 | 0.04 |
| Halifax Br | 6.49 | 58.1 | 7.8 | <0.02 | 2.4 | 0.8 | 1.6 | 1.3 | <0.1 | 7.8 | <0.1 | 0.4 | 0.03 |
| Dungeness | 6.55 | 10700.0 | 5130 | 1.2 | 112 | 0.0 | 112 | 315 | <0.5 | 2870 | <0.5 | 215 | <0.1 |
| Lucinda | 6.10 | 20600.0 | 12450 | 2.9 | 282 | 0.1 | 292 | 760 | <0.5 | 6680 | <0.5 | 522 | <0.1 |

^a These sites cover the stretch of the Herbert between Nash's Crossing, which is just downstream of the gorge which divides the upper and lower parts of the Herbert catchment, and the mouth of the river at Dungeness. An additional sample was taken from the beach at Lucinda. Since the EC of this sample is below that expected for seawater, this site is assumed to be "estuarine" rather than marine. "Pristine Creek" is a small un-named creek draining world heritage rainforest which flows into the Herbert close to Nash's Crossing. All the other sites listed are on the Herbert River moving progressively downstream towards Lucinda, except the Stone River site which is approximately 1 km upstream of the mouth of Stone River, which flows into the Herbert roughly halfway between Abergowrie bridge and the John Row bridge near Ingham (Figure 6).