Identification of sources of sediment to Lake Samsonvale (North Pine Dam), southeast Queensland, Australia

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Abstract Lake Samsonvale (North Pine Dam, NPD) is a major reservoir, of approximately 22 km^2 with a capacity of 215 000 Ml and drainage area of 347 km^2, which supplies drinking water to Brisbane, the capital city of Queensland in eastern Australia. Historically, there are large and persistent blooms of potentially toxic cyanobacteria in NPD, and it was hypothesized that their occurrence and biomass were related to input of sediment-bound phosphorus from the drainage basin. The NPD drainage basin is ungauged and few estimates of (sub)drainage basin sediment loads exist. This paper develops a Bayesian approach utilizing endmember models to estimate, based on major and trace element geochemical signatures, the proportion of various drainage basin sediment sources in sediment samples taken from NPD. This approach not only allows for the incorporation of prior knowledge about the geochemical composition of the sources (or endmembers), but also allows for correlation between spatially contiguous samples and the prediction of the sediment composition at unsampled locations.

Key words algal bloom; Australia; Bayesian mixing model; geochemistry; Monte Carlo Markov Chain; principal component analysis; reservoir; trace elements

INTRODUCTION

A major challenge in the management of ungauged basins is not only the estimation of hydrological balances but also of material fluxes, in particular those of sediment. This is especially critical where the delivery of sediment may compromise the physical function (e.g. due to siltation or channel diversion) or ecology (e.g. via the delivery of associated plant nutrients or contaminants) of the receiving water body.

Lake Samsonvale (North Pine Dam, NPD), located in southeast Queensland, Australia, is a major drinking water source for the city of Brisbane (population ~1 million) (Fig. 1). Historically, there are large and persistent blooms of potentially toxic cyanobacteria in NPD, and it was hypothesized that their occurrence and biomass were

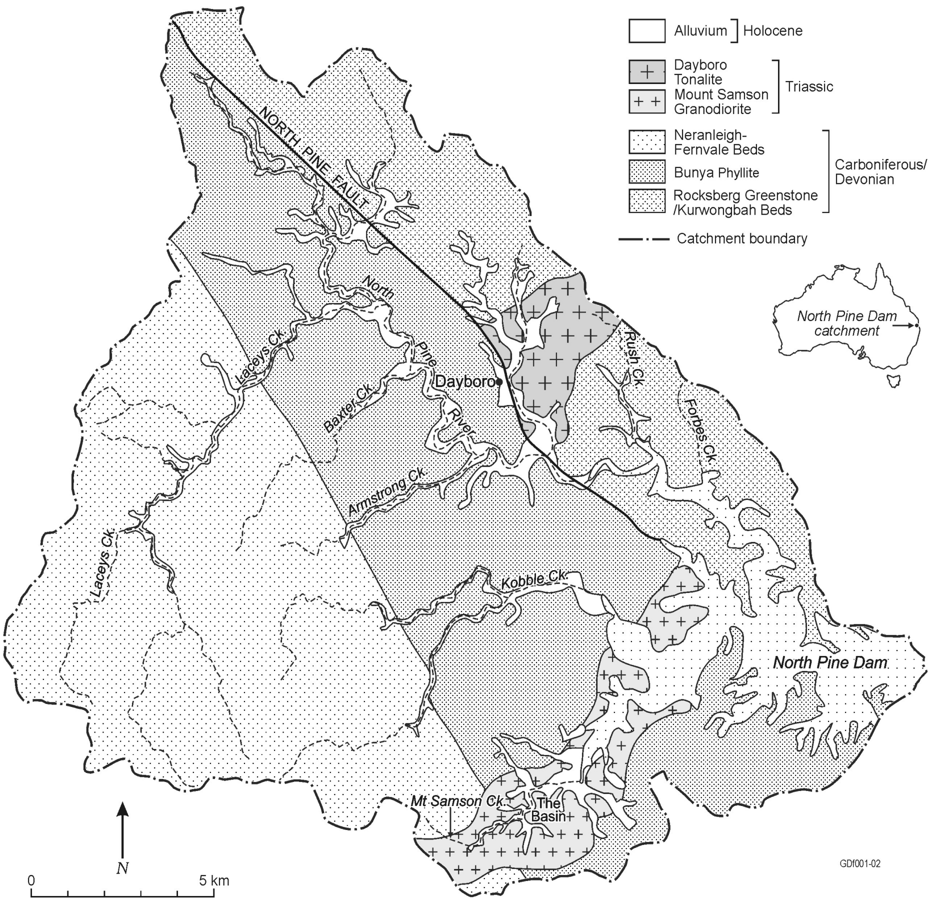

Fig. 1 North Pine Dam location and drainage basin geology.

related to inputs of sediment-bound phosphorus from the drainage basin. Consequently, elucidating sediment sources is of considerable importance. At present there are few estimates of inflows or sediments fluxes into NPD. In this study we have used geochemical and statistical methods to identify the major sediment sources, and utilized a Bayesian multi-component mixing model to estimate the proportions of major rock (sediment) types being delivered into NPD.

Identification of the principal sediment sources in the NPD drainage basin is confounded by sediment diagenesis (post-depositional changes in sediment chemistry and/or mineralogy), anthropogenic inputs and the accumulation of algal detritus. The episodic delivery of sediment into this system associated with highly variable rainfall results in mixing of sediment sources in transit, from tributaries, within temporary storage zones and during transfer between sub-basins within NPD.

STUDY AREA

The drainage area of the NPD basin is approximately 347 km^2. The area of the reservoir at full capacity is approximately 22 km^2, resulting in a drainage area:dam ratio of approximately 16:1. The NPD drainage basin is composed of four major rock types (proportion in parentheses):

(a) Rocksberg Greenstone (19%)—late Devonian to early Carboniferous basic metavolcanics and pelitic schist (Kurwongbah Beds—phyllite, slate/chert).
(b) Bunya Phyllite (39%)—late Devonian to early Carboniferous metasediments (phyllite, minor greywacke) and basic metavolcanics.
(c) Neranleigh-Fernvale Beds (33%)—late Devonian to early Carboniferous metasediments (shale, mudstone, greywacke) and basic metavolcanics.
(d) Granitoids (8%)—early to middle Triassic, principally the Mt Samson Granodiorite and the Dayboro Tonalite.

Three tributaries deliver water into NPD (Fig. 1). The most significant is the North Pine River, which mostly drains the Bunya Phyllite. Kobble Creek and its tributaries, form the second major drainage network, which is developed mainly on the Bunya Phyllite and intersects the Samson Granodiorite. A low-lying area, "The Basin", mostly drains the Samson Granodiorite via Mt Samson Creek.

METHODS

Sampling of North Pine Dam and drainage basin sediments

A reconnaissance sediment geochemical survey was undertaken on NPD in 1999. In total, 64 bottom sediment samples were collected by Eckman grab on a ~400 m grid, and 16 sediment (soil) samples encompassing the major rock types greenstone, phyllite and granitoid (Douglas *et al.*, 1999; Palmer & Douglas, 2003) were collected in the drainage basin.

Major and trace element analysis

Drainage basin soil and NPD sediment samples were analysed by CSIRO using X-ray fluorescence (XRF-Phillips PW1480) for major (SiO_2, Al_2O_3, Fe_2O_3, MnO, MgO, CaO, Na_2O, K_2O, TiO_2, P_2O_5) and trace elements (Ba, Ce, Cl, Cr, Co, Cu, Ga, La, Ni, Nb, Pb, Rb, S, Sr, V, Y, Zn, Zr) on fused glass discs (Norrish & Chappell, 1977; Hart 1989), and by neutron activation analysis (NAA) by Becquerel Laboratories, Australia, for major elements (Ca, Fe, Na and K) and trace elements (Ag, As, Au, Ba, Br, Ce, Co, Cr, Cs, Eu, Hf, Ir, La, Lu, Mo, Rb, Sb, Sc, Se, Sm, Ta, Tb, Te, Th, U W, Yb, Zn, Zr) (Potts, 1987).

Statistical model to determine the proportions of drainage basin sediment sources

The NPD sediment samples can be considered to be comprised of varying proportions of source material (soils) from the different bedrock types in the drainage basin. The problem is to estimate the proportion of various sources within a sample. The approach taken for this study is to model the contribution of the sources as contributing in a linear additive manner. Mathematically, for the *j*th sample, the model can be written as:

$$y_j = Az_j$$

where A is a p × k matrix in which each column of A corresponds to an endmember, and the elements of the vector z_j correspond to the proportions of each endmember in the sample. The concentrations of various major elements (as weight % oxides) and trace elements (as $\mu g\ g^{-1}$) characterizes each sediment sample. At each site j, there corresponds a p column of observations y_j and a k-column vector of unknown proportions z_j of the drainage basin geologies (sources). It is postulated that the sample measurements follow a multivariate normal distribution. Conditional on the proportions z_j, the distribution is:

$$p(y_j \mid z_j, A, \Gamma) = (2\pi)^{-\frac{v}{2}} \mid \Gamma \mid^{-\frac{1}{2}} \exp\left\{-0.5(y_j - Az_j)'\Gamma^{-1}(y_j - Az_j)\right\}$$

The distribution of the unknown z_j is modelled by assuming that the additive log-ratio transformation (alr) of the proportions follows a multivariate-normal distribution; i.e. the k-part composition vector z_j has a logistic normal distribution:

$$p(z_i \mid \mu, \Sigma) = \left(\frac{1}{2\pi}\right)^{\frac{k-1}{2}} \mid \Sigma \mid^{-\frac{1}{2}} \left(\frac{1}{\Pi z_i}\right) \exp\left\{-\frac{1}{2}(\theta_i - \mu)'\Sigma^{-1}(\theta_i - \mu)\right\}$$

with:

$$\theta = \mathrm{alr}(z) = \log\left(\frac{z_{-k}}{z_k}\right) = \left(\log\left(\frac{z_1}{z_k}\right), \log\left(\frac{z_2}{z_k}\right), \ldots., \log\left(\frac{z_{k-1}}{z_k}\right)\right)$$

In considering the spatial requirements, a spatial modelling approach was adopted similar to that of Wikle *et al.* (2001), which was developed for integrating data on different grids, scales and resolutions. Their approach depends on setting up a finer-resolution regular grid on which the "true" but unknown values lie. The actual observations are measured at points generally different from this grid, but are functions of the unknown values on the finer grid comprised in the case of NPD of 883 points. This not only allows for observations to be on a grid of different resolution, but also allows observations to be irregularly located. Furthermore, we assume that this spatial process applies to the compositions and not to the actual measurements. Since in many cases the dimension of the compositions can be much less than the dimension of the data, this allows for a reduction in computational requirements. Thus, we model the mean of their distribution of the unknown compositions dependent on the unknown values on the prediction grid such that:

$$p(\theta_j \mid \zeta, \Sigma)\ N([\zeta K]_j, \Sigma),\ j = 1, \ldots., n$$

where, following Wikle *et al.* (2001), K is an $m \times n$ mapping matrix (where there are m points on the prediction grid, and n observations) of weights that maps the values on the "true" grid (the ζs), onto the mean of the observed points. The notation $[\ ]_j$ denotes the jth column of the matrix. Thus, the conditional means of the unobserved compositions are actually smoothed versions of the "true" compositions on the grid. A Bayesian approach, similar to that described in Billheimer (2001), which allows for the derivation of a joint posterior probability distribution of the parameters, and Monte Carlo Markov Chain (MCMC) algorithms (Gilks *et al.*, 1966) are used to derive estimates of the unknown parameters. This approach not only provides estimates of the endmembers, but can be used to estimate the unknown mixing proportions for not only each sediment sample but also of the compositions on the "true" grid.

RESULTS AND DISCUSSION

Identification of major drainage basin sediment sources to North Pine Dam

A suite of 24 major and trace elements important in defining the geochemistry of the drainage basin endmembers was used in the Bayesian endmember model. Hydrological (based on the distribution of major tributaries and Quaternary sediment) and land-use evidence indicated that only three of the four rock types were likely to be significant sediment sources. Principal component (PC) analysis on the correlation matrix of all 24 elements from the NDP sediment samples was used to examine the distribution of drainage basin sediments (soils) relative to NPD sediments, and identify and validate important endmembers. Analysis of eigenvalues showed that the first three eigenvalues accounted for most of the variation of sediment geochemistry (Palmer & Douglas, 2003), implying the presence of four endmembers. The first two PC scores of the NPD sediment and the drainage basin soil samples (and their mean values) are displayed in Fig. 2. The PC scores for the drainage basin sediment samples (greenstones, phyllites and granites) display an approximate triangular configuration of points, indicative of predominantly three endmember mixing, and account for some of the variation in NPD sediments. However, the Bunya Phyllite endmember does not lie close to a third vertex apparently defined by the NPD sediments (Fig. 2).

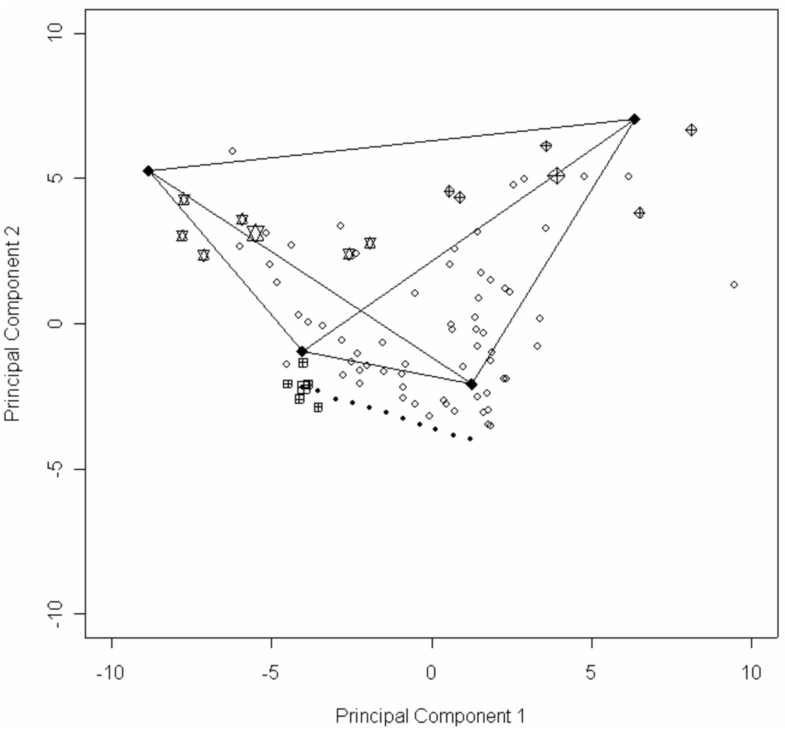

Fig. 2 Plot of first two principal components (PC) scores from analysis of NPD sediments (open black circles) derived PC scores for NPD drainage basin samples (stars, granites; crossed diamonds, greenstones; and crossed squares, phyllites. Larger symbols are the means for each group. Small black squares define a mixing line between 100% to 80% phyllites and diagenetic endmember, in 2% increments. Estimated endmembers (black diamonds) are from MCMC runs transformed into principal component space with lines defining a tetrahedron in pseudo 3-D space.

Sediment samples from NPD that lie adjacent to the vertex and are not constrained within the triangular space defined by the three drainage basin sediment endmembers, are from the deepest (>20 m) parts of NPD, and have a modified geochemical composition, generally being enriched in P, Fe, Mn, S and a range of trace metals (e.g. Ni, Pb). Mineralogical analysis indicates the presence of sulphides (Douglas *et al.*, 1999). This evidence is strongly suggestive of both sediment diagenesis producing metal-rich sulphides below the redox front, and the accumulation of Fe- and Mn-oxides and oxyhydroxides above the redox front in the bottom sediments. The accumulation of Fe- and Mn-oxides and oxyhydroxides is also consistent with the artificial aeration in deeper regions of NPD to remove, via formation of insoluble oxides and hydroxides, these elements and soluble P from the water column.

Initial modelling using three endmembers (based on the drainage basin samples) indicated that the Bunya Phyllite was the predominant sediment type in the deeper areas of NPD, in agreement with its proximity to the deepest NPD samples in PC analysis (Fig. 2). In an attempt to identify a fourth endmember, an estimate of the composition of the diagenetic component was made based on a comparison between the Bunya Phyllite composition and the composition of sediments in deeper areas of NPD. This composition, termed a diagenetic endmember, was then added to the Bunya Phyllite composition in 2% increments to define a simple two endmember mixing line (Fig. 2). A ratio of 80% Bunya Phyllite to 20% diagenetic component (the most distant point from the Bunya Phyllite composition, Fig. 2) appears compatible as a prior estimate of the fourth endmember.

Using three drainage basin sediment (soil) components—greenstones, granite and phyllite—and an 80:20 Bunya Phyllite:diagenetic component ratio, Monte Carlo Markov Chain (MCMC) sample means for the endmembers were computed, and for comparison transformed into PC space (Fig. 2 and Palmer & Douglas, 2003). Lines have been drawn connecting the endmembers or vertices of the tetrahedron (Fig. 2) to emphasize the simplex. The NPD sediments are largely contained within the estimated vertices used as a basis to estimate the endmember proportions (Fig. 2). An advantage of this approach is that the estimated proportions are positive and sum to one.

Estimate of proportions of major drainage basin sediment sources to North Pine Dam

The MCMC process has been used to generate samples of the proportions of the endmembers for each point of the prediction grid, for which average values are shown in Fig. 3. There is clear evidence of contiguous points having similar values reflecting spatial correlation (Figs 1 and 3) and this is often consistent with physical features in NPD such as depth (Douglas *et al.*, 1999).

In general there is a close spatial correlation between the occurrence of sediment in NPD and that in the drainage basin. Noteworthy is the close relationship between the greenstones in the northern section of the easternmost basin and in North Pine River and their occurrence in NPD. Similarly, granitic sediments within NPD correspond spatially with occurrences of Mt Samson Granodiorite in the south and west of NPD and the Dayboro Tonalite adjacent to the North Pine River. Anomalous occurrences of granitic material in the easternmost basin in NPD may reflect the use of this material in

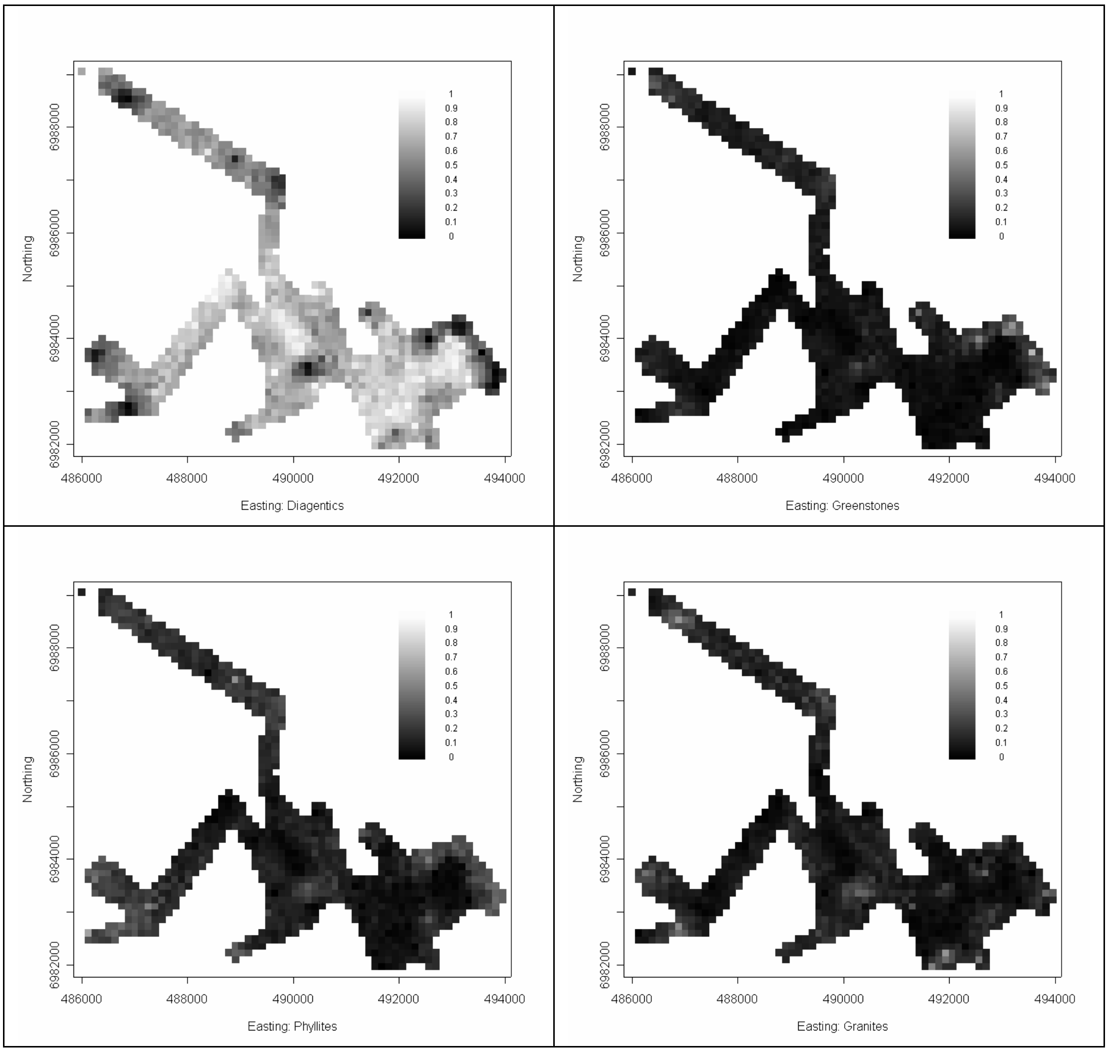

Fig. 3 Predicted proportions of endmembers (diagenetic, greenstones, phyllites, granitoids) in NPD sediments.

construction of the dam wall and as landfill between a series of low ridges in this area. The lack of transport of granitic and greenstone-derived sediment away from their source is indicative of their inherently coarser grain size. In contrast, the fine-grained phyllitic sediment has been transported appreciably greater distances, probably during periods of high flow.

Estimates of the relative proportions of drainage basin rock types and the diagenetic component in NPD are presented in Table 1. The Bunya Phyllite/diagenetic blend is strongly represented in NPD sediments. The spatial distribution of this component is strongly correlated with the deeper areas of NPD (Douglas *et al.*, 1999). These estimates have also been recalculated on a diagenetic-free basis and compared to the relative drainage basin abundance. Based on the Bayesian model estimates, both the Bunya Phyllite and granitoids deliver a disproportionately large amount of sediment to NPD. In contrast, the Rocksberg Greenstone supplies substantially less sediment to NPD relative to its drainage area. These estimates are consistent with both land use and drainage patterns in the NPD drainage basin; most of the cleared land or

Table 1 Drainage basin abundance and estimated abundance of major rock types in NPD sediments.

Drainage basin rock type	Drainage basin abundance	NPD estimated abundance	NPD estimated abundance*	NPD to drainage basin ratio
Rocksberg Greenstone	19%	9.6%	11.0%	0.6
Bunya Phyllite	39%	15.0%	75.3%	1.9
Granites	8%	12.0%	13.7%	1.7
Phyllite/diagenetic	–	63.4%	–	–

*recalculated in absence of diagenetic component.

that used for intensive agriculture and the major tributaries of North Pine River and Kobble Creek are located within the Bunya Phyllite. Extensive local drainage, unconsolidated soils developed on the Mt Samson Granodiorite, and the use of granitic material during dam construction, may also be important local sources of sediment resulting in disproportionate representation in NPD.

Modelling of geochemical variation in NPD sediments

Two parameters with considerable geochemical contrast in terms of their geochemical behaviour and mineralogical affinity (Si:Al molar ratio and the total phosphorus, TP concentration) were chosen to assess the effectiveness of the Bayesian mixing model to broadly describe geochemical variation in NPD sediments.

The Si:Al molar ratio changes with depth (Fig. 4(a)) as a consequence of sediment focussing in NPD (Douglas *et al.*, 1999) with minimal influence from sediment diagenesis or anthropogenic inputs. Sediments in NPD sampled immediately adjacent to the source or within tributaries are in general the most coarse grained (silt with minor sand and clay), particularly in the west and southwest areas of NPD, while those deposited in the deeper parts of NPD are in general extremely fined grained with the clay size fraction dominant in depths >12 m and exceeding approximately 80% of the sediment particle size fraction in depths >20 m (Douglas *et al.*, 1999). The decrease in particle size with depth has a major effect on the sediment geochemistry. The clastic sedimentary component in NPD is primarily composed of Si and Al (as SiO_2 and Al_2O_3 in aluminosilicate minerals—approximately 50–70% by weight, Douglas *et al.*, 1999). The Si:Al molar ratio in shallower zones is consistent with a quartz (Si:Al $\approx \infty$) and clay (Si:Al $\approx$ 2) mixture (hence, Si:Al >>2), while in deeper zones the Si:Al ratio is dominated by a mixed clay mineral suite (Douglas *et al.*, 1999) with 1:1 (kaolinite) and 2:1 (e.g. smectite) Si:Al ratios and substantially less quartz (hence, Si:Al $\approx$ 2, Fig. 4(a)). Estimates derived from the Bayesian mixing model using four endmembers account well for the variation of Si:Al molar ratios (and hence a large proportion of the sediment) in NPD sediments (Fig. 4(b)). The good agreement of model estimates also suggests that changes in mineralogy (e.g. quartz *vs* clay) have been accounted for as a function of depth.

The TP concentration (Fig. 4(c)) in reservoir sediments, in contrast to the Si:Al molar ratio, is frequently affected by three factors: anthropogenic inputs (intensive agriculture present on the S and SW margins), sediment diagenesis, and sedimentation of algal detritus. All three factors potentially affect TP concentrations in NPD

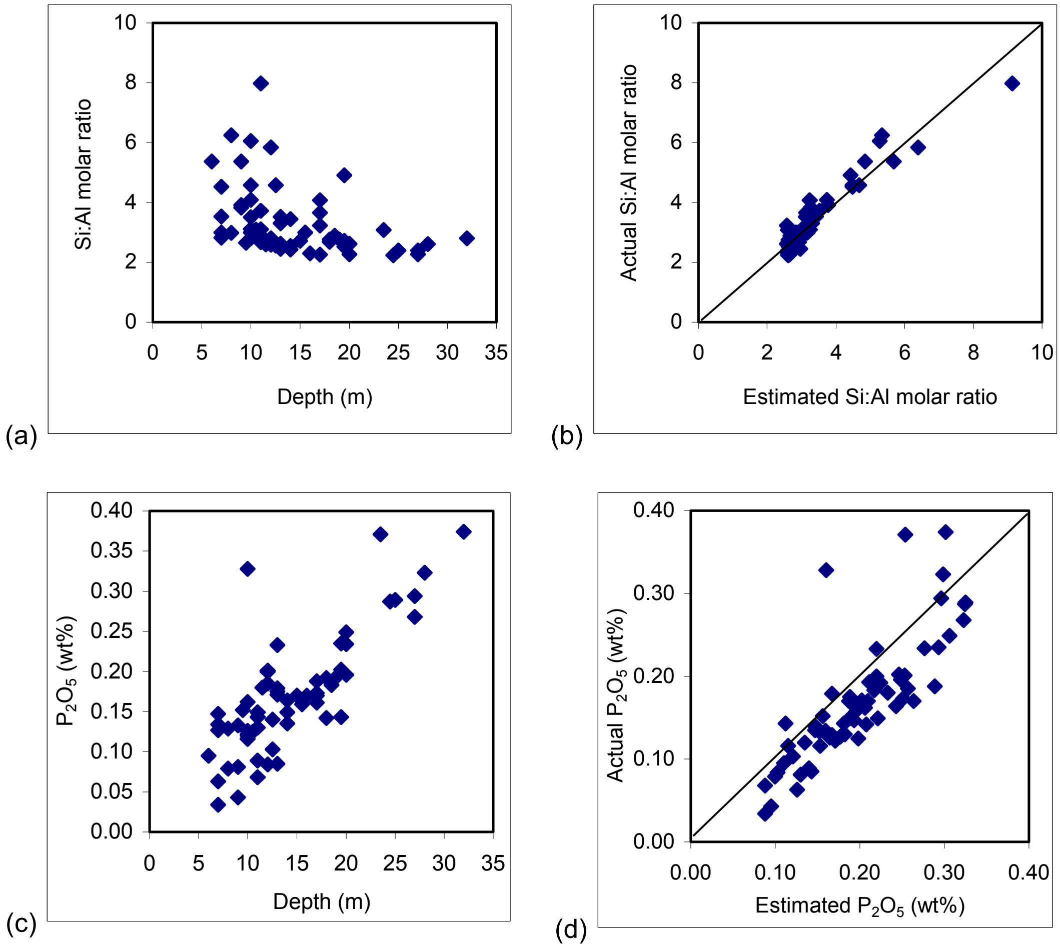

Fig. 4 Relationship between: (a) Si:Al molar ratio and depth; (b) modelled and actual Si:Al ratio; (c) P_2O_5 concentration and depth; and (d) modelled and actual P_2O_5 concentration.

sediments. Model estimates of TP are in reasonable agreement up to concentrations of approximately 0.25 weight % P_2O_5, but may be substantially underestimated at higher TP concentrations (Fig. 4(d)) that occur in deeper zones in NPD. This underestimation may be accounted for by two factors: the accumulation of algal detritus, particularly in deeper zones, as evidenced by a close association of TP and biogenic silica in NPD sediments (Douglas *et al.*, 1999); and the sedimentation of Fe and Mn oxides and/or oxyhydroxides and associated P as a result of artificial aeration of NPD.

CONCLUSIONS

A Bayesian modelling approach utilising endmember models has been used to estimate the proportion of basin sediment sources in sediment samples taken from NPD. Results indicate that one basin sediment source, the Bunya Phyllite, is dominant constituting approximately 75% of the sediment in NPD, being almost twice as abundant in NPD relative to its drainage area. A sedimentary diagenetic component, identified using PCA and comprising Fe, Mn, S and P present as sulphides and oxides or hydroxides, exerts considerable influence on the NPD sediment composition, particularly in deeper areas. Modelled sediment endmember abundances of granitoids and greenstones within NPD display a strong spatial relationship to their drainage basin sources, reflecting differences in grain size and hence, potential for transport and dispersion.

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