Estimating the sources and transport of nutrients in the Waikato River Basin, New Zealand

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[1] We calibrated SPARROW (Spatially Referenced Regression on Watershed Attributes) surface water-quality models using measurements of total nitrogen and total phosphorus from 37 sites in the 13,900-km^2 Waikato River Basin, the largest watershed on the North Island of New Zealand. This first application of SPARROW outside of the United States included watersheds representative of a wide range of natural and cultural conditions and water-resources data that were well suited for calibrating and validating the models. We applied the spatially distributed model to a drainage network of nearly 5000 stream reaches and 75 lakes and reservoirs to empirically estimate the rates of nutrient delivery (and their levels of uncertainty) from point and diffuse sources to streams, lakes, and watershed outlets. The resulting models displayed relatively small errors; predictions of stream yield (kg ha^{-1} yr^{-1}) were typically within 30% or less of the observed values at the monitoring sites. There was strong evidence of the accuracy of the model estimates of nutrient sources and the natural rates of nutrient attenuation in surface waters. Estimated loss rates for streams, lakes, and reservoirs agreed closely with experimental measurements and empirical models from New Zealand, North America, and Europe as well as with previous U.S. SPARROW models. The results indicate that the SPARROW modeling technique provides a reliable method for relating experimental data and observations from small catchments to the transport of nutrients in the surface waters of large river basins. *INDEX TERMS:* 1871 Hydrology: Surface water quality; 1803 Hydrology: Anthropogenic effects; 1806 Hydrology: Chemistry of fresh water; 1857 Hydrology: Reservoirs (surface); *KEYWORDS:* nitrogen, phosphorus, SPARROW, watershed modeling, nutrient retention

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1. Introduction

[2] The major land uses and sources contributing to the nutrient enrichment of surface waters are generally known from the numerous studies of small catchments [e.g., *Bohlke and Denver*, 1995; *Correll et al.*, 1992; *Jaworski et al.*, 1992; *Frink*, 1991; *Boring et al.*, 1988; *Lowrance et al.*, 1984; *Peterjohn and Correll*, 1984; *Beaulac and Reckhow*, 1982] as well as from recent global and continental-scale assessments of nutrient sources [e.g., *Seitzinger and Kroeze*, 1998; *Carpenter et al.*, 1998; *Vitousek et al.*, 1997; *Howarth et al.*, 1996; *Jordan and Weller*, 1996]. Less clear is the origin and fate of nutrients in the diverse network of catchments that make up large watersheds (i.e., those ranging in size from a few hundred to thousands of square kilometers). Improved understanding is needed of nutrient transport over these spatial scales to more effectively manage the variety of pollutant sources responsible for nutrient delivery to downstream water bodies, such as reservoirs and coastal waters where aquatic ecosystems have shown the effects of eutrophication [e.g., *Diaz and Rosenberg*, 1995].

[3] A major challenge in reliably predicting nutrient transport in the surface waters of large watersheds is accounting for the variety of sources and removal processes and the nature of their interactions. Large quantities of nutrients are removed on the landscape and in waterways, but the rates vary widely in response to such factors as climate, topography, soils, vegetation, and the physical and hydraulic properties of streams and reservoirs [*Alexander et al.*, 2000; *Howarth et al.*, 1996; *Johnson*, 1992; *Frink*, 1991; *Seitzinger*, 1988; *Rutherford et al.*, 1987; *Beaulac and Reckhow*, 1982]. Mass-balance assessments of nutrient sources in large watersheds frequently do not explicitly account for the effects of nutrient loss processes on transport [e.g., *Jordan and Weller*, 1996; *Puckett*, 1995; *Jaworski et al.*, 1992]. Moreover, few watershed models have emerged that are capable of accurately estimating the range of contaminant sources and rates of nutrient loss that occur over large spatial scales. The complexity and intensive data requirements of deterministic models often limits their application to small watersheds. Empirical water-quality models, based on linear regression techniques [e.g., *Hainly and Kahn*, 1996; *Osborne and Wiley*, 1988; *Omernik et al.*, 1981; *Lystrom et al.*, 1978] are frequently used in large watersheds; however, the conventional applications of these

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models limit the accuracy and utility of the model predictions for several reasons. First, the lack of mechanistic components (e.g., flow paths, first-order loss functions) and mass-balance constraints in these models produces coefficient estimates with limited interpretability. This limitation complicates attempts to verify how accurately the models quantify the rates of nutrient attenuation and the sources of nutrients in surface waters. Second, the nonlinear effects of nutrient processing on the landscape and in streams and reservoirs are rarely accounted for, including interactions between sources and aquatic loss processes. Finally, the models lack spatially distributed components capable of separating the effects of removal processes on the landscape from those in streams and reservoirs (note some recent advances by *Tufford et al.* [1998] and *Cressie and Majure* [1997]). Instead, sources and sinks are frequently assumed to be uniform throughout watersheds. For these reasons, conventional empirical models poorly address the problem of how to combine and "scale up" nutrient fluxes from small catchments to quantify the transport of nutrients over long distances through stream networks and reservoirs.

[4] A recently developed empirical model, SPARROW (Spatially Referenced Regression on Watershed Attributes [*Smith et al.*, 1997]), uses mechanistic functions with spatially distributed components that account for the dendritic features of watersheds, thereby addressing many of the shortcomings of regression-based empirical models. SPARROW has been used in the United States to separately estimate the quantities of nutrients delivered to streams and watershed outlets from point and diffuse sources over a range of watershed sizes [*Smith et al.*, 1997; *Alexander et al.*, 2000, 2001; *Preston and Brakebill*, 1999]. The model spatially references stream monitoring data, nutrient sources, and watershed characteristics to surface water flow paths defined by a digital drainage network and imposes mass-balance constraints to empirically estimate terrestrial and aquatic rates of nutrient flux. These refinements have been shown to appreciably improve the accuracy and interpretability of model coefficients and predictions of source contributions [*Smith et al.*, 1997; *Alexander et al.*, 2000, 2001; *Stacey et al.*, 2001; *National Research Council* (*NRC*), 2000; *Alexander et al.*, 2002].

[5] Although the applications of the SPARROW model to date have provided important assessments of the performance and validity of the technique, the model has not been previously applied to a fully independent set of river network and watershed data. In this paper we describe an application of SPARROW to nutrient measurements in New Zealand (N.Z.) surface waters. This first application of the technique outside of the United States provided an excellent environmental setting and a comprehensive set of water-resources data for calibrating and validating the models. The watershed characteristics, including stream concentrations, land use, soil drainage, rates of in-stream nutrient loss, and lake/reservoir sizes, represented a wide range of natural and cultural conditions in a temperate climatic setting, which were desirable for calibrating the statistical models. The generally less complex mixture of nutrient sources than found in other industrialized countries, related to the intensive pastoral farming, little row-crop agriculture, and negligible atmospheric N deposition from fossil fuel combustion [*Rutherford et al.*, 1987], allowed for simpler descriptions of diffuse sources in the models. In addition, a comprehensive set of measurements was available for calibrating the model, including a high density of regularly sampled water-quality monitoring stations operated over multiple years according to quality assurance protocols, digital elevation models, land-use and soil surveys, and reliable records of municipal- and industrial-wastewater discharges. Moreover, empirical data were available to validate the models, including literature estimates of land-use yield rates for N.Z. catchments, experimental measurements of in-stream nutrient loss, and models of nutrient attenuation in lakes.

[6] The SPARROW model was applied to stream measurements of total nitrogen and total phosphorus collected during the 1990s at 37 locations in the 13,900-km^2 Waikato River Basin, the largest watershed on the north island of New Zealand (see Figure 1). These sites form a regional monitoring network operated by one of New Zealand's Regional Councils. The Waikato Basin is more than an order of magnitude smaller than previous basins to which SPARROW has been applied. There are also fewer monitoring sites in the Waikato than in previous applications (one half to an order of magnitude fewer), but the station density (number of sites per unit drainage area) is more than an order of magnitude larger. Although studies of N.Z. catchments have identified the major land uses that contribute nutrients to waterways (e.g., see reviews by *Wilcock* [1986] and *Rutherford et al.* [1987]), nutrient measurements from New Zealand's regional and national water-quality monitoring networks have rarely been used to estimate the large-scale effects of land use and sources on nutrient concentrations in streams. One difficulty has been accounting for the variable rates of nutrient flux from watersheds of differing land use and variable rates of nutrient removal in New Zealand streams [*Rutherford et al.*, 1987]. Moreover, numerous reservoirs have been constructed over the past 100 years and have a wide-ranging capacity to remove nutrients from the water column [e.g., *Vant and Hoare*, 1987]. Deterministic simulation models have been applied in subcatchments of the Waikato River Basin and other N.Z. watersheds [*Cooper et al.*, 1992; *Elliott et al.*, 2000] but have not been extended to larger basins. Previous river-basin assessments in New Zealand have used export coefficients in developing nutrient budgets, which involved the extrapolation of nutrient yields from studies of small catchments with uniform land use [*Vant and Bellingham*, 1997; *Vant*, 1999]. One difficulty with these assessments is that the literature yields applied in such approaches vary over a considerable range because of spatial differences in the processing of nutrients on the landscape and in streams [*Vant and Hoare*, 1987; *Cooke*, 1980; *Rutherford et al.*, 1987; *Frink*, 1991; *Ritter*, 1988; *Prairie and Kalff*, 1986; *Beaulac and Reckhow*, 1982].

[7] In this study we used the SPARROW modeling technique to empirically estimate the rates of nutrient delivery from point and diffuse sources to streams and watershed outlets in the Waikato Basin, accounting for watershed processing of nutrients related to streams, reservoirs, and landscape features. Estimates of uncertainty were determined for the model coefficients and predictions to assist in the interpretation of the results. We found strong evidence of the reliability of the SPARROW technique for estimating source contributions to surface waters and the

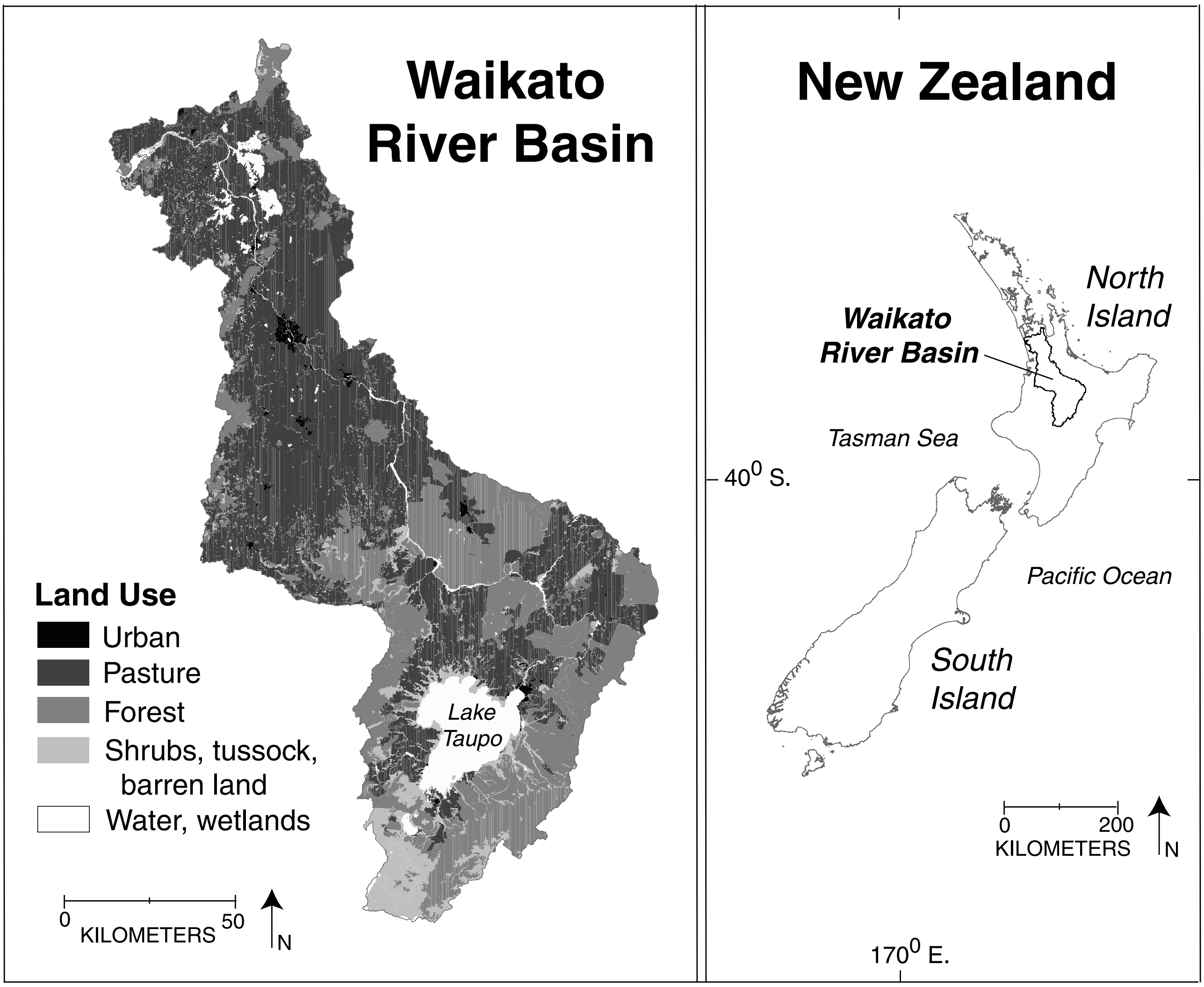

Figure 1. Location and land cover of the Waikato River Basin, New Zealand.

natural rates of nutrient attenuation in watersheds. Selected results from preliminary versions of the models were previously described by *McBride et al.* [2000]. The methods, results, and interpretations of the final models are presented here in five sections. Following the introduction, section 2 describes the SPARROW methodology. Section 3 presents the data sources. The results and discussion are presented in section 4, and the conclusions appear in the final section.

2. Model Development and Application

[8] The model of mean-annual nutrient flux (F_i) in streams is developed for a set of watersheds containing a defined set of nested water bodies (i.e., stream reaches and reservoirs) to which stream monitoring data and data on nutrient inputs and watershed characteristics are spatially referenced. Figure 2 gives a graphical description of the Waikato SPARROW model components, which are described by the equations in this section. The model structure is similar to that described by *Smith et al.* [1997]. The nutrient flux at the downstream end of a given water body i is expressed as the sum of all attenuated nutrient sources (the calibration includes loads from upstream monitoring stations) in the catchments draining to the set of upstream water bodies denoted by $J(i)$ (see illustration in Figure 3). The set $J(i)$ excludes water bodies above monitoring stations located upstream of water body i. An estimable version of the expression for flux is written as

$$F_i = \left\{ \sum_{n=1}^{N} \sum_{j \in J(i)} S_{n,j} \beta_n \exp\left(-\alpha' Z_j\right) H_{i,j}^S H_{i,j}^R \right\} \varepsilon_i, \qquad (1)$$

where $S_{n,j}$ is a measure of the mass contribution or areal extent (in the case of land use) of source type n in the catchment of water body j; β_n is a coefficient for source type n; $\exp(-\alpha' Z_j)$ is an exponential function quantifying the proportion of available nutrient mass delivered to water body j as a function of landscape characteristics (e.g., soils, slope), Z_j, in the catchment of water body j and their associated coefficients (defined by vector α'); $H_{i,j}^S$ is the fraction of nutrient mass present in water body j that is transported to water body i as a function of first-order loss processes in streams; $H_{i,j}^R$ is the fraction of nutrient mass present in water body j that is transported to water body i as a function of first-order loss processes in lakes and reservoirs; and ε is a

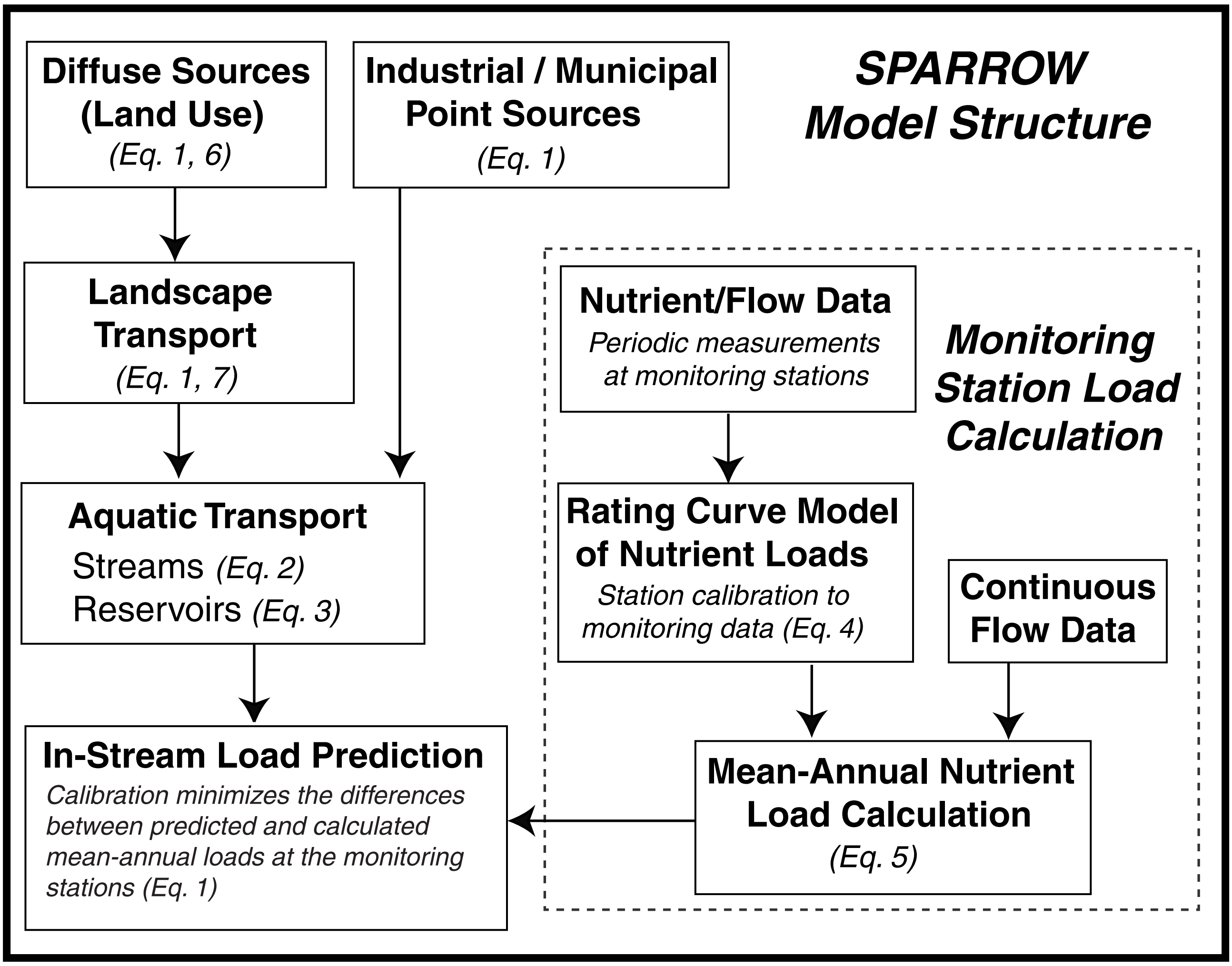

Figure 2. SPARROW (Spatially Referenced Regression on Watershed Attributes) nutrient model structure for the Waikato River Basin. Equations for the model components appear in the text and are referenced by number in parentheses.

multiplicative error assumed to be independent and identically distributed across separate subbasins defined by the intervening drainage area between stream monitoring sites. The term $S_{n,j}\beta_n \exp(-\alpha' Z_j)$ quantifies the mass of nutrients delivered to water body j from source n. The exponential portion of this term is equal to 1 for point-source inputs, which directly enter water body j with no landscape-related attenuation. Upstream monitored inputs are treated as sources introduced directly to water bodies with their source- and landscape-related term, $\beta_n \exp(-\alpha' Z_j)$, constrained to unity. Land characteristics that are positively related to nutrient delivery enter as the reciprocal of the characteristics in Z_j, whereas negatively related delivery characteristics enter as the unadjusted attribute.

[9] The fraction of the nutrient load in water body j that is delivered to water body i as a function of stream channel properties is quantified according to

$$H^S_{i,j} = \prod_m \exp\left(-k^s_m L_{i,j,m}\right), \tag{2}$$

where k^s_m is the first-order loss coefficient (expressed as km^{-1}), m is the number of discrete flow classes, and $L_{i,j,m}$ is

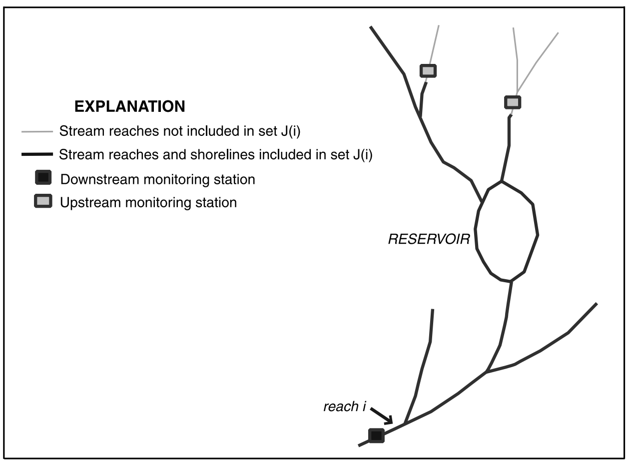

Figure 3. Illustration of a set of nested stream reaches and reservoir shorelines in relation to monitoring stations (modified from *Smith et al.* [1997]). In calibrating the model, reach i refers to any reach containing a monitoring station. In applying the model, reach i refers to any reach where a prediction is made.

the length of stream channel between water bodies j and i in flow class m. This relation provides a first-order approximation to nutrient transport based on theoretical mass-balance properties that describe contaminant transport in streams. Multiple loss coefficients (k_m^s) were estimated to allow for changes in the rate of nutrient loss per unit channel length with stream size. Previous studies have observed an inverse relation between in-stream nutrient loss and channel size, including studies in New Zealand [*Rutherford et al.*, 1987] and in North America and Europe [*Alexander et al.*, 2000]. These observations are generally consistent with theories about the physical and biological mechanisms responsible for nutrient removal in streams [e.g., *Peterson et al.*, 2001; *Stream Solute Workshop*, 1990]. The contact and exchange of stream waters with benthic sediments is generally expected to decline with increasing stream depth, leading to decreases in the rates of nutrient loss related to particulate storage and denitrification.

[10] The fraction of the nutrient load in water body j that is delivered to water body i as a function of lake and reservoir properties is quantified according to

$$H_{i,j}^R = \prod_l \exp\left(-k^r q_{i,j,l}^{-1}\right), \qquad (3)$$

where k^r is an estimated loss rate ("apparent settling velocity"; expressed as m yr^{-1}), $q_{i,j,l}^{-1}$ is the reciprocal areal hydraulic load of lakes and reservoirs (ratio of water-surface area to outflow discharge; units = yr m^{-1}), and l denotes lakes and reservoirs located between water bodies j and i. Empirical applications of mass-balance models [e.g., *Molot and Dillon*, 1993; *Chapra*, 1975; *Kirchner and Dillon*, 1975; *Reckhow and Chapra*, 1982] have shown a strong inverse relation between nutrient retention and the areal hydraulic load of North American and European lakes. Lake mass-balance models have been previously used with limited confidence to predict phosphorus retention in N.Z. lakes and reservoirs [*Vant and Hoare*, 1987]. The apparent settling velocity (or mass-transfer coefficient) quantifies the depth of the water column from which nutrients are removed per unit of time by benthic processes, including denitrification and the settling and burial of particulates [*Chapra*, 1975; *Molot and Dillon*, 1993; *Kelly et al.*, 1987]. Empirical studies have shown several measures of water displacement in lakes, including the areal hydraulic load and the ratio of mean depth to water-residence time, to be equally effective predictors of nutrient retention in lakes [*Reckhow and Chapra*, 1982]. We used the areal hydraulic load in equation (3) because its component measurements were readily determined from available hydrologic data for the Waikato Basin. In addition, the areal hydraulic load is mathematically equivalent to the ratio of depth to water residence time [*Chapra*, 1997]. Lake mass-balance nutrient models [e.g., *Vollenweider*, 1976; *Larsen and Mercier*, 1976] assume a first-order reaction rate under steady state and completely mixed conditions; we estimated nutrient removal by applying equation (3) uniformly throughout lakes and reservoirs of the Waikato Basin (see Figure 3). The lake surface area, used to compute the areal hydraulic load, is assumed to approximate the area of the benthic sediments where nutrient losses occur. The estimated loss rate k^r is a net rate and would be expected to also account for mean inputs from N fixation [*Howarth et al.*, 1988].

[11] Coefficient estimation was performed on the log transforms (natural log) of the summed quantities in equation (1) using nonlinear least squares estimation in the SAS procedure PROC MODEL [*SAS Institute*, 1993]. We applied iterated ordinary least squares estimation (ITOLS; *SAS Institute* [1993]) based on an objective of minimizing the sum of the squared model residuals according to the Gauss-Newton parameter change vectors. The model residuals are defined as the difference between the observed and predicted nutrient flux at the set of stream monitoring stations. The calibration of the model in this procedure minimizes the sum of the squared differences between the observed and predicted values of nutrient flux. Model residuals were examined for normality, constant variance, and nonlinear patterns to determine if regression assumptions were satisfied. The statistical significance of explanatory variables was evaluated according to standard t test statistics (ratio of coefficient mean to the standard error of the coefficient). The standard errors and corresponding t tests are considered to be approximate (i.e., asymptotically valid).

[12] Final estimates of the model coefficients (mean; 90% confidence intervals (CI)) used in model applications were obtained using robust bootstrap techniques [*Efron and Tibshirani*, 1998; *Smith et al.*, 1997]. Model coefficients were estimated by resampling with replacement from the set of mean nutrient fluxes at the 37 stream monitoring stations (see section 3.1) and fitting separate regression models to the resampled data for a total of 200 iterations. The reservoir attenuation coefficient (k^r in equation (3)) was constrained to positive values (i.e., regression iterations with nonpositive coefficients were reestimated until the constraint was satisfied). This constraint avoids the disproportionate (and physically unrealistic) effect of negative loss coefficients on predictions of mean nutrient flux that can occur in reaches below large lakes with very low areal hydraulic loads, such as Lake Taupo (surface area = 612 km^2; see Figure 1). Model accuracy and the estimates of other model coefficients were insensitive to this assumption. Confidence intervals were determined from the coefficient distributions for the 200 model iterations by computing the minimum range of coefficient values such that the fraction of values inside the range equaled the confidence levels [*Smith et al.*, 1997]. Consistent with previous SPARROW studies [*Smith et al.*, 1997; *Alexander et al.*, 2000], we report 90% confidence intervals on the model coefficients.

[13] Predictions of mean nutrient flux, concentration, and source contributions to flux were made for all streams and reservoir outlets in the Waikato Basin by applying the calibrated models to the data for all catchments in the drainage above each reach and reservoir. The mean and variance of model predictions were obtained from the distributions of predictions associated with the 200 bootstrap models [*Smith et al.*, 1997]. The distributions include model-coefficient error and unexplained variability in the model predictions (i.e., model error) as quantified by the regression residuals from each of the 200 bootstrap regressions. Model errors were added at approximately the spatial scale of the incremental drainage areas of the monitoring stations on which the calibrated models were based (about

20 km^2). In this procedure, predictions of flux from the incremental drainages of each of 450 equally sized catchments in the Waikato Basin were multiplied by a randomly selected exponentiated bootstrap residual. Inclusion of the model error corrects the mean predictions for log retransformation bias associated with the application of the log-linear model. Estimates of the model error associated with predictions of flux from point and diffuse sources assumed that each source's share of the total model error is proportional to the source's share of the mean nutrient flux.

3. Watershed Data

3.1. Calculation of Nutrient Flux at Monitoring Sites

[14] The mean-annual nutrient flux (used as the response variable in calibrating the SPARROW models) was computed for 37 fixed monitoring sites (see Figure 4) based on water-column measurements of total nitrogen (TN) and total phosphorus (TP) from monthly water-quality samples and continuous flow measurements for the period from 1993 to 1998. Additional samples were taken during high flows at many sites. The median number of observations was 68 (interquartile range = 66–112). Field sampling, analytical techniques, and quality assurance protocols were those specified for New Zealand's national water quality network [*Smith and McBride*, 1990]. Watersheds for the sites range in size from 22 to 12,700 km^2 (median = 298 km^2) with mean streamflow ranging from 0.2 to 460 m^3 s^{-1}. The mean-annual flux for TN and TP was estimated at each monitoring station by applying standard flux-estimation techniques [e.g., *Cohn et al.*, 1989]. A regression-based rating curve was first used to model the observed values of in-stream flux (f) according to

$$\ln(f_y) = \lambda_0 + \lambda_1 t_y + \lambda_2 \sin(2\pi t_y) + \lambda_3 \cos(2\pi t_y) + \lambda_4 \ln(Q_y) + \varepsilon_y, \tag{4}$$

where t_y is time for the yth stream sample, Q_y is the yth streamflow value, $\sin(2\pi t_y)$ and $\cos(2\pi t_y)$ are trigonometric functions that jointly estimate seasonal variations in flux, $\lambda_{1,\ldots,4}$ are regression coefficients, ε_y is the sampling and model error assumed to be independent and identically distributed, and ln is the natural logarithm. At 12 sites with incomplete records of streamflow, the records were extended by correlating the available instantaneous flows at the water-quality site with those from a nearby gauged site.

[15] The mean-annual flux (F) for the 1993–1998 period was then estimated for each station by integrating over observations of hourly streamflow according to

$$F = \frac{1}{T}\sum_{h=1}^{T} \exp[\lambda_0 + \lambda_1 t_h + \lambda_2 \sin(2\pi t_h) + \lambda_3 \cos(2\pi t_h) + \lambda_4 \ln(Q_h)]\exp(0.5S^2), \tag{5}$$

where T is the number of observations of hourly flow for the period of record, t_h is time for the hth observation of hourly flow, Q_h is the hourly flow value, and S is the root-mean-square error of the regression in equation (4). The exponential term containing the root-mean-square error provides a correction of the mean flux for log-transformation bias according to the *Ferguson* [1986] variance adjustment factor; this provides a reasonable approximation of the mean for large n (>30 samples) and relatively small variance (<0.5).

3.2. Streams and Reservoirs

[16] A digital river-reach network provided the spatial framework for relating in-stream measurements of flux with watershed characteristics in the model. Data on the attributes of streams, reservoirs, and the landscape of the Waikato River basin provided information for describing the surface-water flow paths and were used to develop explanatory variables for the model (see Table 1). The digital traces for nearly 5000 stream reaches in the Waikato Basin (Figure 4) were developed from 100-m digital elevation model (DEM) data by applying conventional flow accumulation algorithms to the DEM cells. The reach traces associated with lakes and reservoirs were identified from GIS overlays of water-body boundaries with reaches. Catchment drainage areas for stream reaches were determined from the accumulated areas of the DEM. The areas of reach catchments range from 0.01 to 38 km^2 with a median of 2 km^2 (interquartile range of 1.2–4 km^2). Estimates of the streamflow for the total drainage area above each reach were determined through an accumulation of the mean-annual runoff (R. Woods, NIWA, written communication, 1999) for reach catchments. These estimates of mean streamflow ranged from about 0.01 to 320 m^3 s^{-1} (median = 0.14 m^3 s^{-1}; interquartile range = 0.05–0.60 m^3 s^{-1}). The mean-annual streamflows at the monitoring sites (based on gauging records for the period 1993–1998) were typically about 30% larger than the DEM-generated mean-annual streamflows.

[17] The total channel distance from downstream monitoring stations to upstream river reaches (used in estimating in-stream attenuation in equation (2)) was computed by applying a "network climbing" algorithm to sum reach lengths [*Smith et al.*, 1997; *White et al.*, 1992]. Total channel distances were summed separately for 10 streamflow classes (using the mean-flow breakpoints of 0.1, 0.5, 1, 2, 5, 10, 50, 100, 200 m^3 s^{-1}) to allow estimation of in-stream nutrient attenuation as a function of discrete ranges of mean streamflow in equation (2). Because separate stream and reservoir/lake attenuation rates are estimated, the reach lengths (i.e., shorelines) associated with reservoirs and lakes (see Figure 3) are subtracted from the estimates of the total channel distance between downstream monitoring stations and upstream reaches. Estimates of the areal hydraulic load in equation (3) were computed for 75 lakes and reservoirs as the ratio of the reservoir outflow discharge to water surface area. The mean flow for the outlet reach of each reservoir was used to estimate the mean discharge from the reservoir.

[18] Flow diversions and interbasin water transfers in the upper portions of the Lake Taupo drainage were included into the modeled flow paths of the stream network. Two pseudo reaches were added to the network above Lake Taupo to account for flow diversions from the Tongariro River to Lake Rotoaira and from Lake Rotoaira to Lake Taupo. The estimated nutrient flux associated with interbasin water transfers into the watersheds of Lake Rotoaira and the Tongariro River were treated as direct inputs to these

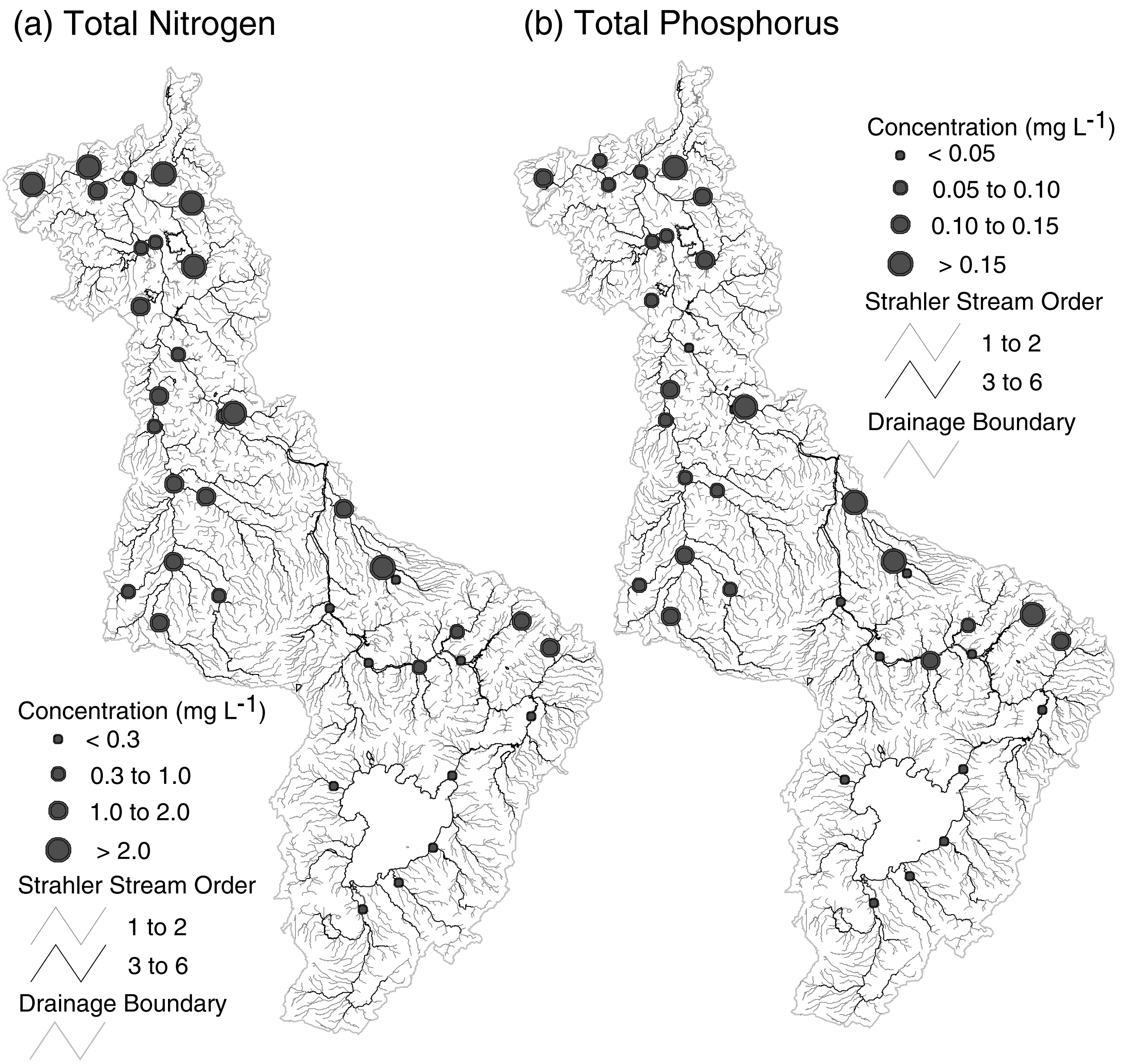

Figure 4. Mean-annual nutrient concentrations at 37 monitoring locations in the Waikato River Basin, 1993–1998: (a) total nitrogen, (b) total phosphorus.

watersheds in the models. Measured nutrient loads to Lake Rotoaira from the Wairehu Canal included interbasin transfers and nutrient contributions from upstream catchments (as a result, the catchments of 16 stream reaches were not included as part of the modeled drainage).

3.3. Nutrient Sources

[19] The major sources of nutrients to waterways in the Waikato Basin include municipal wastewater-treatment plants, industries (dairies, wood processing, piggeries, geothermal utilities), and livestock wastes from pasture runoff and farm storage ponds (primarily dairying, sheep, and beef cows). Pastureland represents the predominant land use (56%) in the Waikato (see Table 2) followed by exotic pine forests (17%). We characterized the sources of nutrients according to the variables listed in Table 1 for use in exploratory SPARROW models. Estimates of nutrient discharges to rivers from municipal wastewater-treatment plants and major industries were made for 22 of the largest facilities. These facilities were spatially referenced to the reach network through automated GIS analytical methods and verified through manual inspection of the locations and reach assignments. Various measures of nutrient inputs from diffuse sources were evaluated by using land-resources data [*Terralink International Limited* (*TIL*), 1992] on land cover, cow population densities, and soil erosion potential. Land area with apatite mineral deposits [*TIL*, 1997] was evaluated in the TP model as a natural source of phosphorus to the watershed. Atmospheric sources of nutrients are negligible and therefore were not explicitly defined in the models (note that nitrogen forms in N.Z. precipitation are within the range reported for remote areas of the world; P rates are similar to those reported overseas [*Rutherford et al.*, 1987]). Horticulture is limited to a small area in the northern portion

Table 1. Explanatory Variables Used in Exploratory SPARROW Models of Total Nitrogen (TN) and Total Phosphorus (TP)

Explanatory Variable	Units
Sources	
Point source loads (TP, TN)	metric tons yr^{-1}
Pastureland	hectares
Pine forests	hectares
Scrublands	hectares
Other lands (urban, barren, wetlands)	hectares
Soil erosion index	index units (1–6; low to high)
Cow populations (ponds, field disposal)	number of livestock
Apatite minerals (land area)	hectares
Landscape	
Rainfall	millimeters
Runoff	mm yr^{-1}
Slope	percent
Soil drainage index	index units (1–7; low to high soil drainage)
Stream density	km km^{-2}
Streams and Lakes/Reservoirs	
Channel length	meters
Reservoir channel length	meters
Water velocity	m s^{-1}
Lake and reservoir discharge	m^3 s^{-1}
Lake and reservoir volume (15 cases)	m^3
Lake and reservoir surface area	km^2

of the Waikato Basin; estimates of fertilizer use on these lands were not included in the models because of the lack of detailed sales information. Phosphate fertilizer use on pasturelands is believed to be relatively uniform. Nitrogen fertilizer is not routinely used on pasturelands, where N-fixing clover is frequently planted (see section 4.5).

[20] The diffuse source characteristics of the reach catchments were determined by intersecting watershed boundaries with the polygonal areas associated with the Land Resources Inventory data [*TIL*, 1997] in a GIS. We estimated the source characteristics ($S_{n,j}$) for water body j and source type n as

$$S_{n,j} = \sum_{k \in P(k)} S_{n,k}\left(A_{j,k}/A_k\right), \tag{6}$$

where $P(k)$ is the set of all source-related polygons associated with water body j, $S_{n,k}$ is the quantity of source-type n associated with polygon k and containing water body j, $A_{j,k}$ is the area of the watershed associated with water body j and source-related polygon k, and A_k is the total area of the source-related polygon k. Where the diffuse source is associated with a land-cover type (e.g., pastureland), the term $\beta_n \exp(-\alpha' Z_j)$ in equation (1) quantifies the mass per unit area contributions to water (i.e., yield) from the particular land-cover type. Because the point sources are discharged directly to streams, and enter equation (1) in units of mass (that are identical to the SPARROW response variable) without any land-to-water attenuation applied, a fitted point-source coefficient (β_n) of 1 is expected.

3.4. Physical Characteristics of the Landscape

[21] We examined the effect of a various climatic and landscape characteristics on the delivery of diffuse sources of nutrients to reservoirs and rivers in exploratory calibrations of the models (see Table 1), including the slope of the terrain, soil drainage, and runoff within the catchments. Estimates of the slope and soil-drainage attributes of the watersheds were obtained from the Land Resources Inventory [*TIL*, 1997]. Area-weighted mean estimates of slope and soil drainage were computed for each reach catchment. We estimated the mean land characteristics (Z_j) for water body j as

$$Z_j = \sum_{x \in P(x)} Z_x\left(A_{x,j}/A_j\right), \tag{7}$$

where $P(x)$ is the set of all land-characteristics polygons in water body j, Z_x is the land characteristic of polygon x containing water body j, $A_{x,j}$ is the portion of the area of the watershed of water body j associated with land-characteristic polygon x, and A_j is the total area of the water body watershed j. Stream density was computed as the ratio of reach length to catchment area.

4. Results and Discussion

4.1. Monitoring Station Flux, Concentration, and Yield

[22] The rating curves (equation (4)) used to calculate the mean-annual nutrient flux (equation (5)) at each monitoring station were found to provide an acceptable fit to the measurements of instantaneous nutrient flux; median R-squared values were 0.92 for TN and 0.83 for TP (interquartile range = 0.75–0.96 for TN and 0.55–0.92 for TP). Regression residuals displayed approximate normality and constant variance. The mean square error (MSE) values typically ranged from 0.18 to 0.35 for TN and from 0.24 to 0.42 for TP. Only two stations had MSE values greater than 0.50. The MSE values were sufficiently low for the *Ferguson* [1986] method to provide acceptable correction for log transformation bias in the station nutrient loads. The median bias-correction factors for the stations were 3% for TN and 5% for TP (interquartile range from 2 to 9%).

[23] The percentiles of the mean estimates of flow, concentration, flux, and yield for the 37 monitoring stations are summarized in Table 3. The mean-nutrient flux, the response variable in the SPARROW models, ranges over approximately 3 orders of magnitude. Nutrient flux increases with streamflow and displays the highest values for higher-order streams at the outlets of the largest catchments. Maps of the mean nutrient concentrations at the sites (Figure 4) provide initial evidence of the effects of nutrient

Table 2. Land Cover of the Waikato River Basin[a]

Land-Cover Type	Drainage Basin Area, km^2	Percentage of Area
Pastureland	7,863	56.4
Forest		
Exotic pine	2,435	17.5
Native	1,569	11.3
Scrub	753	5.4
Urban	133	1.0
Water, wetlands	908	6.5
Other (barren lands, horticulture, mines, coastal)	270	1.9
Total	13,931	100.0

[a] Estimated from the Land Resources Inventory [*Terralink International Limited*, 1992].

Table 3. Mean-Annual Streamflow, and the Mean-Annual Flux, Concentration, and Yield for Total Nitrogen and Total Phosphorus at 37 Stream Monitoring Stations in the Waikato River Basin

Station Metric	Minimum	25th	50th	75th	Maximum
Total nitrogen					
Flux, metric tons yr^{-1}	3.9	53	147	703	12,206
Concentration, mg L^{-1}	0.10	0.31	0.94	1.5	4.5
Yield, kg ha^{-1} yr^{-1}	1.1	3.2	8.6	11	28
Total phosphorus					
Flux, metric tons yr^{-1}	0.50	5.2	23	81	1,054
Concentration, mg L^{-1}	0.01	0.04	0.07	0.12	0.60
Yield, kg ha^{-1} yr^{-1}	0.11	0.36	0.60	0.83	2.4
Streamflow, m^3 s^{-1}	0.20	1.6	5.9	95	464
Drainage area, km^2	22	101	198	2,551	12,730

sources on in-stream conditions. In the Waikato, nutrient concentrations are generally lowest in headwater streams and the less culturally affected southern catchments, including tributaries to Lake Taupo where large amounts of forested land are found. By contrast, the highest nutrient concentrations occur in the northern and eastern portions of the basin where larger human and livestock populations are found. Although concentrations (Figure 4) show a general correspondence with land use (Figure 1), additional spatial variations in concentrations occur in response to interactions between nutrient sources and attenuation processes as described by the calibrated SPARROW models in the next section.

4.2. Model Calibration

[24] The parametric and bootstrap estimates of the SPARROW model coefficients are given in Tables 4 and 5 for TN and TP, respectively. Interpretations of the coefficient values are discussed for each of the major model components in subsequent sections. The models account for the effects of municipal/industrial point sources, diffuse sources from pasture and nonpastureland areas, and nutrient attenuation in soils, streams, and reservoirs. These models reflect the outcome of evaluations of exploratory models using various properties of the catchments as described in Table 1. The statistical significance of t tests was used to guide the selection of explanatory variables. Priority was given to fitting the source variables (point, diffuse) and stream and reservoir loss terms; landscape-attenuation factors were included provided the overall fit of the model improved (i.e., lower MSE) and the statistical significance and interpretation of the other model components was not degraded. The final models contain from five to seven coefficients with the approximate parametric t values displaying relatively high ($p < 0.05$) to moderate ($p < 0.18$) levels of statistical significance for most coefficients. The TP model coefficients show the highest levels of statistical significance. The bootstrap models are generally more robust than the parametric-based models with more accurate estimates of coefficient variability; the parametric estimates are only asymptotically valid. The mean bootstrap coefficients were generally similar to the parametric coefficients, although the TN bootstrap model had somewhat larger inputs from point and diffuse sources and larger losses in soils, streams, and reservoirs.

[25] Model convergence in the SAS nonlinear regression procedure was relatively efficient and resulted in final parameter values having the appropriate sign and magnitude (see literature comparisons in the following sections). Initial values for TN and TP model parameters in the nonlinear regressions were guided by literature estimates for selected parameters (e.g., a summary of in-stream attenuation from studies of New Zealand streams by *Rutherford et al.* [1987]; an expected point-source coefficient of 1.0; and land-use yields from literature reviews by *Cooke* [1980], *Rutherford et al.* [1987], and *Wilcock* [1986]). Parameter estimates displayed reasonable stability; little change occurred in the values of the most statistically significant model coefficients when additional variables were added in exploratory regressions. The initial models converged within about 10–12 iterations; subsequent exploratory models converged within five iterations once refinements were made in the model

Table 4. SPARROW Total Nitrogen Model Coefficients Calibrated to 37 Stations in the Waikato River Basin

Model Parameter	Parametric Coefficient	Parametric p value	Bootstrap Coefficient	Lower 90% CI	Upper 90% CI	Units
Sources, β						
Point	1.03	0.183	1.08	0.25	1.81	dimensionless
Pastureland	49.56	0.040	71.39	18.21	146.80	kg ha^{-1} yr^{-1}
Nonpasture land	5.97	0.104	8.63	0.98	15.58	kg ha^{-1} yr^{-1}
Soil drainage, α	0.155	0.073	0.182	0.043	0.322	index $unit^{-1}$
Aquatic loss[a]						
Small streams, k_1^s	0.174	0.024	0.223	0.017	0.514	km^{-1}
Large streams, k_2^s	−0.0001	0.981	0.001	−0.003	0.004	km^{-1}
Reservoirs, k^r	4.38	0.014	6.21	2.56	10.22	m yr^{-1}
R-squared	0.968					
Mean-square error	0.142		0.116			

[a] Small and large streams are defined according to a mean streamflow below and above 1 m^3 s^{-1}. The reservoir loss coefficient is constrained to positive values in the bootstrap estimation.

Table 5. SPARROW Total Phosphorus Model Coefficients Calibrated to 37 Stations in the Waikato River Basin

Model Parameter	Parametric Coefficient	Parametric p value	Bootstrap Coefficient	Lower 90% CI	Upper 90% CI	Units
Sources, β						
Point	1.02	0.062	0.96	0.21	1.47	dimensionless
Pastureland	2.84	<0.001	2.78	1.88	3.79	kg ha^{-1} yr^{-1}
Nonpasture land	0.72	0.001	0.81	0.39	1.30	kg ha^{-1} yr^{-1}
Aquatic loss[a]						
Small streams, k_1^s	0.430	<0.001	0.426	0.234	0.613	km^{-1}
Large streams, k_2^s	−0.0006	0.901	–	–	–	km^{-1}
Reservoirs, k^r	8.03	<0.001	10.15	1.14	9.76	m yr^{-1}
R-squared	0.968					
Mean-square error	0.145		0.122			

[a] Small and large streams are defined according to a mean streamflow below and above 1 m^3 s^{-1}. The in-stream loss coefficient for large streams is assumed equal to zero, and the reservoir loss coefficient is constrained to positive values in the bootstrap estimation.

form and initial coefficient values. The use of initial values outside of the literature ranges gave identical coefficient estimates, providing strong evidence that the regression models converged to a global minimum.

[26] Both TN and TP models fit the observational data well (Figures 5a and 6a), explaining approximately 97% of the spatial variations in the natural logarithms of mean-annual nutrient flux. Models based on the parametric estimation of model coefficients have MSE values of 0.14. The logged residuals provide acceptable adherence to error assumptions. The residuals are approximately normal and relatively constant in variance, although there is some evidence of higher variance for several sites in small catchments. No distinct geographic patterns were evident in maps of the station residuals; therefore the assumption of independence in the model errors among subbasins is reasonably valid. Errors in the predicted TN flux range from −6% to 15%, based on the interquartile range for the differences between the predicted and observed values at the monitoring sites (median = 2.5%). Errors in the predicted TP flux are somewhat larger with an interquartiles range of −20% to 28% (median = 5.8%). The plots of observed and predicted nutrient yields (Figures 5b and 6b) adjust for the effects of drainage area on nutrient flux and also show reasonably good agreement (R-squared = 0.48 and 0.71 for TN and TP, respectively). The lower R-squared value for TN is primarily caused by a single, large outlier (Figure 5b) corresponding to an underprediction of TN yield of −75% at the Whakapipi River monitoring site. This underprediction is probably explained by the application of fertilizer for horticulture in this catchment, a source not explicitly included in the model. The model also underpredicts TP at this monitoring site (−51%). Fertilizer use in other catchments occurs primarily as phosphorus applications to pastureland; the application rates outside of the horticultural areas are generally much lower and relatively uniform (see section 4.5). The underprediction of TN yield at the Mangatangi River site, the other outlier visible in Figure 5b, may be potentially explained by the bottom release of nutrient-enriched waters from an upstream reservoir. One of the largest underpredictions in TP is for the monitoring site Tongariro River at Turangi, where the nutrient concentrations in the incoming interbasin transfer waters may actually be higher than those used in the model.

[27] A comparison of the performance of the Waikato nutrient models with previous SPARROW applications in the United States [*Smith et al.*, 1997; *Preston and Brakebill*, 1999] indicates that the Waikato models generally provide a more accurate fit to nutrient observations than the U.S. models. The R-squared and MSE of the Waikato TN

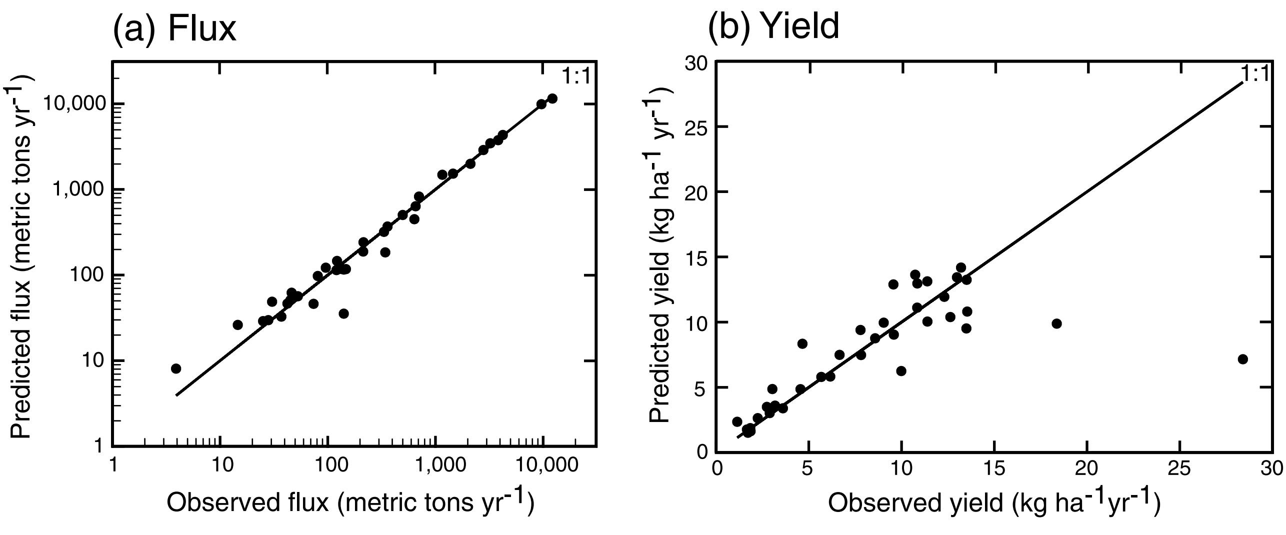

Figure 5. SPARROW total nitrogen (TN) model: (a) predicted versus observed flux, (b) predicted versus observed yield.

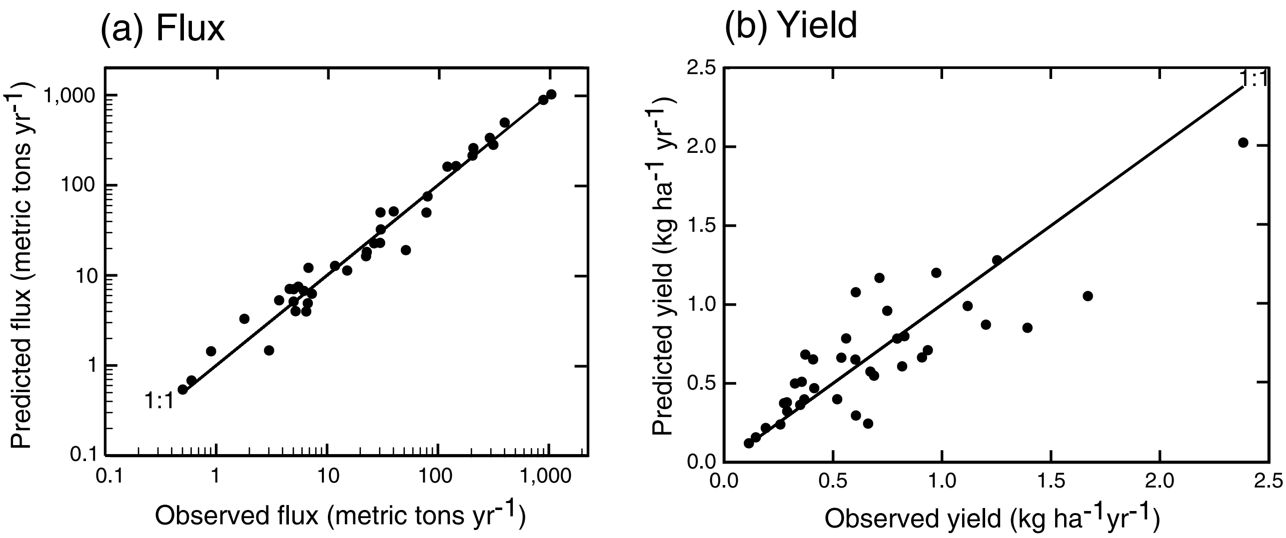

Figure 6. SPARROW total phosphorus (TP) model: (a) predicted versus observed flux, (b) predicted versus observed yield.

and TP models are similar to those observed for the Chesapeake Bay (CB) SPARROW, which was fit to data from 79 stations in the 164,000-km^2 Bay watershed [*Preston and Brakebill*, 1999]. However, the Waikato TN model shows consistently smaller prediction errors than observed for either the U.S. national model or CB model; prediction errors, expressed as a percentage difference between the predicted and observed flux, are typically 30–50% smaller. The prediction errors of the Waikato TP model are similar to those for the CB model but about 50% smaller than those for the U.S. national TP model. The smaller prediction errors in the Waikato models may be explained by the high spatial density of monitoring sites combined with steep spatial gradients in watershed characteristics. The smaller spatial variability in nutrient flux in the Waikato Basin as compared to that in U.S. watersheds may also contribute to the differences.

4.3. Attenuation in Streams, Reservoirs, and Lakes

[28] The most reliable models (positive coefficients, highest *t* statistics, and lowest MSE) for both TN and TP describe the aquatic attenuation of nutrients as a function of two in-stream loss coefficients and a single reservoir/lake loss coefficient (Tables 4 and 5). These loss rates reflect the mean-annual rate of nutrient removal in streams and reservoirs based on the steady state form of the models.

4.3.1. In-Stream Attenuation

[29] The in-stream loss coefficients indicate that considerably larger quantities of nutrients are removed per unit of channel length in small streams (i.e., mean flow from 0.01 to 1.0 $m^3\ s^{-1}$) than in the large streams (mean flow from 1.0 to 460 $m^3\ s^{-1}$). The estimated mean loss rates for small streams in the bootstrap nutrient models exceed those for large streams by more than 2 orders of magnitude. Nitrogen is removed from small streams at a rate of about 20% km^{-1} of channel length (0.223 km^{-1}) in comparison to a rate of about 0.1% km^{-1} in large streams (Table 4). These rates are statistically separable based on the lack of overlap in the 90% confidence intervals (also separable at the 95% level); the lower bound on the confidence interval for the small-stream rate exceeds the upper bound on the confidence interval for the large-stream rate by a factor of 4. The confidence interval on the large-stream loss rate also includes zero and has an upper bound of 0.4% km^{-1}. Phosphorus is removed from small streams at a rate of about 35% km^{-1} (0.426 km^{-1}), nearly twice the rate of removal of nitrogen. The TP loss rate in large streams was assumed to be zero in the final bootstrap model because a small negative rate was estimated in the initial bootstrap model.

[30] The choice of streamflow classes for estimating the in-stream loss coefficients was based on an evaluation of model fit (MSE and *t* statistics) and the sign of the in-stream loss rates in exploratory and final bootstrap models. The exploratory models evaluated as many as 10 mean flow classes (see the flow breakpoints described in section 3.2). Models based on the two selected mean flow classes performed appreciably better with lower MSEs than other exploratory models. Models based on a single in-stream loss rate for all streams displayed a significantly larger model error (i.e., 50% higher MSE) and negative in-stream loss coefficients. Continuous flow-function models were also evaluated for TN and TP; however, the MSE of these models was from 20 to 60% higher than that for the discrete-function models. Models based on the use of water time-of-travel estimates rather than stream channel length (water velocity was estimated from studies of the hydraulic geometry of N.Z. streams [*Jowett*, 1998]) showed slightly poorer fit to the observations (i.e., MSE 4–7% higher).

[31] The inverse relation between the rate of nutrient loss and streamflow observed in this study is consistent with current theories about the physical and biological mechanisms responsible for nutrient removal in streams [*Stream Solute Workshop*, 1990] as well as with literature estimates of nutrient loss in streams and rivers of North America, Europe, and New Zealand (see Figures 7 and 8 and *Rutherford et al.* [1987], *Smith et al.* [1997], *Alexander et al.* [2000], *Seitzinger et al.* [2002], and *Howarth et al.* [1996]). Streamflow is related to channel depth and provides a measure of the extent of contact of the water column

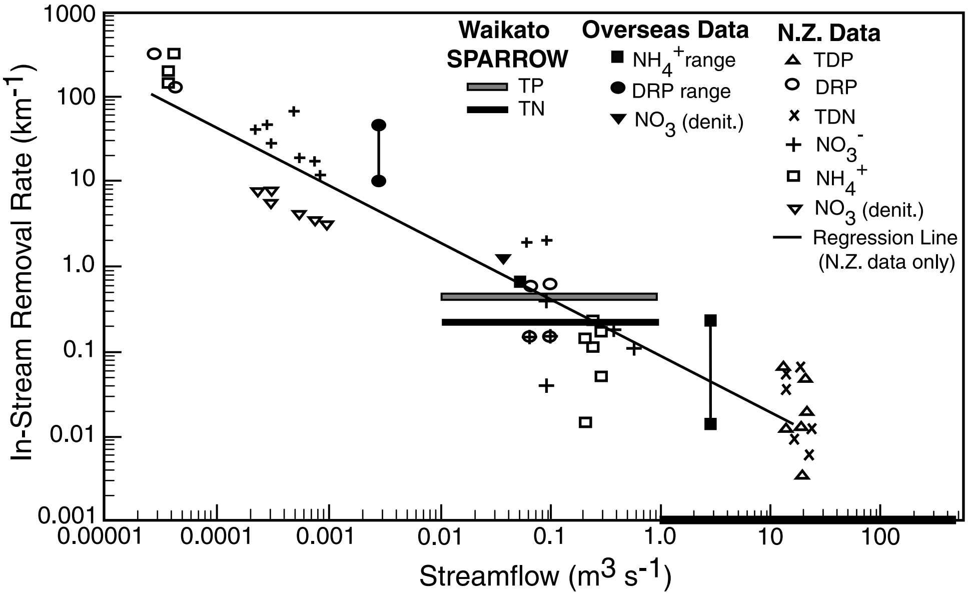

Figure 7. In-stream rates of nutrient removal for the Waikato SPARROW models and other watershed studies in relation to streamflow (modified from *Rutherford et al.* [1987]). Nutrient forms include TN, NH_4^+ (ammonium), NO_3 (nitrate), TDN (total dissolved nitrogen), TP, DRP (dissolved reactive phosphorus), and TDP (total dissolved phosphorus).

with benthic sediments, which affects losses via denitrification and particulate storage. Denitrification is the principal mechanism for permanently removing nitrogen from streams. The depth of the stream channel may affect the supply of nitrate for denitrification by controlling the quantities of water-column nitrogen in contact with the benthic sediment through processes such as diffusion and hyporheic exchange [*Seitzinger*, 1988; *Kelly et al.*, 1987; *Triska et al.*, 1993]. Channel depth is also related to variations in the dynamics of streams (e.g., turbulence, water velocity, photosynthesis) that affect the rates of nitrogen and phosphorus removal from the water column by stream biota and the storage of particulates [*Peterson et al.*, 2001; *Rutherford et al.*, 1987]. Thus nutrients are more readily removed in small, shallow streams because the high benthic surface area to water-volume ratio in these streams

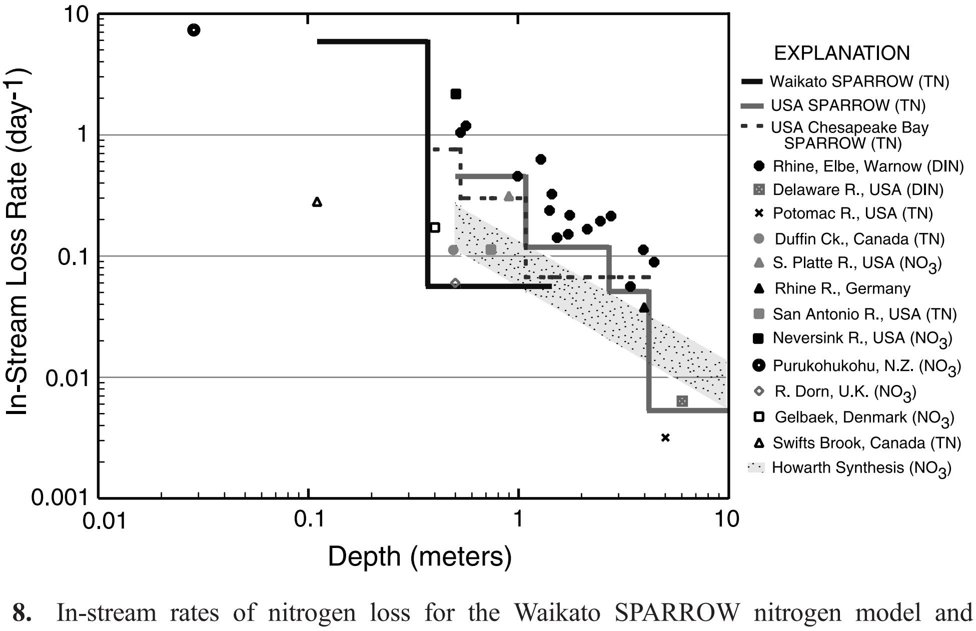

Figure 8. In-stream rates of nitrogen loss for the Waikato SPARROW nitrogen model and other watershed studies in relation to stream channel depth (modified from *Alexander et al.* [2000]; data for Purukohukohu from *Cooper and Cooke* [1984]; data for R. Dorn, Gelbaek, and Swifts Brook from *Seitzinger et al.* [2002]; other estimates are from *Alexander et al.* [2000]. Nitrogen forms are DIN (dissolved inorganic nitrogen), TN, and NO_3 (nitrate-N)).

ensures greater contact and exchange of the water-column nutrients with the benthic sediment than occurs in large, deep streams and rivers.

[32] We find that the in-stream nutrient loss rates for the SPARROW Waikato models are consistent with nutrient loss rates (expressed per unit channel length) from experimental studies of N.Z. streams (Figure 7). The SPARROW loss rates are for streams with mean flows ranging from about 0.01 to 460 $m^3\ s^{-1}$ and apply to the upper two thirds of the range of stream sizes reported by *Rutherford et al.* [1987] in Figure 7. The SPARROW rates for small streams (mean flow 0.01–1 $m^3\ s^{-1}$) fall within the range of the literature measurements, which include denitrification measurements for streams with flow less than about 0.1 $m^3\ s^{-1}$. The SPARROW TN loss rate for large streams (mean flow >1 $m^3\ s^{-1}$) falls at the lower end of the reported literature rates. Because the SPARROW loss rates are calibrated for mean conditions during a 5-year period, they generally reflect more long-term nutrient losses, such as denitrification and the multiyear storage of particulates. The loss rates reported by *Rutherford et al.* [1987] were measured during base flow and, in addition to denitrification, reflect the uptake of nutrients by aquatic plants (e.g., macrophytes). These loss rates are generally similar to the mean SPARROW rates or somewhat higher for large streams. In general, higher nutrient losses (and rate coefficients) might be expected during base flow when less turbulence, longer water-travel times, and shallower depths may lead to greater rates of attenuation via denitrification and biological uptake and particulate settling. In addition, literature rate coefficients, associated with a temporary removal of nutrients from the water column by stream biota, may be higher in magnitude than the long-term mean loss rates estimated by SPARROW, which are unaffected by the short-term cycling of nutrients.

[33] We also find that the in-stream TN loss rates for the SPARROW Waikato model generally agree with earlier SPARROW estimates for the United States and literature estimates of long-term N removal rates for North American and European streams [*Alexander et al.*, 2000; *Seitzinger et al.*, 2002]. SPARROW loss rates for U.S. streams, expressed in units of reciprocal time, were shown previously to be consistent with the available literature rates from mass-balance studies and experimental measures of denitrification when plotted as a function of channel depth [see *Alexander et al.*, 2000]. We compared the Waikato SPARROW rates and additional literature rates [*Seitzinger et al.*, 2002], including estimates from N.Z. streams [*Cooper and Cooke*, 1984], with the reported rates from *Alexander et al.* [2000] in Figure 8. The Waikato TN loss rates (in units of reciprocal channel length) were transformed to units of reciprocal time based on estimates of flow velocity from studies of the hydraulic geometry of N.Z. streams ($v = 0.36\ Q^{0.241}$, where v = velocity as $m\ s^{-1}$ and Q is the mean flow as $m^3\ s^{-1}$ for each of the two mean flow classes [*Jowett*, 1998]). Mean channel depth is estimated as a function of mean streamflow ($d = 0.37\ Q^{0.239}$, where d = depth in meters and Q is flow as $m^3\ s^{-1}$ [*Jowett*, 1998]). The comparisons indicate general similarities in the magnitudes of the rates and their inverse relation to channel depth (Figure 8). For streams with depths ranging from 0.4 to 1.5 m (i.e., Waikato high-flow class), the Waikato mean loss rate of 0.056 day^{-1} (0.223 km^{-1}) plots near the lower end of the range of literature estimates. The 90% confidence interval for the mean includes zero and has an upper bound of 0.424 day^{-1} (0.004 km^{-1}). The Waikato mean loss rate of 0.056 day^{-1} is within a factor of 1–5 of the SPARROW mean loss rates for moderate to large streams in the Chesapeake Bay watershed and within a factor of 2–8 of the U.S. SPARROW mean rates for similar stream sizes. Few literature estimates of nitrogen loss are available for streams with depths less than 0.4 m (Waikato low-flow class). The Waikato loss rate of 5.9 day^{-1} for this flow class agrees most closely with estimated denitrification-induced losses of nitrate of 7.2 day^{-1} for a shallow N.Z. stream [*Cooper and Cooke*, 1984]. In general, the greater variability among the literature rates for streams less than about 2 m in depth may reflect the effects of variations in water column nitrate concentrations or substrate conditions on nitrogen removal, including such factors as the carbon and oxygen content of sediments [*Seitzinger*, 1988; *Cooper and Cooke*, 1984].

[34] A recent study of nitrogen cycling in 15 shallow streams (depth = 0.04–0.23 m) in North America [*Peterson et al.*, 2001] reported that the rates of inorganic N removal measured over short time intervals (i.e., days) generally decline with increases in channel depth. When expressed as a loss rate per unit time, the rates of N removal range from 7 to 280 day^{-1} (median = 56 day^{-1}). These rates are larger than the rates shown in Figure 8 but are consistent with the overall inverse relation with depth. In addition to denitrification, these rates include the effects of temporary losses related to biological uptake (instantaneous estimates of inorganic N regeneration and release to the water column ranged from negligible quantities to about 60% of the nitrogen uptake). The nitrogen loss rates estimated from other literature data and by SPARROW for similar sized streams in Figure 8 reflect more permanent losses (i.e., denitrification, storage [*Alexander et al.*, 2000; *Seitzinger et al.*, 2002]), which may explain their differences with the higher short-term loss rates estimated from the *Peterson et al.* [2001] data.

4.3.2. Reservoir and Lake Attenuation

[35] The SPARROW estimates of the TN and TP mean settling velocities for lakes and reservoirs of the Waikato Basin are 6.2 and 10.2 $m\ yr^{-1}$, respectively (Tables 4 and 5), and are among the most statistically significant of all coefficients in the nutrient models. We found that estimating a constant settling velocity for all lakes and reservoirs provided the best fit to the observed data; additional settling velocity coefficients, fit to various discrete classes of the areal hydraulic load, were not statistically significant ($p >$ 0.50). The estimates of the mean settling velocity were determined from positively constrained coefficient distributions (see section 2) and are 20–35% higher than estimates based on unconstrained distributions (i.e., TN = 4.6 $m\ yr^{-1}$; TP = 8.4 $m\ yr^{-1}$). The constrained coefficient distribution for TP shows sufficient positive skew to produce a high mean settling velocity relative to the upper 90% CI (the minimum CI calculation also contributes to this result).

[36] The mean SPARROW settling velocities and their corresponding confidence intervals are well within the range of mean settling velocities that have been reported for North American and European lakes. Literature estimates for total phosphorus typically range from about 5 to 20 $m\ yr^{-1}$ [*Chapra*, 1997]. Literature estimates for nitrogen

(see Table 6) are typically less than about 10 m yr^{-1} in lakes where denitrification is the dominant removal process [e.g., *Kelly et al.*, 1990; *Molot and Dillon*, 1993]. Such lakes frequently have moderate to large N to P ratios (also typically phosphorus limited) and relatively high N inputs. By comparison, nitrogen settling velocities of more than 25 m yr^{-1} have been observed in lakes where uptake and sedimentation are the dominant removal processes; these lakes are generally characterized by low N to P ratios [*Kelly et al.*, 1990]. Although direct measurements of the rates of benthic denitrification and sedimentation are unavailable for Waikato lakes and reservoirs, comparisons of the SPARROW TN settling velocity with those from literature studies suggest that denitrification is likely to be a major mechanism for removing nitrogen in lakes and reservoirs of the Waikato River Basin.

[37] The mean fractions of TN and TP removed from reservoirs and lakes of the Waikato (Figures 9a and 9b) were computed by applying the estimated settling velocity rates from the bootstrap distributions and measured areal hydraulic loads of each water body in equation (3). The lake-surface area and outflow rates of the 75 Waikato reservoirs span a very large range with areal hydraulic loads ranging over about 4 orders of magnitude (median = 84 m yr^{-1}; 17–720 m yr^{-1} interquartile range). The corresponding nutrient removal fractions also display a considerable range. For TP, the mean percentage of external inputs removed by lakes and reservoirs range from less than 1% to 92% (median = 10%; interquartile range = 1–37%). In 13 of the 75 reservoirs, more than 50% of the external inputs of TP are removed. The mean TN removal percentage ranges from less than 1% to 87% (median = 6%; interquartile range = 1–27%). More than 50% of the TN is removed in each of 10 reservoirs. Less than 2% of the TN and TP loads that enter each of the eight hydrodam reservoirs located on the main stem Waikato River below Lake Taupo is removed. Collectively, these main stem reservoirs remove a total of 4% and 6% of the external inputs of TN and TP, respectively. Lake Taupo, the largest lake in the Waikato River Basin (surface area = 612 km^2), is estimated to remove 63% and 75% of the external inputs of TN and TP, respectively.

Table 6. Nitrogen Settling Velocities in Lakes and Reservoirs

Location	Settling Velocity,[a] m yr^{-1} Mean	Range
Waikato lakes and reservoirs (SPARROW; TN)	6.2	2.6–10.2[b]
Danish lakes [*Windolf et al.*, 1996] (TN)[c]	8.3	3.2–18.2
Southern Ontario lakes		
Molot and Dillon [1993] (TN)	3.5	3.0–4.5
Molot and Dillon [1993] (NO_3)	5.5	2.4–12.5
Kelly et al. [1987] (NO_3)	9.2	2.3–12.9
Kelly et al. [1990] (NO_3)	6.2	1.0–11.0
Dillon and Molot [1990] (NO_3)	5.6	2.3–11.4
Dillon and Molot [1990] (inorganic N)	5.6	3.5–10.8
Molot and Dillon [1993] (organic N)	1.5	1.0–2.1
Lake Superior [*Bennett*, 1986; *Kelly et al.*, 1990]	5.0	

[a] Settling velocities greater than 25 m yr^{-1} have been observed in selected southern Ontario lakes [*Kelly et al.*, 1990; *Dillon and Molot*, 1990]; these lakes have predominantly algal-dominated N losses and typically low N:P ratios.

[b] Ninety percent confidence interval (Table 4).

[c] Settling velocities are calculated from observations of depth, residence time, and percent retention for 16 lakes [*Windolf et al.*, 1996] according to the retention model described by *Dillon and Molot* [1990].

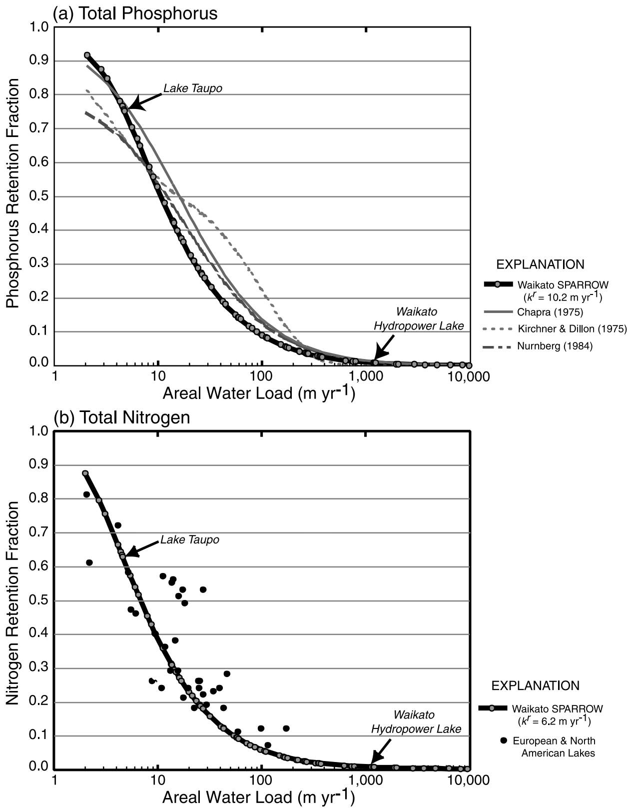

Figure 9. Nutrient attenuation in lakes and reservoirs of the Waikato River Basin in relation to the areal hydraulic load: (a) total phosphorus, (b) total nitrogen.

[38] The SPARROW estimates of the fraction of TP removed in Waikato lakes and reservoirs agree well with the fractions predicted by conventional steady state "well-mixed" lake models [*Nurnberg*, 1984; *Dillon and Rigler*, 1974; *Chapra*, 1975] that have been previously applied to the range of hydraulic loads in New Zealand lakes and reservoirs [*Vant and Hoare*, 1987]. The phosphorus settling velocities of these lake models are based on empirically derived rates for lakes in the Northern Hemisphere. A comparison of TP retention percentages in relation to the areal hydraulic loading is shown in Figure 9a. The SPARROW estimates are most similar to estimates based on the *Chapra* [1975] (settling velocity = 16 m yr^{-1}) and *Nurnberg* [1984] models. Comparisons with these models indicate that the phosphorus retention estimates typically differ by less than about 10 percentage points over much of the range of the areal hydraulic loads. Insufficient mass-balance measurements are available from New Zealand lakes to conclusively validate either the lake models or the SPARROW-based estimates of phosphorus retention. A budget analysis for Lake Taupo [*White and Downes*, 1977] indicated somewhat higher nutrient losses than estimated by the various lake models, but that generally fall within the reported confidence intervals of the results.

[39] We also find that the SPARROW estimates of the fraction of TN removed in Waikato lakes and reservoirs are

generally consistent with literature estimates of nitrogen removal (Figure 9b). The literature measurements are from mass-balance studies of 30 lakes in North America and Europe [*Seitzinger et al.*, 2002; *Howarth et al.*, 1996; *Kelly et al.*, 1987; *Billen et al.*, 1985; *Windolf et al.*, 1996]. These measurements show a similar rate of decline in the nitrogen removal fraction over the range of areal hydraulic loads in comparison with that estimated by SPARROW. Most literature estimates of nitrogen removal are within about 10 percentage points of the SPARROW estimates for Waikato reservoirs.

4.4. Landscape Variables

[40] The soil drainage index was found to be statistically significant (p = 0.07) in the TN model and is inversely related to in-stream TN flux. Thus catchments with poorly drained soils are associated with higher TN flux in streams, whereas catchments with well-drained soils are associated with lower TN flux in streams. Two factors may explain this relation. First, larger quantities of nitrogen may be removed via denitrification in the subsurface of catchments with well-drained soils where water may more readily infiltrate. Second, tile drains are commonly used on many poorly drained pasturelands in the Waikato watershed and can rapidly transport nitrogen to stream channels with little removal by natural attenuation processes [*Wilcock et al.*, 1999]. The inverse relation between stream nitrogen flux and soil permeability previously observed for watersheds in the United States (including calibrations of U.S. SPARROW models) has been partially attributed to the effects of tile drainage systems [*Smith et al.*, 1997; *Mueller et al.*, 1997; *Sauer et al.*, 2001]. The product of the soil drainage coefficient (Table 4) and the drainage class provides an approximate index of nitrogen attenuation in soils. For the seven soil drainage classes in the Waikato, this index varies by about a factor of 4 from 0.17 to 0.72. The product of this index and the diffuse source components of the model in equation (1) (i.e., land area and its estimated coefficient) quantify the amount of nutrients delivered to streams by this source.

[41] The soil drainage index was not found to be statistically significant in the TP model (p = 0.46), which may be explained by the tendency for particulate phosphorus to be carried to streams bound to sediment in overland flow. For TP, land-to-water processes are reflected entirely by the diffuse source terms in the model.

[42] Other landscape variables listed in Table 1 (e.g., runoff, slope) either were not statistically significant (p > 0.40) or degraded the statistical significance or physical interpretation of other model coefficients and were therefore not included in the final models. For example, the landscape slope variable lowered the significance of the diffuse source terms by raising the p values by a factor of 2–3. Neither soil-erosion class nor runoff were statistically significant in the TP model. The runoff coefficient, although statistically significant (p = 0.003) in the TN model, was negatively correlated with stream flux and produced unreasonable estimates of the land-use yields and the stream and reservoir loss coefficients. In general, the small spatial variability in runoff in the Waikato Basin may limit the utility of this factor in explaining variations in nutrient flux. The inclusion of monitoring sites from other regions would expand the range of runoff conditions and potentially improve the chances of obtaining a more accurate description of its effects.

4.5. Sources

[43] Three source coefficients were fit in the TN and TP models and account for diffuse nutrient sources and the major point sources (municipal and industrial discharges) in the Waikato watershed. The model specifies two coefficients for diffuse sources (pastureland and nonpastureland) and a point-source coefficient. A value of 1 is expected for the point-source coefficient because municipal and industrial wastewaters are discharged directly to streams with no attenuation (see section 3.3); in both the parametric and bootstrap models, we obtained estimates of nearly 1. The final bootstrap estimates of 1.08 and 0.96 for TN and TP, respectively, were within 4–8% of the expected value of 1, which provides evidence that the model estimates of nutrient sources and transport are generally well specified. The diffuse source coefficients for TP quantify the mass of phosphorus supplied and delivered to streams per unit area (kg ha^{-1} yr^{-1}) by diffuse sources associated with the land uses; no separate landscape delivery terms were fit for TP. For TN, the product of the diffuse source coefficients and the soil-drainage index (and its associated coefficient) quantifies the mass that is supplied and delivered to streams by diffuse nitrogen sources. Nutrient sources on pasturelands (about 56% of the Waikato watershed area) include livestock wastes, fertilizers, and N fixation from clover. New Zealand pastures are periodically fertilized with phosphorus, and clover is frequently used to maintain adequate nitrogen levels in soils [*Rutherford et al.*, 1987; *Glasby*, 1986]; these practices are believed to apply uniformly in the Waikato Basin. The model coefficient for nonpastureland areas reflects nutrient inputs from exotic pine forests (17% of total land area), scrub vegetation, urban and residential runoff (including septic systems), native forests, and remaining natural and cultural sources of nutrients associated with these land types. Exotic forests typically receive N and P fertilizer applications once or twice per crop rotation (25–40 years [*Rutherford et al.*, 1987]). The pasture and nonpastureland model coefficients also reflect the small nitrogen inputs from atmospheric sources [*Rutherford et al.*, 1987]. Nitrate deposition from fossil fuel combustion is negligible in New Zealand because of the lack of major local and regional sources. Ammonia emissions from livestock are generally deposited relatively close to the source [*Howarth et al.*, 1996]. Groundwater nutrients originating from pasture and other land types are also accounted for by the land-use coefficients because subsurface nutrient contributions are included in the stream measurements at monitoring stations on which the SPARROW response variable is based.

[44] The model predictions of stream nutrient yields are within the range of values reported in the literature for N.Z. catchments, including those in the Waikato Basin (Table 7) and therefore provide reasonable confirmation of the validity of the SPARROW predictions of diffuse nutrient sources in surface waters. The literature estimates of nutrient yields reflect variations in nutrient supply, management practices, and the effects of attenuation processes in soils and streams, which are not readily quantified from the

Table 7. Stream Yields of Total Nitrogen and Total Phosphorus Reported for New Zealand Catchments and Predicted by the Waikato SPARROW Nutrient Models for Catchments of Varying Size

Location	Total Nitrogen, kg ha^{-1} yr^{-1}	Total Phosphorus, kg ha^{-1} yr^{-1}
Waikato River Basin (SPARROW)[a]		
Pastureland		
Small (200 ha)	16–50	2.2
Medium (800 ha)	13–41	1.6
Large (2000 ha)	10–30	1.0
Nonpastureland		
Small (200 ha)	1.8–6.0	0.65
Medium (800 ha)	1.5–5.0	0.48
Large (2000 ha)	1.2–3.8	0.30
New Zealand catchments[b]		
Pastureland[c]	4–14 (8)	0.3–1.7 (0.4)
Toenepi (76% dairy farming; 1500 ha)[d]	35.3	1.16
Oteramika (<50% dairy farming)[e]	18	0.34
Exotic pine forest[c]	0.4–8 (1)	0.06–0.8 (0.5)
Native forest[c]	2–6 (3)	0.04–0.68 (0.2)
Scrubland[f]	6	0.12–1.2

[a] The range of modeled total nitrogen yields corresponds to the highest and lowest soil-drainage index values.
[b] Median yield of literature studies shown in parentheses.
[c] *Cooke* [1980] and *Wilcock* [1986].
[d] *Wilcock et al.* [1999].
[e] *Thorrold et al.* [1997].
[f] *Rutherford et al.* [1987].

reported data. Therefore we compared the literature yields to SPARROW estimates computed for a set of hypothetical catchments having a range of land-use types, soil-drainage conditions, and drainage sizes (see Table 7). The SPARROW predictions of nutrient yield in Table 7 are reported separately for pastureland and nonpastureland catchments for three drainage sizes. We applied the SPARROW small-channel attenuation rates to account for in-stream losses of nutrients. Nutrient yields decline with catchment size reflecting the increasing cumulative removal of nutrients. The range of TN yields corresponds to the highest and lowest soil-drainage index values. The lowest TN SPARROW yield for each catchment size is associated with well-drained soils. In the calculations, we assumed a median drainage area (2 km^2) for each reach catchment in the Waikato network and uniform nutrient yields, based on the model coefficients for pasture and nonpasturelands. A mean channel length of 1 km was used for each reach catchment of 2 km^2, based on a length-area relation developed from the Waikato DEM-based stream network.

[45] The nutrient yields reported in the literature for N.Z. catchments and those predicted by SPARROW for catchments in the Waikato Basin (Table 7) show general agreement by land-use type. Nutrient yields reported in the literature display considerable variability within land-use types but are typically highest for pasture-dominated catchments and lowest for catchments predominantly in exotic pine forest, native forest, and scrubland [*Wilcock*, 1986; *Cooke*, 1980; *Rutherford et al.*, 1987]. The highest SPARROW nutrient yields are also predicted for pastureland catchments, which are generally similar to those reported for N.Z. catchments. The SPARROW yields for nonpasturelands closely correspond to the range of literature yields reported for catchments in exotic pine forest, native forest, and scrubland.

[46] SPARROW pastureland yields for TN agree most closely to the yields reported for pastureland catchments with extensive dairying operations [*Thorrold et al.*, 1997; *Wilcock et al.*, 1999]. These studies showed higher TN yields (18 and 35.3 kg ha^{-1} yr^{-1}, respectively) than previously reported for N.Z. catchments (4–14 kg ha^{-1} yr^{-1} [*Cooke*, 1980]). *Wilcock et al.* [1999] attributed their observations to higher farm stocking densities and the extensive use of tile drains in the Toenepi catchment and noted the consistency of the TN yield in this Waikato catchment to paddock-scale N leaching losses reported for dairy farms in the Waikato Basin. *Thorrold et al.* [1997] observed a somewhat lower TN yield in the Oteramika catchment, where less than 50% of the catchment is in dairy farming and lower stocking densities are maintained. These studies suggest that higher TN yields may be typical of pastureland catchments in the Waikato watershed, where dairying operations are more commonplace, than in other N.Z. pastureland catchments.

[47] Variables describing specific nutrient sources were also evaluated in exploratory SPARROW models (Table 1); however, these variables were not included because they were statistically insignificant or lowered the statistical significance of the land-use variables. We concluded that land-use area provided a more reliable and comprehensive predictor of nutrient contributions from farms and other diffuse sources in the Waikato Basin. For example, although soil erosion was statistically significant in the TP model (p = 0.02), the statistical significance of the nonpastureland coefficient was lowered appreciably. The nonpastureland source was given preference over soil erosion to maintain a consistent mass accounting in the model. The apatite phosphorus source (land area in apatite minerals) was not statistically significant (p = 0.90). Cow populations were not a significant predictor in the TP model (p = 0.59) and entered with a negative sign in the TN model. In general, the power of the model to include additional source terms may be either limited by the few remaining number of degrees of freedom (d.f. = 30 for TN

Table 8. Waikato SPARROW Equations for Predicting the Point- and Diffuse-Source Nutrient Flux at the Outlet of a River Reach, Based on the Application of the Model in Equation (1) Using Bootstrap Parameter Estimates From Tables 4 and 5

Model Component	Total Nitrogen Equations	Total Phosphorus Equations
1. Stream/reservoir transport of reach sources (T^R) (applies stream attenuation over half the reach length (i.e., average) and reservoir attenuation to sources in the reach catchment; L_1 = channel length (mean flow < 1 m^3 s^{-1}); L_2 = channel length (mean flow > 1 m^3 s^{-1}); $I = 1$ for stream reach, $I = 0$ for reservoir reach; q = areal hydraulic load)	$T^R = \exp\left[\left(-0.223\frac{L_1}{2} - 0.001\frac{L_2}{2}\right)I - \left(6.21\frac{1}{q}\right)(1-I)\right]$	$T^R = \exp\left[\left(-0.426\frac{L_1}{2} - 0.000\frac{L_2}{2}\right)I - \left(10.22\frac{1}{q}\right)(1-I)\right]$
2. Stream/reservoir transport of upstream sources (T^U) (applies stream attenuation over the entire reach length and reservoir attenuation to sources entering from the adjacent upstream reaches)	$T^U = \exp\left[(-0.223L_1 - 0.001L_2)I - \left(6.21\frac{1}{q}\right)(1-I)\right]$	$T^U = \exp\left[(-0.426L_1 - 0.000L_2)I - \left(10.22\frac{1}{q}\right)(1-I)\right]$
3. Landscape transport factor (T^L) (SD = soil drainage index)	$T^L = \exp(-0.182SD)$	
4. Pastureland nutrient flux at the reach outlet (PST) (PL = pastureland area of the reach catchment; PST^U = pastureland nutrient flux from the adjacent upstream reaches)	$PST = [71.39PL(T^L)]T^R + PST^U T^U$	$PST = [2.78PL]T^R + PST^U T^U$
5. Nonpastureland nutrient flux at the reach outlet ($NPST$) (NPL = nonpastureland area of the reach catchment; $NPST^U$ = nonpastureland nutrient flux from the adjacent upstream reaches)	$NPST = [8.63NPL(T^L)]T^R + NPST^U T^U$	$NPST = [0.81NPL]T^R + NPST^U T^U$
6. Point-source nutrient flux at the reach outlet (PS) (P = point-source nutrient loading to the reach; PS^U = point-source nutrient flux from the adjacent upstream reaches)	$PS = [1.08P]T^R + PS^U T^U$	$PS = [0.96P]T^R + PS^U T^U$
7. Nutrient flux from all sources at the reach outlet (F)	$F = PST + NPST + PS$	$F = PST + NPST + PS$

Table 9. SPARROW Model Predictions of Mean-Annual Concentration and Yield for Total Nitrogen and Total Phosphorus in Reaches (n = 4873) of the Waikato River Basin

Metric	Percentiles 10th	25th	50th	75th	90th
Total Nitrogen					
Concentration, mg L^{-1}	0.20	0.49	1.6	3.1	5.1
Yield, kg ha^{-1} yr^{-1}	1.9	3.8	11	18	26
Standard deviation, % of mean	15	19	26	36	56
Total Phosphorus					
Concentration, mg L^{-1}	0.04	0.06	0.13	0.25	0.41
Yield, kg ha^{-1} yr^{-1}	0.20	0.49	0.84	1.5	2.3
Standard deviation, % of mean	12	15	20	42	59

and d.f. = 32 for TP) or may reflect the presence of insufficient spatial variability in these additional explanatory variables in the Waikato Basin.

4.6. Model Applications

4.6.1. Predictions of Yield and Concentration

[48] Predictions of yield (flux per unit drainage area) and concentration for TP and TN were generated for the nearly 5000 reach locations and 75 lakes and reservoirs in the Waikato River basin by applying the final bootstrap models. The predictive equations associated with these model coefficients are shown in Table 8; these indicate how the models were used to predict the nutrient flux for point and diffuse sources at the outlet of each reach. Table 9 presents the model predictions of mean-annual concentration and yield for the 4873 reaches in the Waikato Basin; these predictions reflect source contributions from the total drainage above each reach. We found that the percentiles of the distribution of model predictions of yield and concentration are generally higher than those based on the observations at the monitoring sites (Tables 3 and 9). The somewhat higher concentration and yield percentiles for the model predictions (Table 9) reflect the larger number of unmonitored, small headwater catchments and high-yielding, pasture-dominated catchments represented in the reach network. There is generally less cumulative removal of nutrients in the small catchments because of the shorter channel distances over which nutrients are transported. Differences in predicted concentrations can be additionally explained by the lower estimates of streamflow for the reaches (reach flows based on the mean-annual estimates of runoff were about 30% less than the monitoring station estimates for the 1993–1998 period).

[49] The standard deviations of the model predictions typically range from about 15% to 42% of the mean values (i.e., 25th and 75th percentiles) with medians of 26% and 20% for TN and TP, respectively (Table 9). Because the model residuals generally satisfy the model assumptions, the estimates of the standard deviation provide reasonably accurate measures of the uncertainty in the model predictions. The addition of the residual variance (i.e., model error) to the model predictions resulted in a small average increase in the magnitude of the predictions (about 10%) that corrected for log retransformation bias. The summation of the mean predictions of nutrient flux over incremental drainage areas resulted in a greater averaging of model errors over large drainage areas, which generally reflects the lower variance expected for flux estimates in large watersheds [*Alexander et al.*, 2001].

4.6.2. Origin and Fate of Nutrients

[50] Because of the separate quantification of point and diffuse sources and nutrient attenuation in streams and reservoirs, the Waikato SPARROW models can be used to estimate the sources and sinks of nutrients at locations throughout the drainage network, including reservoirs, lakes, and the outlets of watersheds. We present two analyses to illustrate these model applications.

[51] We first present nutrient budgets for four major interior watersheds of the Waikato Basin (see Tables 10 and 11 and Figure 10). These watersheds separate the basin along major physiographic drainages and land-use types. The budgets in Tables 10 and 11 present estimates of the quantities of nutrients (per unit of drainage area) entering streams and reservoirs from the landscape (“landscape yield”), the percentage of these inputs that are subsequently removed in streams and reservoirs, and the quantities of nutrients that exit specified watersheds (“watershed yields”; only nutrients originating within the specified watershed are included in these yield estimates).

[52] The four major interior watersheds display a range of land-use types. The Taupo watershed (Figure 10) is the least developed, with forested land and the lake surface representing more than 50% of the drainage area of the catchment. Stream nutrient yields for the Taupo watershed are dominated by the considerable processing of nutrients in Lake Taupo, a large caldera lake (surface area = 612 km^2,

Table 10. Total Nitrogen Budget for the Waikato River Basin and Four Major Watersheds

Watershed	Area, km^2	Landscape Yield,[a] kg ha^{-1} yr^{-1}	Sources of Landscape Yield, % Point	Pasture	Nonpasture	Stream and Reservoir Loss,[b] %	Watershed Yield, kg ha^{-1} yr^{-1}	Sources of Watershed Yield, % (Standard Error)[c] Point	Pasture	Nonpasture
Waikato (total)	13,517	19.2	6	88	6	45	10.6	11 (55)	83 (12)	5 (28)
Lower Waikato	4,614	28.1	10	87	3	45	15.6	17 (51)	78 (11)	3 (25)
Upper Waikato	3,384	11.0	6	82	12	42	6.4	11 (55)	78 (8)	11 (26)
Taupo[d]	2,686	7.7	0	74	25	76	1.9	0	72 (14)	26 (27)
Waipa	2,833	24.0	1	96	3	39	14.7	2 (51)	96 (2)	2 (34)

[a] Delivery to streams and reservoirs from diffuse and point sources.
[b] Nutrient removed in streams and reservoirs as a percentage of the quantities of nitrogen delivered to water bodies from diffuse and point sources.
[c] Standard error expressed as a percentage of the mean estimate.
[d] Interbasin water transfers represent less than 2% of the nitrogen sources of landscape and watershed yields.

Table 11. Total Phosphorus Budget for the Waikato River Basin and Four Major Watersheds

Watershed	Area, km^2	Landscape Yield,[a] kg ha^{-1} yr^{-1}	Sources of Landscape Yield, %			Stream and Reservoir Loss,[b] %	Watershed Yield, kg ha^{-1} yr^{-1}	Sources of Watershed Yield, % (Standard Error)[c]		
			Point	Pasture	Nonpasture			Point	Pasture	Nonpasture
Waikato (total)	13,517	2.2	10	75	15	57	1.0	23 (48)	66 (19)	10 (61)
Lower Waikato	4,614	2.9	18	74	8	51	1.4	38 (35)	55 (23)	7 (46)
Upper Waikato	3,384	1.7	5	70	25	59	0.7	13 (47)	65 (14)	22 (42)
Taupo[d]	2,686	1.3	0	53	46	89	0.2	0	52 (30)	47 (34)
Waipa	2,833	2.4	1	91	8	53	1.1	2 (48)	93 (3)	5 (48)

[a] Delivery to streams and reservoirs from diffuse and point sources.
[b] Nutrient removed in streams and reservoirs as a percentage of the quantities of phosphorus delivered to water bodies from diffuse and point sources.
[c] Standard error expressed as a percentage of the mean estimate.
[d] Interbasin water transfers represent less than 1% of the phosphorus sources of landscape and watershed yields.

23% of the drainage area). The Upper Waikato also has large amounts of forested land (39% of the watershed area) with pastoral farming present on nearly half of the drainage (44%); urban land represents less than 0.5% of the drainage. The Waipa and Lower Waikato have the largest areas of pastureland (>75%). The Lower Waikato also has the largest area in urban land (2%), which includes the fourth largest city in New Zealand, Hamilton.

[53] The model predictions (Tables 10 and 11) indicate that the more forested watersheds of Taupo and the Upper Waikato display the smallest stream nutrient yields ("watershed yields"), whereas stream yields from the more pasture-dominated drainages of the Waipa and Lower Waikato are larger by factors of 2 or more. On the basis of the model estimates of the source shares of the watershed yields, much larger fractions of the nutrients originate from pasture and urban areas (and much smaller shares originate from nonpastureland) than suggested by the percentages of land use in these watersheds. More than 90% of the stream nutrients are estimated to originate from pastureland in the Waipa watershed (77% of land area in pasture), whereas more than 53% of the TP and 74% of the TN originate from pastureland in the Taupo and Upper Waikato watersheds (20 and 45% of land area in pasture). About 25% of the TN and 47% of the TP in streams originate from nonpasturelands in the Taupo and Upper Waikato watersheds, although nonpastureland area in these watersheds is more than twice these percentages. Despite the small quantities of urban land area in the watersheds (<2%), municipal- and industrial-point sources are major contributors to stream export in the Lower Waikato (17% for TN; 38% for TP) and the Upper Waikato watersheds (11 and 13%). On the basis of model estimates of uncertainty (e.g., standard error), the lowest variability in the predicted source contributions is estimated for the diffuse sources from pasturelands (2–30%). Uncertainties in the point sources and diffuse contributions from nonpasturelands are somewhat larger (25–61%).

[54] Nutrient removal in streams and reservoirs expressed as a percentage of the external inputs from the landscape ranges from 39% (Waipa) to 76% (Taupo) for TN and from 51% (Lower Waikato) to 89% (Taupo) for TP. Lakes and reservoirs account for 30% and 44% of the TN and TP, respectively, removed in all water bodies throughout the entire Waikato Basin; Lake Taupo accounts for 33% and 36% of this loss.

[55] Accounting for nutrient removal in lakes, reservoirs, and streams as well as the location of point and diffuse source inputs significantly alters the assessment of source contributions in the Lower Waikato. Here, point-source contributions represent 10% and 18% of the TN and TP delivered to streams and reservoirs ("landscape yield"), but their contributions are approximately twice this magnitude at the watershed outlet (17% and 38% of the TN and TP). By contrast, watersheds with a more uniform distribution of

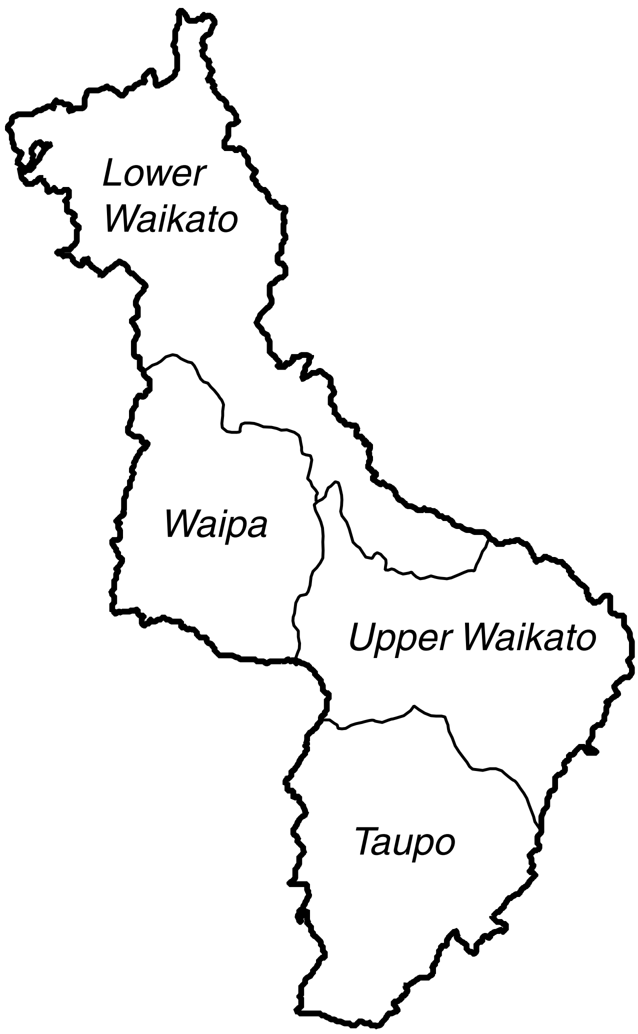

Figure 10. Major regional watersheds of the Waikato River Basin.

nutrient sources, such as the Waipa, display few differences in the relative contributions of the nutrient-source types delivered to streams and the watershed outlet.

[56] A previous assessment of nutrient sources in the Waipa and the Upper and Lower Waikato watersheds [*Vant*, 1999] estimated the nonpoint-source nutrients as the difference between monitored loads at the watershed outlets for the period 1990–1996 and measures of point-source loads discharged directly to streams. The estimates did not account for the removal of point-source nutrients in streams and reservoirs by biological and physical processes. Comparisons with the SPARROW budget estimates indicate that the SPARROW estimates of nonpoint-source yields are from 5% to 20% larger in the Waipa and Lower Waikato watersheds and from 60% to 70% larger in the Upper Waikato. The percentage of the total TN and TP sources attributed to point sources in the Lower Waikato is 10% and 20% for SPARROW, respectively, as compared to 15% and 27% for the earlier assessment [*Vant*, 1999].

[57] Whereas budgets are useful for characterizing the aggregate effects of sources and the attenuation of nutrients in large watersheds, the management of sources frequently requires more spatially detailed descriptions of nutrient flux. The models can be used to quantify the effects of nutrient yields of individual catchments on the nutrient conditions at downstream locations. Figure 11a presents the estimated quantities of nitrogen delivered to the Waikato outlet to the Tasman Sea from diffuse and point sources in the watershed. The quantities are adjusted for catchment area and expressed as a "delivered yield" (i.e., the mass delivered to the Waikato outlet reach per unit area of the contributing catchment drainage). Spatial variations in the delivered yields reflect differences in the magnitude of the source inputs and the processing of nitrogen in streams and reservoirs. The largest delivered yields (>10 kg ha^{-1} yr^{-1}) occur frequently in the lower portion of the Waikato (especially in the Waipa watershed) in many pasture-dominated catchments located near large streams. Large quantities of nitrogen (>10 kg ha^{-1} yr^{-1}) are also delivered from catchments near large streams in the Upper Waikato watershed located hundreds of kilometers from the Waikato outlet.

[58] Figure 11b illustrates the effects of in-stream and reservoir loss on the delivery of nutrients to coastal waters. The "delivery percentage" describes the percentage of in-stream nitrogen that is delivered to the Tasman Sea from interior catchments exclusively as a function of the loss properties of streams and reservoirs (i.e., channel size and distance, lake areal hydraulic load, estimated first-order loss coefficients). The delivery percentages show a distinct dendritic pattern that is consistent with the inverse relation between the rates of nitrogen loss and stream channel size in Figure 7. Higher percentages of nitrogen are delivered from catchments drained by large streams, where the nitrogen loss rate is relatively low. For example, more than 75% of the nitrogen in catchments near the main stem Waikato below Lake Taupo is transported over 300 km to the Waikato River outlet. By contrast, lower percentages of the in-stream nitrogen are delivered from catchments draining to small streams, where the rate of nitrogen removal is large and the travel distances to large streams are long. Lower percentages are also delivered from catchments above Lake Taupo because of the large capacity of the lake to remove nitrogen. Within most areas of the Waikato, neighboring catchments display a wide range of efficiencies in the delivery of nitrogen to the Waikato outlet that is largely a function of channel size and associated nutrient loss properties. Moreover, catchments located hundreds of kilometers from the Tasman Sea near large streams deliver a much larger percentage of their in-stream nitrogen than is delivered from catchments on small streams located only tens of kilometers from the sea. A dendritic pattern in nitrogen delivery was previously observed in the Mississippi River Basin based on an application of the SPARROW model [*Alexander et al.*, 2000] (see rates in Figure 8). This characteristic of nitrogen delivery may be important for developing efficient strategies for managing nutrient sources. One implication is that the management of sources in catchments near large streams may have a much greater effect on the delivery of nutrients to downstream locations, including lakes and reservoirs, than a commensurate level of management applied in catchments near small streams (with long travel distances to larger streams and much higher rates of natural attenuation). For example, the nitrogen model predicts that 1 kg of nitrogen could be removed from the Waikato River at its outlet to the Tasman Sea by removing 1.1 kg of nitrogen from the inputs to a hypothetical location on a large stream that delivers 90% of its nitrogen to the outlet (i.e., kilograms removed from inputs = 1.0 kg/90%). By contrast, three times this level of effort (i.e., the removal of 3.3 kg from inputs) would be required on a small stream, where only 30% of the nitrogen is delivered to the outlet (i.e., kilograms removed from inputs = 1.0 kg/30%), to have the same effect of removing 1 kg at the Waikato outlet.

5. Summary and Conclusions

[59] We developed SPARROW (Spatially Referenced Regression on Watershed Attributes) nutrient models for surface waters in the Waikato River Basin, the largest watershed on the North Island of New Zealand, using stream water-quality monitoring records collected at 37 sites from 1993 to 1998. This first application of SPARROW outside of the United States relied on a comprehensive set of water-resources data, which were representative of a wide range of natural and cultural conditions and well suited for calibrating and validating the model. The nutrient models explained 97% of the spatial variability in stream nutrient flux and displayed relatively small prediction errors; predicted stream yields (kg ha^{-1} yr^{-1}) were typically within 10–15% of the observed values for TN and within 20–30% for TP. The models identified appreciable effects of land use and point sources (wastewater treatment plants and industrial sources) on the supply of nutrients to surface waters and the effects of soils, streams, and lakes and reservoirs on nutrient transport over large spatial scales. There was strong supporting evidence for the accuracy of the model estimates of the natural rates of nutrient attenuation and point-source and diffuse-source contributions to surface waters. Model coefficient estimates for point-source discharges were within 4–8% of the expected value of one. Model estimates of diffuse sources and the rates of nutrient attenuation compared favorably with observations reported in the literature for watersheds in New Zealand, North

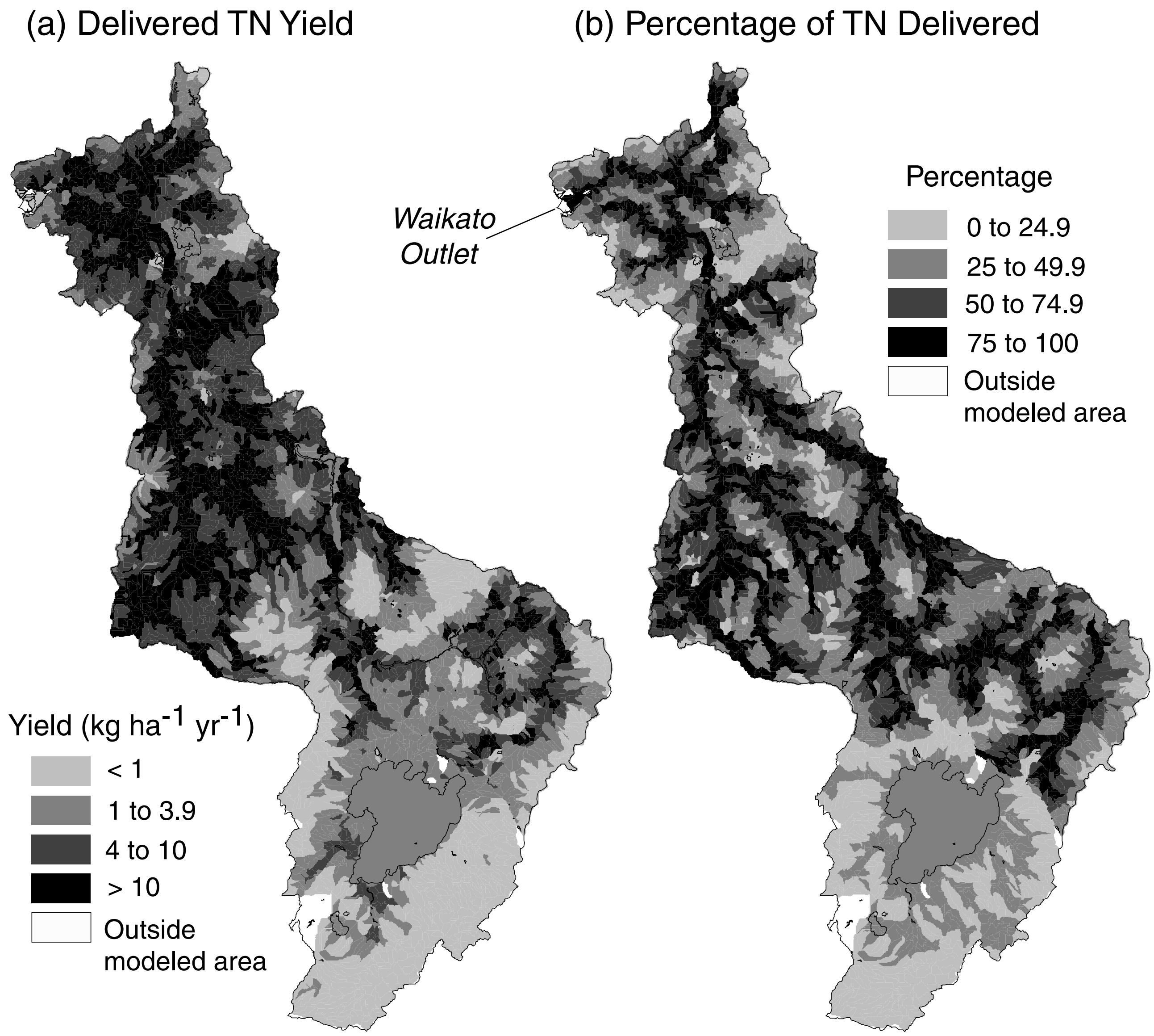

Figure 11. Predicted quantities of TN delivered from reach catchments to the Waikato River Basin outlet to the Tasman Sea: (a) yield, (b) the percentage of in-stream nitrogen.

America, and Europe. These included the measured rates of nutrient yield from pasture and nonpasture catchments and the estimated rates of nutrient loss in streams and reservoirs. The results suggest that the models provide a reasonably valid description of nutrient transport and source contributions to surface waters in the Waikato Basin. Estimates of statistical uncertainty provide useful information to guide interpretations of the model rate coefficients and predictions of sources and in-stream nutrient conditions.

[60] The SPARROW estimates of the rates of nutrient removal from the water column of streams and reservoirs of the Waikato River Basin contribute new information on the factors affecting nutrient transport in the surface waters of large watersheds. The Waikato loss rates are generally consistent with current understanding of the physical and biochemical mechanisms responsible for the permanent removal and long-term storage of nutrients in aquatic systems, including denitrification and particulate settling and burial. The findings indicate that physical and hydrologic factors affecting water contact with the benthic sediments are major limiting factors governing nutrient removal in both streams and lakes. Smaller quantities of nutrients are generally removed from the water column in deeper stream channels and more rapidly flushed lakes and reservoirs, where there is less contact and exchange of nutrients with the benthic sediment. The relatively conservative behavior of nutrients under such conditions leads to the transport of nutrients over hundreds of kilometers through drainage networks and the preferential delivery of nutrients from areas in the vicinity of large rivers and streams.

[61] The Waikato applications of SPARROW provide strong evidence that conventional stream-monitoring data and spatially referenced information on watershed characteristics can be reliably used in this modeling technique to empirically estimate nutrient transport in large watersheds. Few empirical or experimental techniques are available for estimating nutrient loss over large spatial scales. Extrapolation of experimental measurements from small catch-

ments to the watershed scale may entail large temporal and spatial uncertainties. SPARROW provides a complementary method for relating experimental data and observations from small catchments to the transport of nutrients in streams and reservoirs of large river basins. The mass-balance constraints and spatial referencing in SPARROW coupled with the simultaneous estimation of nutrient loss in streams, lakes, and reservoirs provide an effective technique for obtaining spatially consistent estimates of nutrient attenuation in surface waters. The method presented here for estimating nutrient loss as a nonlinear function of the hydraulic flushing rate of lakes and reservoirs significantly improves the interpretability of SPARROW reservoir attenuation rates and, more generally, provides a new technique for empirically estimating nutrient losses in reservoirs of varying sizes.

[62] Future studies in the Waikato Basin may provide an opportunity to refine the nutrient models to describe landscape processes or diffuse nutrient sources in greater detail. The description of sources might be improved by including specific estimates of nutrient inputs from fertilizer and animal wastes; however, their inclusion will have to await the availability of more refined spatial data than are currently available. Improved descriptions of landscape processes may potentially be achieved by incorporating the components or predictions of deterministic landscape models such as TOPMODEL [*Wolock*, 1993], which simulates the surface and shallow subsurface hydrologic processes that generate streamflow. The significance of soil drainage in the TN Waikato model (a partial determinant of overland flow in TOPMODEL) suggests that subsurface pathways affect nitrogen processing in the Waikato Basin. This coupling of deterministic and empirical methods may advance understanding of the factors affecting nutrient transport in the watershed.

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