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TE RAUHĪTANGA TAIAO

Modelling Sediment Loads to the Mahurangi Estuary

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Modelling Sediment Loads to the Mahurangi Estuary

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Table of Contents

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Executive Summary

1. The Mahurangi Estuary has been recognised by ARC Environment as an important resource in need of careful management, in order to simultaneously protect the estuary and provide for reasonable economic use of the surrounding land.

2. This report addresses the issue of catchment land-use activities and their effect on water quality. The main focus is on sediment but nutrients are also considered.

3. Our approach was to develop a computer simulation model that is able to predict sediment and nutrient loadings to the Mahurangi Estuary, using detailed information on its catchment and long term climate record.

4. The BNZ model has been established for the Mahurangi Estuary catchment and the sediment component of the model has been shown to agree with measured data for three sub-catchments (a predominantly pasture, mature pine and mixed land-use sub-catchment)

5. The long term average total sediment load delivered to the Mahurangi Estuary from its surrounding catchment was predicted by the model to be 52,270 t year^{-1} (448 t km^{-2} year^{-1}) and ranged from just over 13,000 tonnes year^{-1} to approximately 136,000 tonnes year^{-1}.

6. Despite forming approximately half the entire catchment of the Estuary, the Mahurangi River system was predicted to contribute only 29% of the total sediment load to the Estuary. The Western shore was predicted to contribute 41% and the Eastern shore 30%.

7. The model predicts that the combination of steep slope and pastoral land-use is the dominant factor behind high sediment loss from the land surface

8. The model is now ready to be used in the predictive mode to evaluate the potential risk of possible land-use changes to sediment and nutrient loads

1.0 INTRODUCTION

The Mahurangi Estuary has been recognised by ARC Environment as an important resource in need of careful management, in order to simultaneously protect the estuary and provide for reasonable economic use of the surrounding land (ARC 1993).

To increase their information base and provide scientifically-valid management strategies for the Estuary, the ARC asked NIWA to conduct a series of studies in the Mahurangi Estuary and its catchment. These studies have looked at:

- pesticide use and its risk of movement to waterways (Wilcock 1994);
- colour and clarity of estuary water (Davies-Colley and Nagels 1995);
- sediment and nutrient loads to streams and the estuary (this study);
- sediment history in the estuary (Swales et al 1997);
- movement of water and contaminants within the estuary (Oldman 1997);
- patterns and trends in the ecology of the estuary (Cummings et al 1995)

This report addresses the issue of catchment land-use activities and their effect on water quality The traditional approach to this issue has been to use land/water interaction results established elsewhere or the measurement of sediment and nutrient loads from single land-use catchments for a year or two and a somewhat tenuous extrapolation of the findings across a wider area and for a longer time period. Such approaches can be valid at a broad scale or may be the only option where information is lacking but have major drawbacks when the findings are to be used to aid decision-making at the finer scale, particularly in relation to cumulative adverse effects, frequently most relevant to resource management. Resource decisions often need to incorporate more detailed components of the relationship between land-use and water quality, such as:

- the effect of a land-use on sediment and nutrient loadings is dependent upon the local setting, being strongly influenced by such factors as soil type and slope;
- the effect of a land-use on sediment and nutrient loadings will vary with rainfall patterns and therefore may not be understood by a short-term measurement programme;
- within each broad land-use (pasture, forestry, etc.) there are a whole range of management practices that can significantly alter sediment and nutrient loadings (e.g., grazing practices, fertiliser timing);
- cumulative adverse effects particularly at a distance from the source.

In this study we took a different approach to overcome these problems Our approach was to develop a computer simulation model that is able to predict sediment and nutrient loadings to the Mahurangi Estuary from detailed information on its catchment and a long term climate record The main focus is on sediment, due to its influence on recreational and ecological values within the estuary, but nutrient loads are also considered

Predictions made by computer simulation models need to be tested against measurements in the real world before they can have credibility. In this report, we describe this validation of the sediment component of a simulation model for the Mahurangi catchment and present model outputs of current sediment and nutrient loads to the Estuary. The modelled nutrient loads were more of a by-product of the sediment work and were not tested against any measured data. As such they are presented as qualitative information and so should be used for indicative purposes only e.g., identifying areas of potentially high nutrient loss that need further study. However, the nutrient data gathered could be used to validate the nutrient component of the model should this be required in the future.

Using a modelling approach to address the issue of land-use effects on water quality in the Mahurangi Estuary has the advantages of:

- revealing those parts of the catchment that are major contributors of sediment and nutrients to the Estuary under current conditions;
- predicting the likely range of sediment and nutrient loadings from a particular area if a land-use were to change

This latter ability of a simulation model is particularly valuable as it provides a risk analysis tool to aid decision-making on appropriate resource use The validated model that has been developed for the Mahurangi catchment is now ready to be used in this mode as it is able to run 'what if' scenarios for potential future land-use changes.

2.0 BNZ MODEL

BNZ (Basin — New Zealand) is a computer simulation model that predicts sediment and nutrient losses from catchments. A full description of BNZ is given in Cooper and Bottcher (1993), and its structure is shown in Fig. 1. BNZ divides the catchment into equal-sized grid squares or 'cells' and also allows the catchment to be split into user defined sub-catchments For each cell, the user appoints a sub-catchment that the cell drains into and inputs land use, soil, and slope information. For every unique combination of these inputs, BNZ uses climate information (rainfall, radiation, temperature) with a modified version of the water quality simulation model 'CREAMS' (Chemicals, Runoff and Erosion from Agricultural Management Systems) (Cooper et al 1992) to estimate diffuse losses of water (surface and sub-surface), sediment and nutrients from each cell

The model works on a daily time step and keeps a soil moisture budget using rainfall, soil hydraulic properties and plant evapotranspiration. Daily rainfall can be stored in the soil, move through the soil to the stream as baseflow or run over the surface of the soil to the stream as surface runoff. Surface runoff invokes a series of equations in the model which determines the transport and deposition of sediment down a hillslope. The sediment carrying capacity of surface runoff varies with the runoff velocity, which is dependent on slope and vegetation cover, runoff volume and characteristics of the soil Sediment bound nutrients are carried with the soil particles in surface runoff while water soluble nutrients are extracted into both baseflow and surface flow depending upon their soil concentrations and characteristics of the soil

The sediment and nutrient losses from each cell are spatially distributed by BNZ and routed down the drainage network, via sub-catchment outlets, to the catchment outlet During routing, loadings from point sources are added and riparian and stream channel removal processes are simulated. In our early visits to the Mahurangi we noticed a considerable number of farm dams which could act as sediment and nutrient traps. In response to this, we upgraded BNZ to take this removal process into account.

2.1 Setting up the BNZ Model

The BNZ model was set up and run for the Mahurangi Estuary catchment and for the 44 sub-catchments it was divided into. Flow, sediment and nutrient data was collected at the outlets of three of these sub-catchments and the sediment data was used to test the predictive ability of BNZ. The three subcatchments chosen were designed to provide a thorough test of BNZ: a small, predominantly pasture catchment (Wylies Road), a small exotic forest catchment (part of the Redwood Forest) and a large, mixed land use catchment (Mahurangi River at College) Characteristics of each of the test sub-catchments are listed in Table 1. Their location and the division of the Mahurangi Estuary catchment into sub-catchments is shown in Fig 2.

Table 1: Characteristics of the catchments

	Wylies Road	Redwood Forest	Mahurangi College	Mahurangi total catchment
Area (km^2)	1 26	0.60	46 80	115
Location of catchment outlet (flow recorder)	R09:566302	R09:568259	R09:586319	various
Cell size (m x m)	(62.5 x 62.5)	(125 x 125)	(500 x 500)	(500 x 500)
Number of cells	323	38	188	468
Number of unique cell types	78	11	70	146
No of subcatchments	11	0	16	44
Land-use	mostly sheep & beef farming	pine forest	mixed	mixed

2.2 Model Input Information

Soils

The distribution of soil types in the Mahurangi catchment was obtained from Landcare's 1:50 000 Land Resource Inventory database and modified according to field studies commissioned by us and carried out by Malcolm McLeod from Landcare in June 1993. Catchment grids were overlaid on the soil map and the main soil type within each grid cell was allocated to it in the model. Fig. 3 shows the soil type of each cell and the pattern of the soils throughout the catchment.

The predominant soils are the Warkworth and Whangaripo hill clays formed from sedimentary rocks. The Warkworth soils (WA and WAH) are more common in the North and East of the catchment and the Whangaripo soils (WR, WRH, WRe and WReH) in the steeper land to the West. Both soils are poorly draining, particularly through their subsoils, with a saturated hydraulic conductivity of 0.4 mm h^{-1}. A full listing of the catchment soil types along with their hydraulic conductivity and porosity values is given in Appendix 1. Detailed information on other soil values entered into the model are available on request.

Topography

Slope angle and shape were determined by a field survey of all 323 cells in Wylies Road and by use of a 1:10 000, 5 metre contour map supplied by Carter Holt Harvey for Redwood Forest. Predominant slope angles for Mahurangi College and Estuary catchment cells were obtained from a 1:50 000, 20 metre contour map. Because of the coarse scale of this map, slope shapes for these catchments were assumed to be uniform. Slope angles were placed in one of six slope classes (as per the Land Resource Inventory) and the median values of each slope class (Appendix 2) were used as inputs to BNZ (Fig. 4).

The majority of the catchment is rolling to strongly rolling land with flatter areas around the mainstem left and right branches of the Mahurangi River. There is a large area of steep land in the west of the catchment stretching from the estuary to Dark Summit and Moirs Hill. Most of the exotic forest in the catchment is located in this region. There is also some steeply sloping land in the northern tip near the Dome.

Land-use

Land-use information for each cell in the model was obtained from a survey of landowners carried out by ARC Environment, a 1:10 000 aerial photograph of the region, vegetation cover given in the Land Resource Inventory, and a visit to the area to fill in any information gaps. From these data, four land-use categories were determined for the Wylies Road catchment and 32 for the College and Estuary catchments (Redwood Forest was obviously a single land-use). These land-use classes are listed in Appendix 3 and their spatial distribution shown in Fig. 5.

The Mahurangi is predominantly a pastoral farming catchment with patches of native bush and scrub scattered throughout the region and a significant pine plantation belonging to Carter Holt Harvey in the west. There are a number of lifestyle blocks. Warkworth township is the main urban area.

Farm Ponds and Point Sources

As part of the land-use survey of landowners, ARC Environment staff also gathered information on farm ponds (location and size) and point sources. ARC Environment consent information for point sources was also collated and combined with published information on effluent characteristics (Hickey et al 1989, Davies-Colley et al 1995, Gibbs 1977, Vanderholm 1984, Metcalf and Eddy 1979) to estimate sediment and nutrient loadings

The location of point sources and ponds are shown in Fig. 6 and were entered into BNZ

There are over 50 ponds in the catchment, but many of these are located in the upper parts of subcatchments and have little ability to influence stream sediment loads. The effective pond volume used in the modelling is listed in Appendix 4.

Table 2: Point source loadings in the Mahurangi Estuary Catchment

Parameter	Annual Load
Sediment	52 5 tonnes
Total phosphorus	2 472 kg
sediment phosphorus	592 kg
soluble phosphorus	1 880 kg
Total nitrogen	10 573 kg
sediment nitrogen	2 785 kg
soluble nitrogen	7 788 kg

The largest point source is the Warkworth sewage and storm-water discharge. At the time of gathering land use and point source information there were eight dairy farms in the catchment, of which five were using oxidation ponds to treat dairy shed effluent and three were using land disposal methods Two of these farms are no longer functioning as dairy units with one having been subdivided and sold Other point sources include a piggery, abattoir and landfill. A list of point sources (and loads) is given in Appendix 5. The sixteen point sources entered into the model were estimated to have an annual input to the streams of 52.5 tonnes of sediment, 2.5 tonnes of phosphorus and 10 6 tonnes of nitrogen (Table 2).

Climate

Monthly mean air temperature data used in model runs were from the Warkworth Satellite Station (site A64463) and monthly mean daily solar radiation data were from the Leigh Marine Laboratory (A64282). Daily rainfall totals were averaged from all the rainfall sites within the catchment (A64461, A64462, A64463) that had a record for each day. The model was run from 1976 to 1995 (inclusive), with gaps in the radiation and temperature records being filled with long-term mean values for that month. Average rainfall, temperature and radiation data from 1976 to 1995 are presented in Fig 7.

On average, rainfall is reasonably well-distributed through the year, although with somewhat higher monthly averages in winter (June — August). Temperature and radiation show expected seasonal patterns and may be expected to play a major role in determining the fate of rainfall, with soil moisture deficits in summer due to high potential evapotranspiration (PET) and moisture excesses in winter.

3.0 MODEL VALIDATION

In order to test the model predictions, the outlets to the three test catchments were equipped by ARC Environment staff with an automatic sampler that took a water sample whenever a pre-programmed volume of water passed by the flow station Eight samples were composited into one bottle (pre-loaded with $HgCl_2$ preservative) before the sampler moved on to filling a new bottle The preserved samples were gathered by ARC staff and sent to NIWA Hamilton laboratories for analysis of turbidity, suspended sediment, and nutrients (total phosphorus (TP), dissolved reactive phosphorus (DRP), nitrate, ammonium, total Kjeldahl nitrogen (TKN)) This sampling regime was designed to sample as much of the flow variability at each site as possible (given that the concentration of contaminants is often related to flow), and achieved this aim (e g., Fig 8) The samplers were operating at all three sites simultaneously for the year 1 July 1994 to 30 June 1995 and data collected over this period was used in model validation

3.1 Flow

Monthly and annual surface runoff and baseflow model predictions were compared with similar flow separations derived from the hydrographs at all the sites using the standard Hewlett and Hibbert technique. Annual comparisons are shown in Table 3 and the hydrographs of the three recording sites for that year in Fig. 9.

Examination of the monthly runoff patterns through the year show the model, in general, simulated the seasonal variation in base and storm flows (data not shown)

Table 3: Flow (mm), for the year 1 July 94 to 30 June 95 at the three sites as measured and as predicted by the model.

Site	Baseflow	Stormflow	Total
Wylies			
- measured	409	525	934
- predicted	400	512	912
Redwood			
- measured	253	227	480
- predicted	220	219	439
Mahurangi at College			
- measured	370	511	881
- predicted	371	388	759

3.2 Suspended Solids

Because suspended solid (SS) concentrations were related to flow at all three monitored sites, SS load — flow relationships (Fig. 10) were used to estimate SS loads and their 95% confidence limits using the technique of Cooper and Thomsen (1988) The technique includes a correction factor to remove bias inherent in log — log plots and accounts for the error introduced when the distribution of flow used to derive the rating curve is different from the flow distribution for the time period over which the rating curve is applied

Monthly and annual sediment loads and 95% confidence intervals from all three catchments were estimated for the year 1 July 1994 to 30 June 1995 and used to test the sediment loss component of the BNZ model. The high degree of correlation between the regression calculated and model predicted SS loads (Fig. 11) demonstrates the model's ability to provide a good simulation of sediment loss for pasture and forested land-uses, at both small and large scales.

The suspended sediment load for the pasture catchment at Wylies (241 t km^{-2}) was higher than that measured for the mature pine catchment at Redwood (146 t km^{-2})

3.3 Nutrients

Using the results from the analyses of the automatically collected water samples, nutrient loads at the three monitored sites were estimated either by the rating curve method (as for suspended solid load calculations) where a significant relationship occurred between concentration and flow or as the product of the arithmetic mean concentration and quantity of water exported. Nutrient concentrations for each site are listed in Table 4 and nutrient loads in Table 5.

Table 4: Nutrient concentrations. Values in mg m^{-3}, n is the number of samples.

	Median	Arithmetic Mean	Range	n
Redwood				
TP	154	395	15 — 10790	184
DRP	10	12.6	2 — 321	250
TKN	920	2297	110 — 64700	198
NH_4	32	66	1 — 706	252
NO_3	226	237	3 — 612	252
Wylies				
TP	134	325	16 — 1940	129
DRP	6	9	1 — 242	242
TKN	1200	2086	220 — 14300	120
NH_4	26	36.7	0 — 730	242
NO_3	95.5	124	31 — 422	242
College				
TP	129	475	8 — 3220	256
DRP	26	28.1	5 — 131	494
TKN	1365	2527	320 — 15700	287
NH_4	57	68.9	0 — 373	494
NO_3	350	414	49 — 1350	494

Nutrient concentrations are fairly typical for their land-use except that particulate concentrations (TP and TKN) in Redwood Forest are high compared with other New Zealand forest studies (Cooper and Thomsen 1988, Cooke 1980). Concentrations at Wylies Road pasture catchment are generally less than concentrations at Redwood Forest which is opposite to what might be expected (Cooper and Thomsen 1988). This could possibly be due to factors other than land-use, such as slope, soil type and presence of wetlands.

The estimated nutrient loads generally fall within the wide ranges previously reported in New Zealand for these land-uses (Wilcock 1986), but particulate forms are in the higher end of this range. This finding probably reflects a greater input of fine, nutrient-rich material from the erosion of clay soils in the catchment. The pine catchment had lower nutrient loads than that measured for the pasture catchment and the large mixed land-use catchment.

Table 5: Estimated nutrient loads (and 95% confidence intervals) from 1 July 1994 to 30 June 1995 for Redwood Forest, Wylies Road and Mahurangi College catchments.

Parameter	Load (kg km^{-2} year^{-1})		
	Redwood	Wylies	College
TP	118 (108 — 129)	342 (312 — 375)	278 (268 —288)
DRP	6.03 (4 8 — 7.26)	8 38 (6.48 — 10.3)	26 1 (25 2 — 26.9)
TKN	745 (690 — 804)	1802 (1643 — 1977)	1606 (1555 — 1660)
NH_4-N	31.7 (25 2 — 38 3)	34 0 (28 2 — 39 8)	64 (60.3 — 67 7)
NO_3-N	114 (107—121)	115 (106 — 124)	384 (366 — 402)

4.0 MODEL SIMULATION FOR THE MAHURANGI ESTUARY CATCHMENT

Given the agreement between modelled and measured suspended sediment loads for our three study catchments, we then predicted runoff and suspended sediment exports from the whole of the Mahurangi Estuary catchment over 20 years (1976 to 1995) The outputs from this model simulation are shown in Figs 12 to 15.

Long-term average annual predicted runoff varied from < 300 mm (< 18% of rainfall) to > 600 mm (> 35% of rainfall). The 300 mm coincided with sub-catchments under permanent forest cover The 600 mm coincided with sub-catchments in predominantly pastoral land-use and on low infiltration soils Most of the catchment had average annual runoff of between 400-600 mm

Predicted long-term average sediment loads for each cell ranged from < 200 t km^{-2} year^{-1} to > 700 t km^{-2} year^{-1}, with many of the cells displaying high sediment losses being located in sub-catchments bordering the estuary, particularly Te Kapa Inlet, Pukapuka Inlet, Dyers Creek and Cowans Bay These areas are dominated by pastoral land-uses, strongly rolling to steep slopes, and soil types that have low infiltration capacity. The model highlights the combination of steep slope and pastoral land-use as being the dominant factor behind high sediment yield as over 90% of the catchment fitting this description produces an average yield of more than 700 t km^{-2} year^{-1}.

The model can predict sediment losses from sub-catchment outlets as well as from cells Predicted sub-catchment losses include the effects of stream channel deposition (i.e , sediment delivery). Sediment output for each sub-catchment is shown in Fig. 15. The long-term average sediment load delivered to the Mahurangi Estuary from its surrounding catchment was predicted by the model to be 52270 t year^{-1} (448 t km^{-2} year^{-1}) This long-term average load comes from highly variable annual loads (Fig.

16) The annual sediment delivery to the Estuary over the 20 year period of modelling ranged from just over 13,000 to approximately 136,000 tonnes year^{-1}. Sediment loss does not demonstrate a strong seasonal pattern and although late winter/early spring often shows an increase in suspended sediment loads, major events happen at any time.

Using the sub-catchment suspended sediment loads, it is possible to examine the contribution of sediment to the Estuary on a regional basis (Fig 17) Despite forming half the entire catchment, the Mahurangi River (including land draining into the uppermost parts of the estuary) only contributes 29% of the total load to the Estuary with an average loading of 260 t km^{-2} year^{-1}. The catchments draining the Eastern and Western shores contribute approximately 71% of the sediment load, with average loadings of 630 t km^{-2} year^{-1} and 650 t km^{-2} year^{-1}, respectively. This is due to pastoral land-use on steeper slopes, coupled with a higher sediment delivery ratio resulting from the shorter, faster journey for sediment between land and estuary Much of the sediment deposited in the infilled embayments of the Eastern and Western Shores (e.g., Cowans Bay, Te Kapa Inlet) is presumably derived from these catchments rather than from transport from the Mahurangi River Overall, the model predicts for the total catchment annual average sediment erosion of 83,850 t year^{-1}, of which 52,270 t year^{-1} (or 62%) reaches the Estuary. For the Mahurangi River catchment, just under 50% of the eroded sediment reaches the estuary compared to about 70% for the catchments of the Eastern and Western shores.

Relative nutrient losses for each sub-catchment are shown in Figs 18 to 21 As may be expected the spatial patterns in sediment associated phosphorus and nitrogen loss reflect the spatial patterns of sediment loss Soluble nutrients can be lost in surface runoff and/or percolation to groundwater that contributes to the baseflow in streams. The model predicts that most phosphorus is lost in a particulate form, some is lost as soluble P in surface runoff but very little is lost in baseflow. This is because phosphorus is dominantly a particulate-bound nutrient, and as water moves through soil to groundwater, any dissolved phosphorus tends to adsorb to soil particles. Nitrogen however is more soluble and is readily lost in a dissolved form, to both surface runoff and groundwater. Although all the high soluble N loss cells predicted by the model are in pasture and have high percolation to groundwater, the reverse is not true, i.e., not all pasture cells with high percolation to groundwater have high soluble N loss This indicates that N loss from soils to groundwater is sensitive to land management decisions such as, fertiliser use, stock type and stock density.

5.0 SCENARIO RUNNING

In addition to providing information on the effects of current land-use on sediment and nutrient inputs to the Estuary, the catchment model can be used in the predictive mode to help answer 'what if' type questions relating to possible land-use changes For example, the effects of urbanisation can be evaluated, both in terms of sediment and nutrient loss from a particular site as well as at the larger-scale in terms of altering total inputs to the Estuary

Scenario running using the BNZ model should be viewed as a risk analysis methodology. In effect, the changed land-use information is combined with a long-term historical climate record to predict a range of possible sediment and nutrient responses to land-use change. The risk of a certain load occurring is thereby predicted - what will actually occur will be dependent upon future rainfall patterns.

6.0 ACKNOWLEDGEMENTS

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8.0 APPENDICES

Appendix 1:

Soils of the Mahurangi Estuary catchment and their saturated hydraulic conductivity and porosity.

Soil abbreviation	Soil name	Saturated hydraulic conductivity (mm hour^{-1})	Porosity - average of profile (%)
ANS	Atuanui steepland soil	2 6	57.3
C1	Otao-Waitemata-Albany-Coatesville-Otonga complex & Otao silt loam	5.4	50.3
KR	Kara silt loam	1	55.6
MT	Motatau clay	30	68.5
PBuH	Puhoi light brown clay loam	1	54 2
WA	Warkworth clay and sandy clay loam	0.4	57.7
WAH	Warkworth clay and sandy clay loam hill	0.4	57.7
WF	Whakapara silt loam and clay loam	6 6	56
WO	Whareora clay loam	6.6	56
WR	Whangaripo clay loam	0.4	56 8
WRe	Whangaripo clay	0 4	56.8
WRH	Whangaripo clay loam hill	0.4	58.7
WReH	Whangaripo clay hill	0 4	58 7
YK	Waikare silt loam	1	50.4

Appendix 2:

Land Resource Inventory slope classes

LRI Slope class	Slope range (degrees)	Median slope of range used in modelling (degrees)	(m m^{-1})
A	0 - 3	1 5	0 0262
B	4 - 7	5 5	0 0963
C	8 - 15	11.5	0.203
D	16 - 20	18	0 325
E	21 - 25	23	0.424
F	26 - 35	30.5	0.589

Appendix 3:

A. Mahurangi Estuary catchment land-use classes

Land-use	Sheep	Beef	Fertiliser	Septic tanks	Other
1	low	low	low	low	
2	low	low	low	medium	
3	low	low	low	high	
4	low	low	medium	low	
5	low	low	medium	low	
6	low	low	high	low	
7	low	medium	low	low	
8	low	medium	low	medium	
9	low	medium	medium	low	
10	low	medium	high	low	
11	low	high	low	low	
12	medium	low	low	low	
13	medium	low	medium	low	
14	medium	low	high	low	
15	medium	low	high	medium	
16	medium	medium	low	low	
17	medium	medium	medium	low	
18	medium	medium	medium	medium	
19	medium	medium	high	low	
20	medium	high	low	low	
21	medium	low	medium	medium	
22	high	low	high	low	
23	high	medium	high	low	
24	high	medium	medium	low	
25	medium	medium	high	medium	
26					deer
27				low	native bush & scrub
28					exotic forest
29					urban
30					dairy
31					young pines & pasture
32				high	native bush & scrub

B. Wylies Road catchment land-use classes

Land-use	Sheep	Beef	Fertiliser	Septic tanks	Other
1	medium	low	medium	low	
2					bulls
3					retired pasture
4					native bush & scrub

C. Numerical definition of land-use classes. The range of values for each category is listed and the value used in the model is in brackets

Category	Sheep (number ha^{-1})	Cattle (number ha^{-1})	Fertiliser (kg P ha^{-1} $year^{-1}$)	Septic tanks (number of people on septic tanks ha^{-1})
Low	<3 (0)	≤1 (0)	<20 (0)	<3 (0)
Medium	3 - <10 (5.5)	>1 - <2 (1.3)	20-50 (40)	3-9 (4.5)
High	≥10 (14)	≥2 (2.6)	>50 (65)	≥10 (18)

Appendix 4:

Effective pond volumes used in the BNZ model

Sub-catchment	Pond volume (m^3)
4	6
13	15
16	5320
20	3000
25	254
44	275

Appendix 5:

Point source discharges

Sub-basin	Source	Discharge (L s^{-1})	Soluble P (g m^{-3})	Soluble P (kg $year^{-1}$)	Sediment N (g m^{-3})	Sediment N (kg $year^{-1}$)	Soluble N (g m^{-3})	Soluble N (kg $year^{-1}$)
13	RDC public toilets	0.116		0		0	65	237.78
14	Warkworth	25.1	5.42	4290.22	9 7	7678.07	13.9	11002 6
15	Memberry - dairy	0 0745	12 2	28 66	17	39.94	93	218.5
15	Stevenson - dairy	0 194	12.2	74.64	17	104 01	93	568.97
16	Adolf - dairy	0.083	12.2	31.93	17	44.5	93	243 43
16	Nicolls - dairy	0.087	12 2	33.47	17	46.64	93	255.16
18	Landfill	0.046		0		0	190	275.62
23	ARC public toilets	0 035		0		0	65	71 74
24	Davey-Martin - dairy	0.087	4.5	12.35		0	83 6	229.37
29	Davey-Martin dairy	0 1025	4 5	14 55		0	83.6	270.23
30	Stubbs abbatoir	0 098	4.5	13 91		0	83.6	258 37
31	orchard	0 001	7610	239.99		0		0
31	Civil Estate - dairy	0.156	4 5	22.14		0	83.6	411.28
32	piggery	0 052	24	39 36	12	19 68	243	398 49
32	caravan park	0 024		0		0	65	49.2
45	Bradman - dairy	0.149	12.2	57.33	17	79.88	93	436.99

Appendix 6: Figures

Figure 1: Structure of the BNZ model

Figure 2: Catchment of the Mahurangi Estuary showing the sub-catchments used in the BNZ model and the location of Wylies Road, Redwood Forest and Mahurangi College flow recorder sites.

Figure 3: Soil types of the Mahurangi Estuary, Wylies Road and Redwood Forest catchments.

Figure 4: Slopes (degrees) of the Mahurangi Estuary, Wylies Road and Redwood Forest catchments.

Figure 5: Land-use categories of the Mahurangi Estuary, Wylies Road and Redwood Forest catchments.

Figure 6: Location of ponds and point sources in the Mahurangi Estuary catchment

Figure 7: Average monthly rainfall totals, temperature and radiation data from 1976 to 1995.

Figure 8: Hydrograph for each site for time period 1 April 95 to 8 April 95 showing timing of water sampling during a storm event

Figure 9: Hydrographs of daily mean flow for 1-Jul-94 to 30-Jun-95 used in model validation and regression analysis.

Figure 10: Suspended solid (SS) load - flow regression plots for Redwood Forest, Wylies Road and Mahurangi College flow recorder sites.

Figure 11: Rating curve derived monthly and annual sediment loads and 95% confidence intervals compared to loads predicted by the BNZ model for Redwood Forest, Wylies Road and Mahurangi College catchments, for the year 1 July 1994 to 1 July 1995.

Figure 12: Model predicted cell runoff (mm)

Figure 13: Model predicted sub-catchment runoff (mm).

Figure 14: Model predicted cell sediment load (tones km^{-2} year^{-1})

Figure 15: Model predicted sub-catchment sediment load (tonnes km^{-2} year^{-1}).

Figure 16: Model predicted annual suspended sediment loads to the Mahurangi Estuary. Annual average for the 20 year period is also shown.

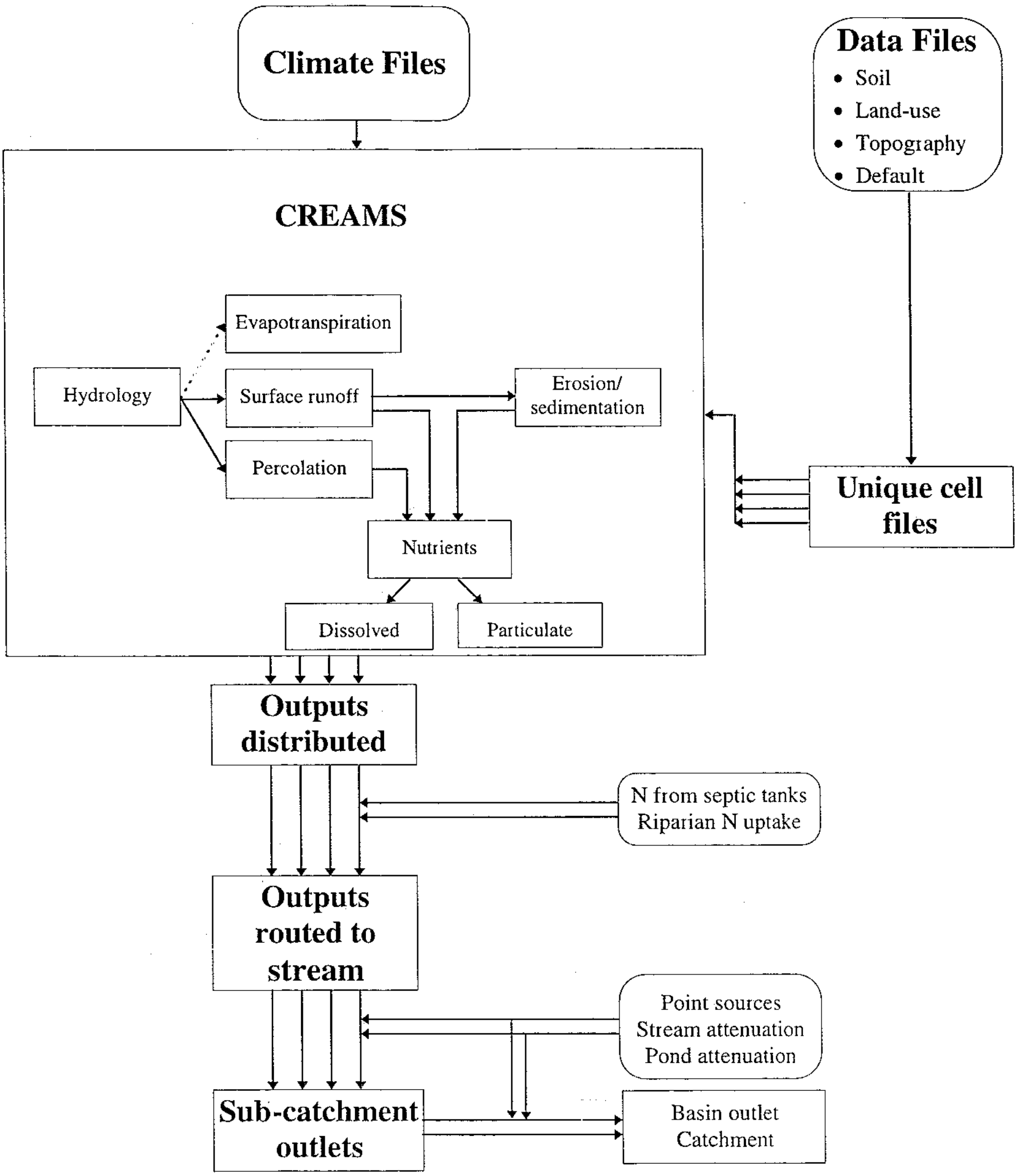
Figure 17: Predicted annual average contribution to the Mahurangi Estuary sediment load by the Mahurangi River system catchment (58.25 km^2 - includes catchment area at the very top of the estuary above Ducks Creek), Western Mahurangi (33.25km^2) and Eastern Mahurangi (25.25 km^2) shores.

Figure 18: Model predicted relative sub-catchment loads of sediment phosphorus.

Figure 19: Model predicted relative sub-catchment loads of sediment nitrogen.

Figure 20: Model predicted relative sub-catchment loads of soluble phosphorus.

Figure 21: Model predicted relative sub-catchment loads of soluble nitrogen



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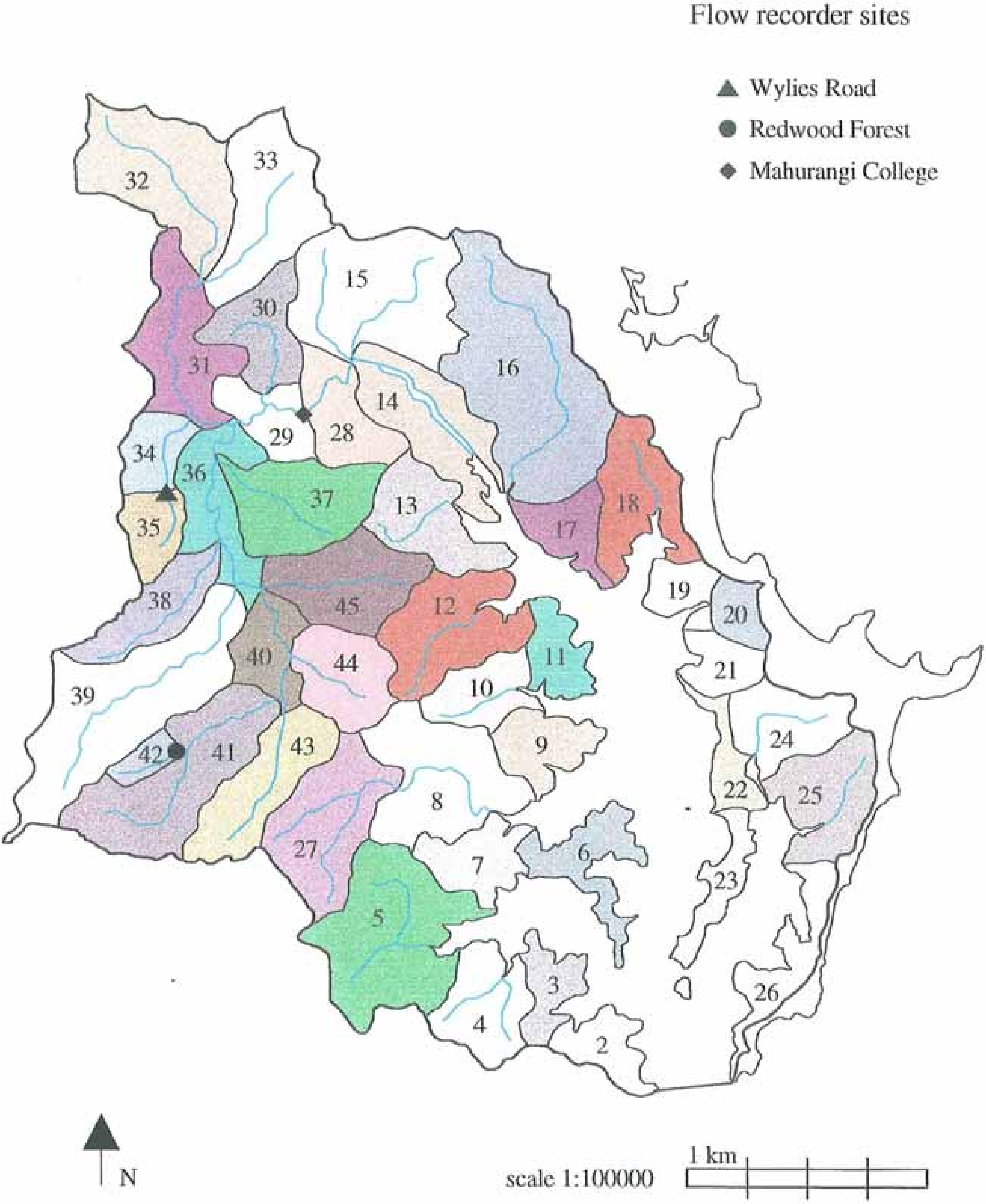

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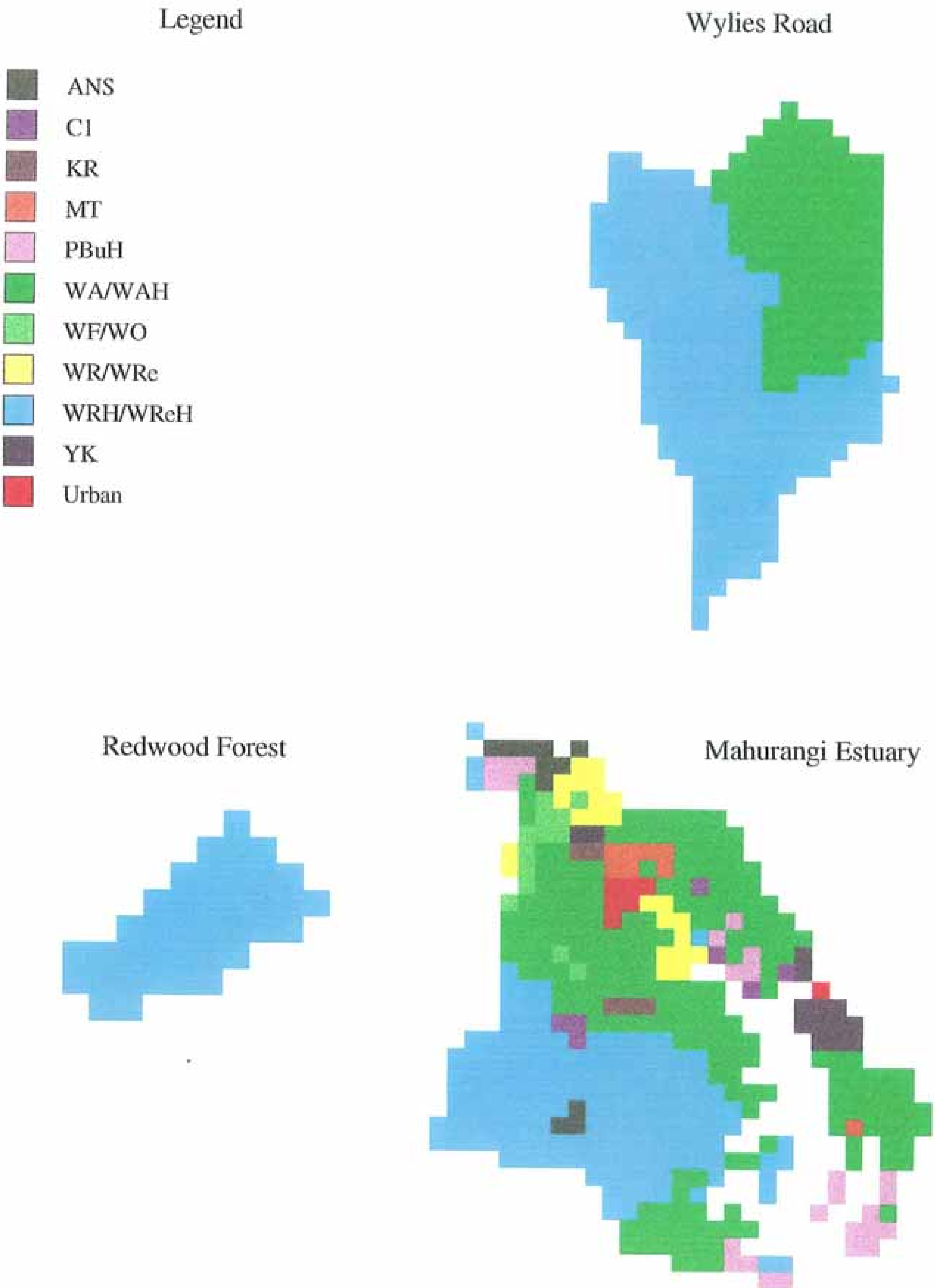

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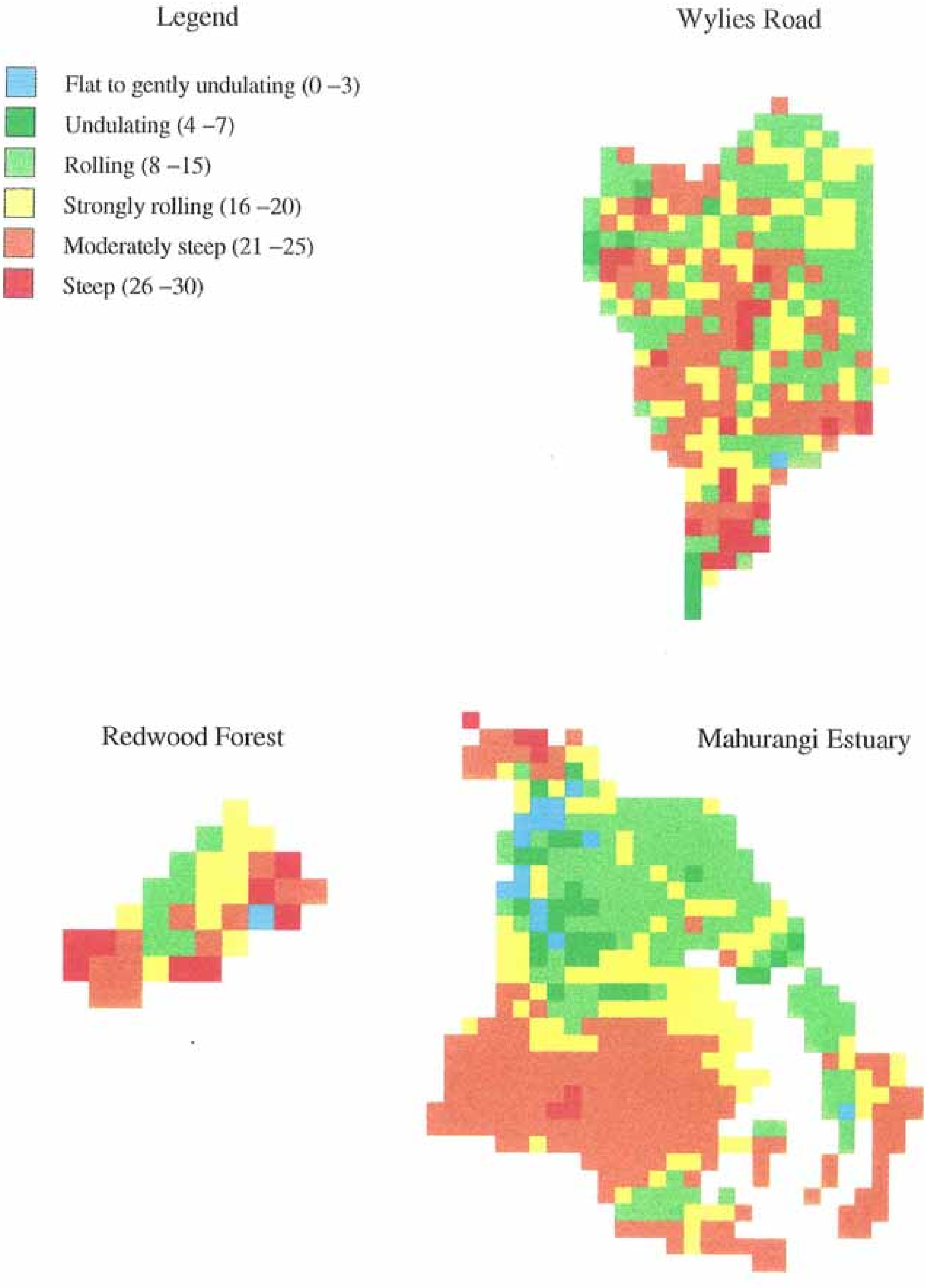

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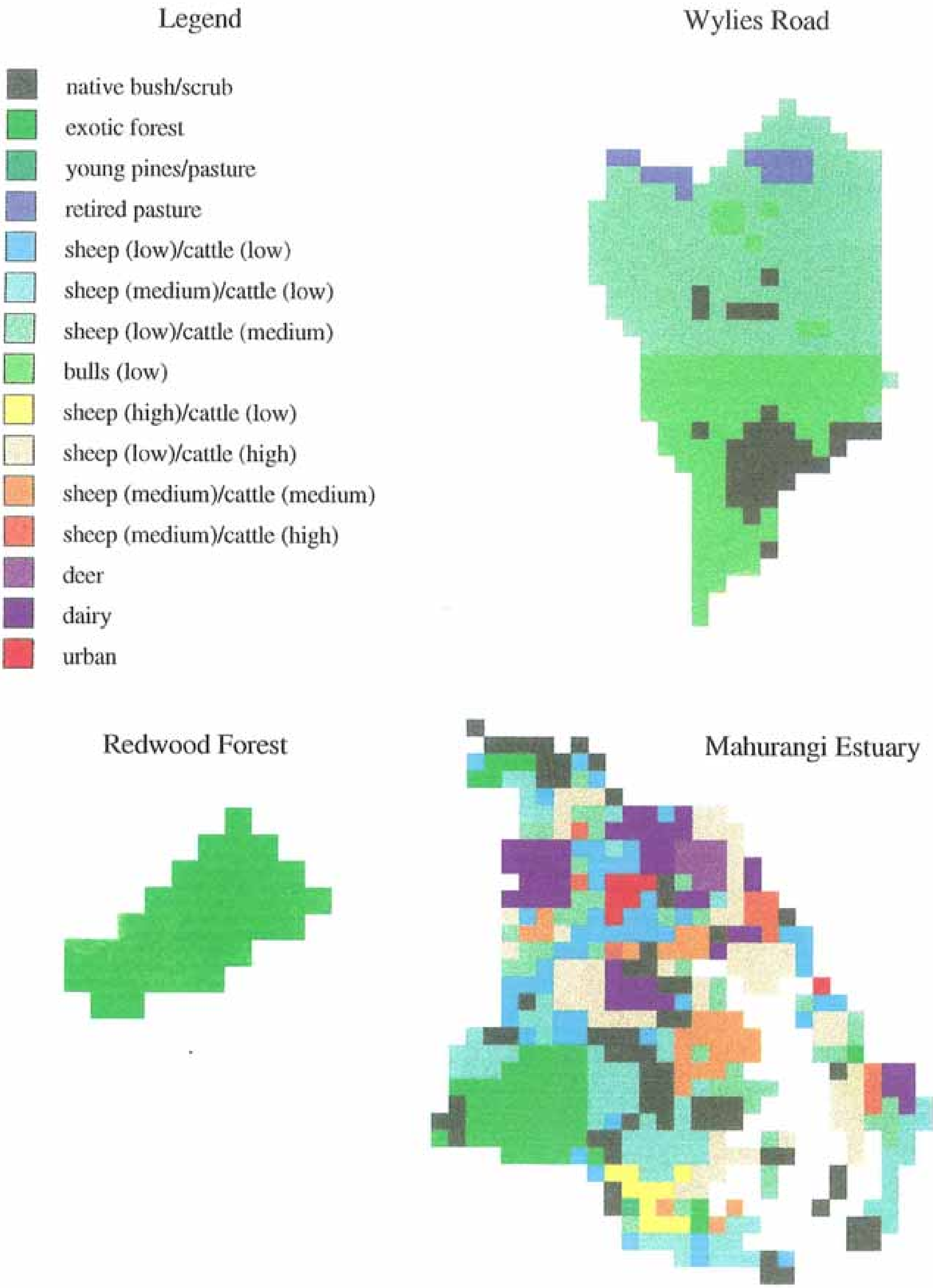

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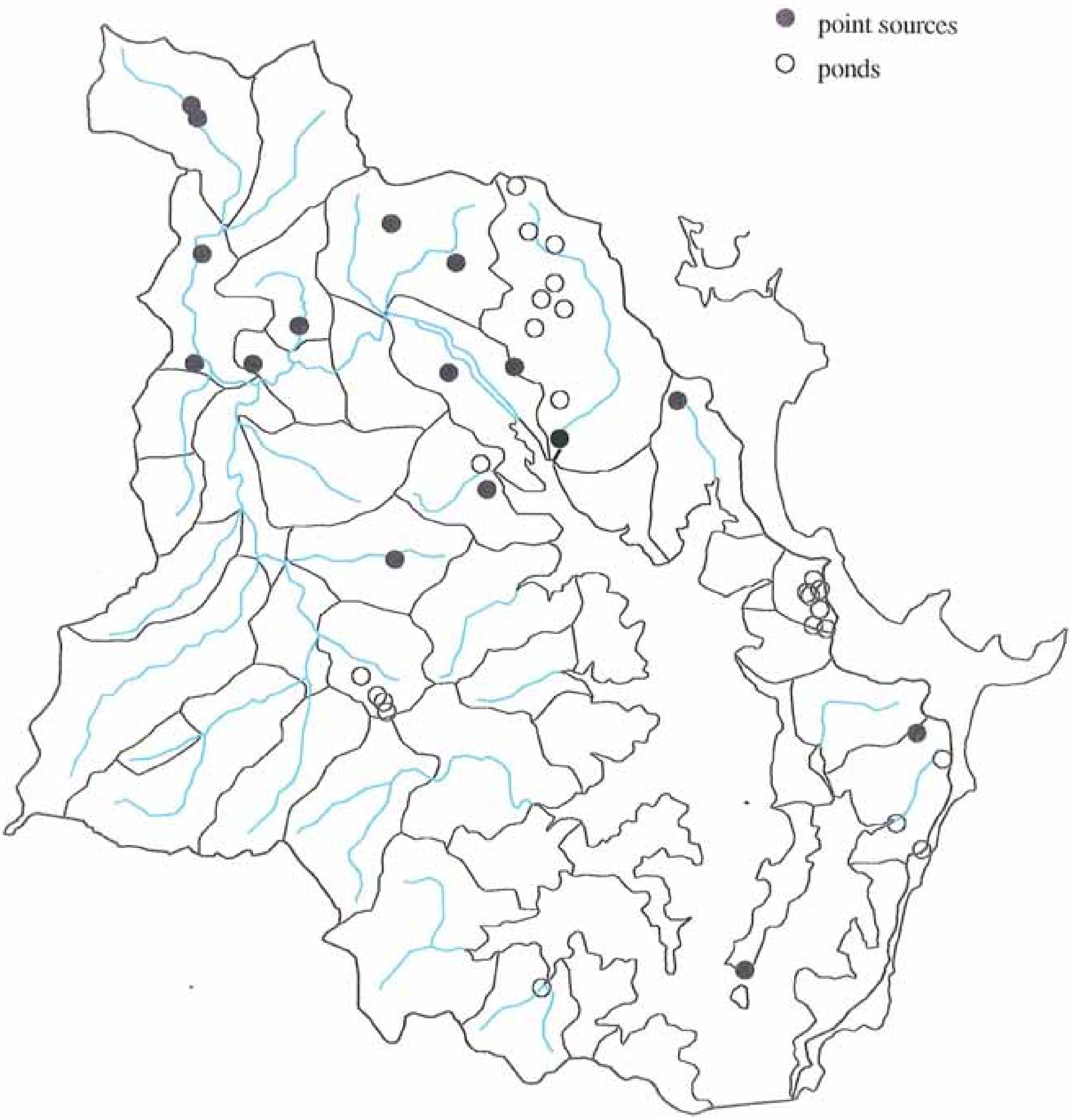

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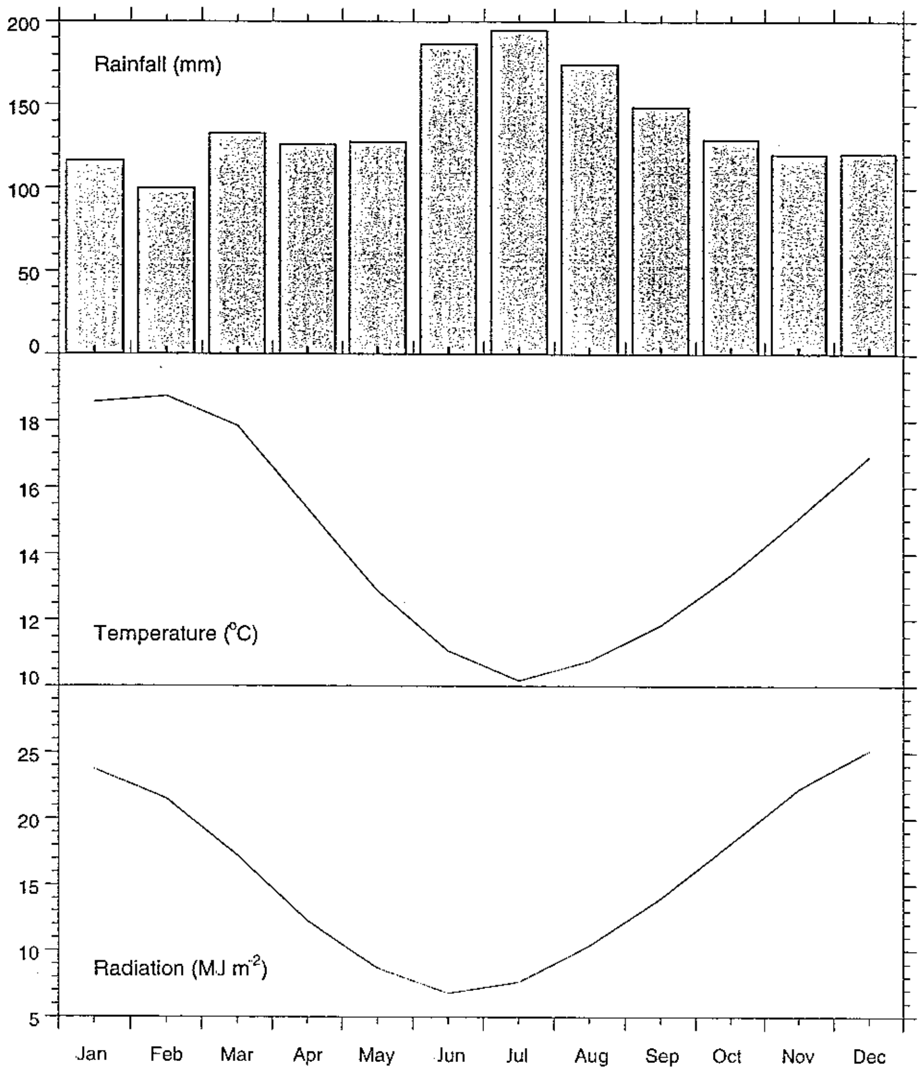

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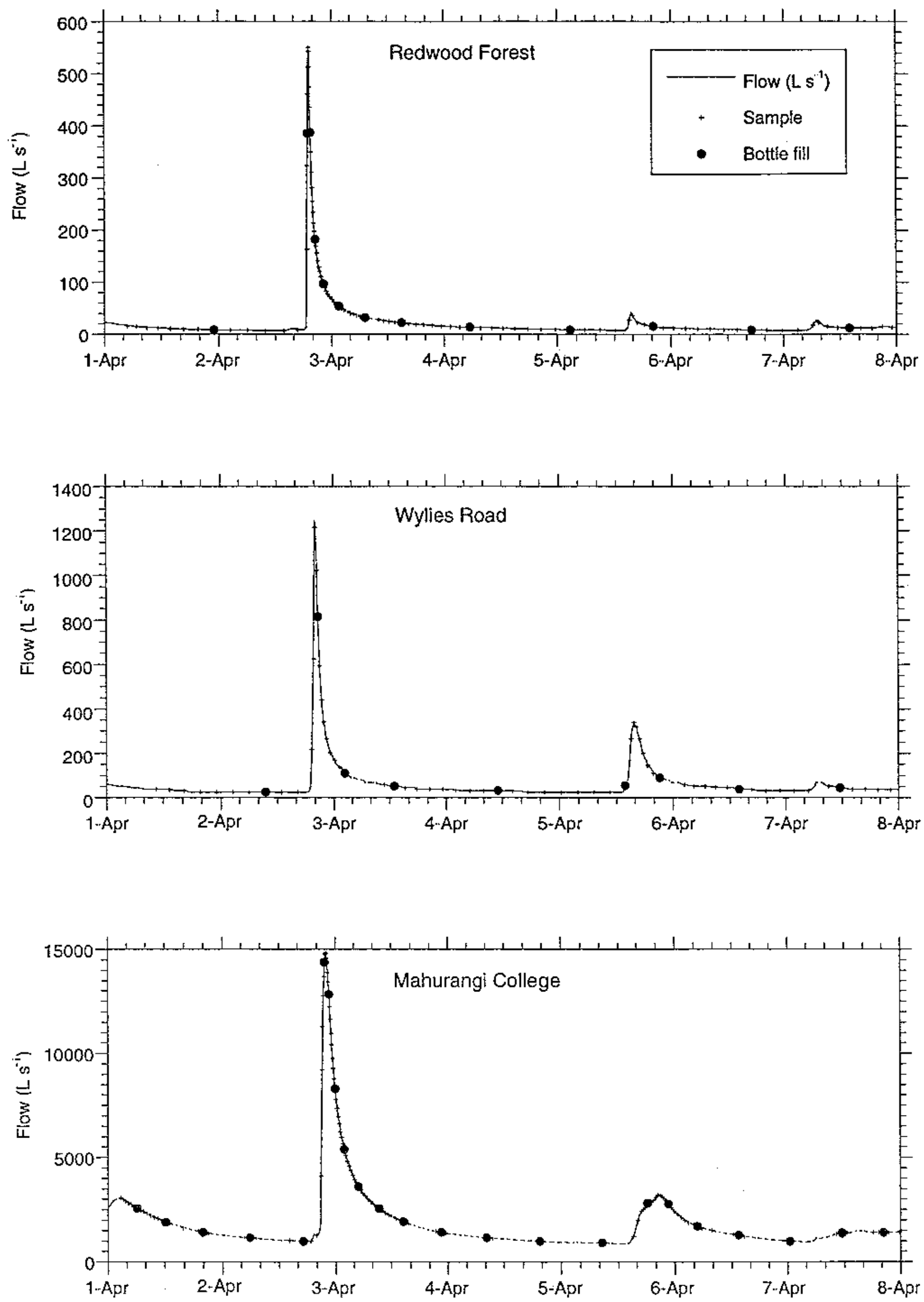

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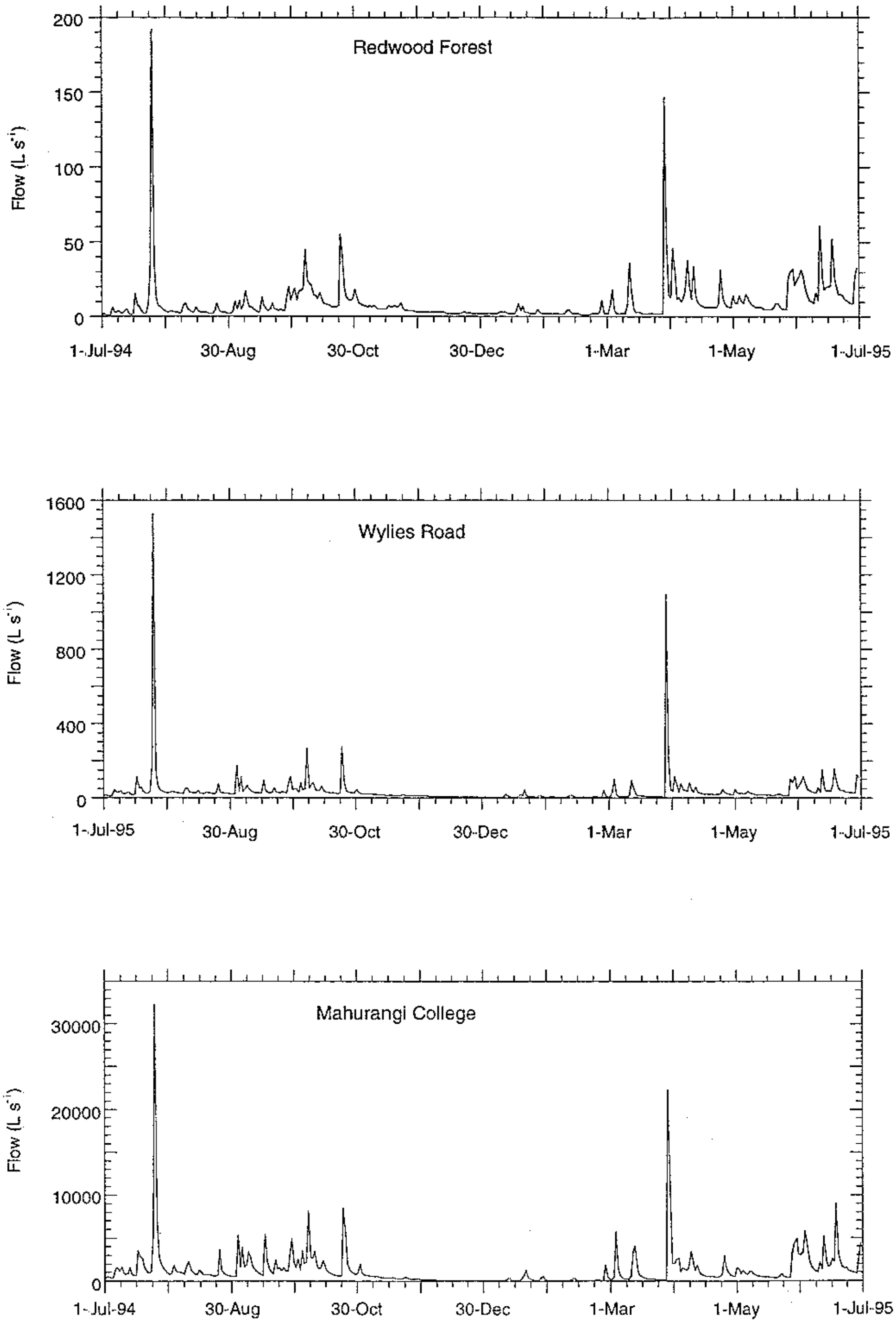

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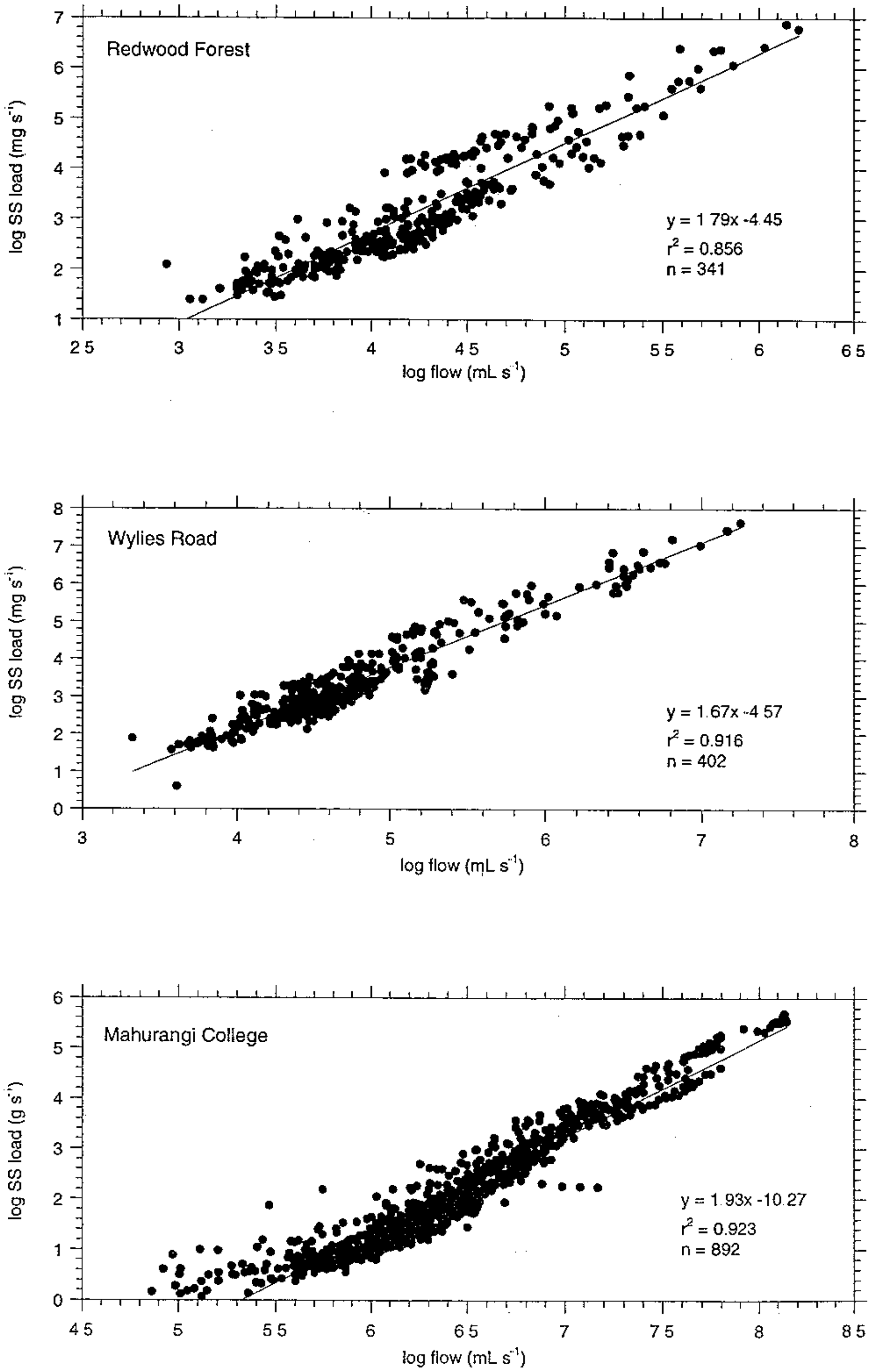

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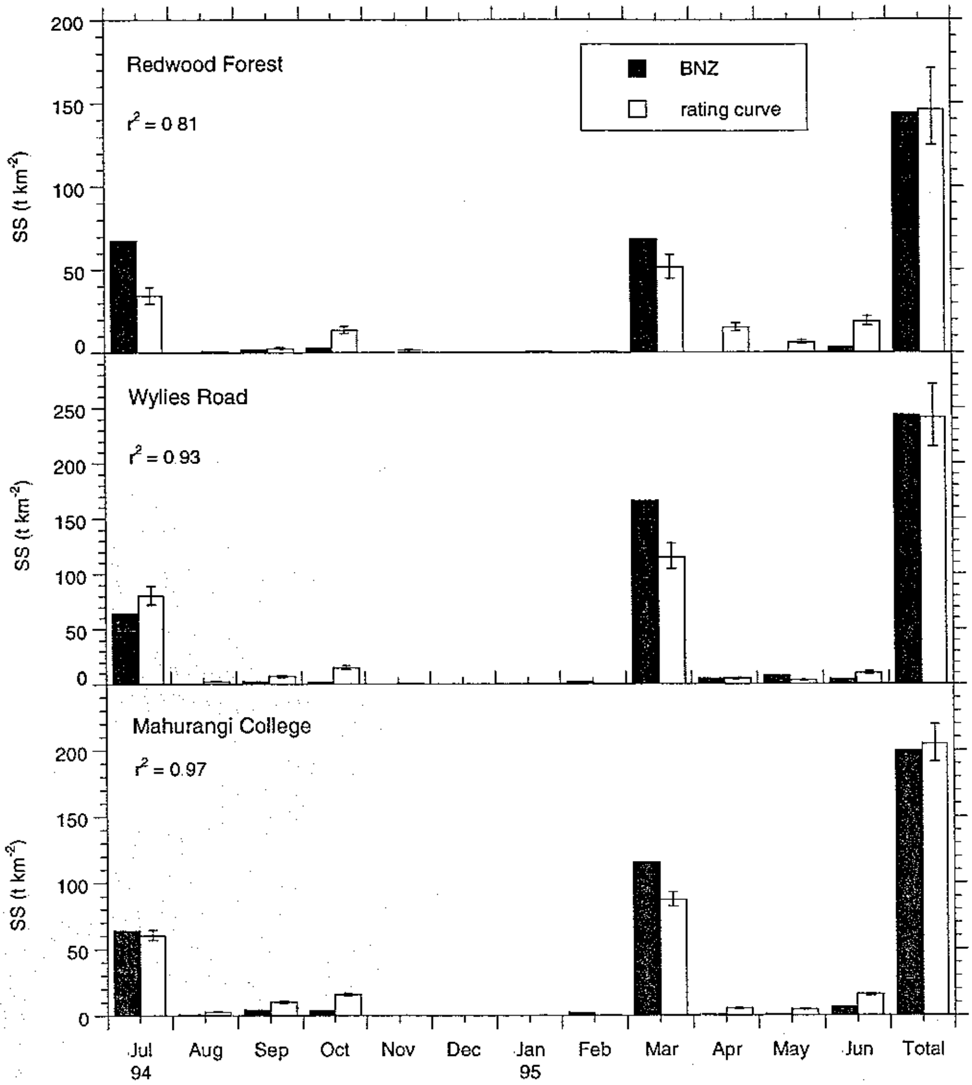

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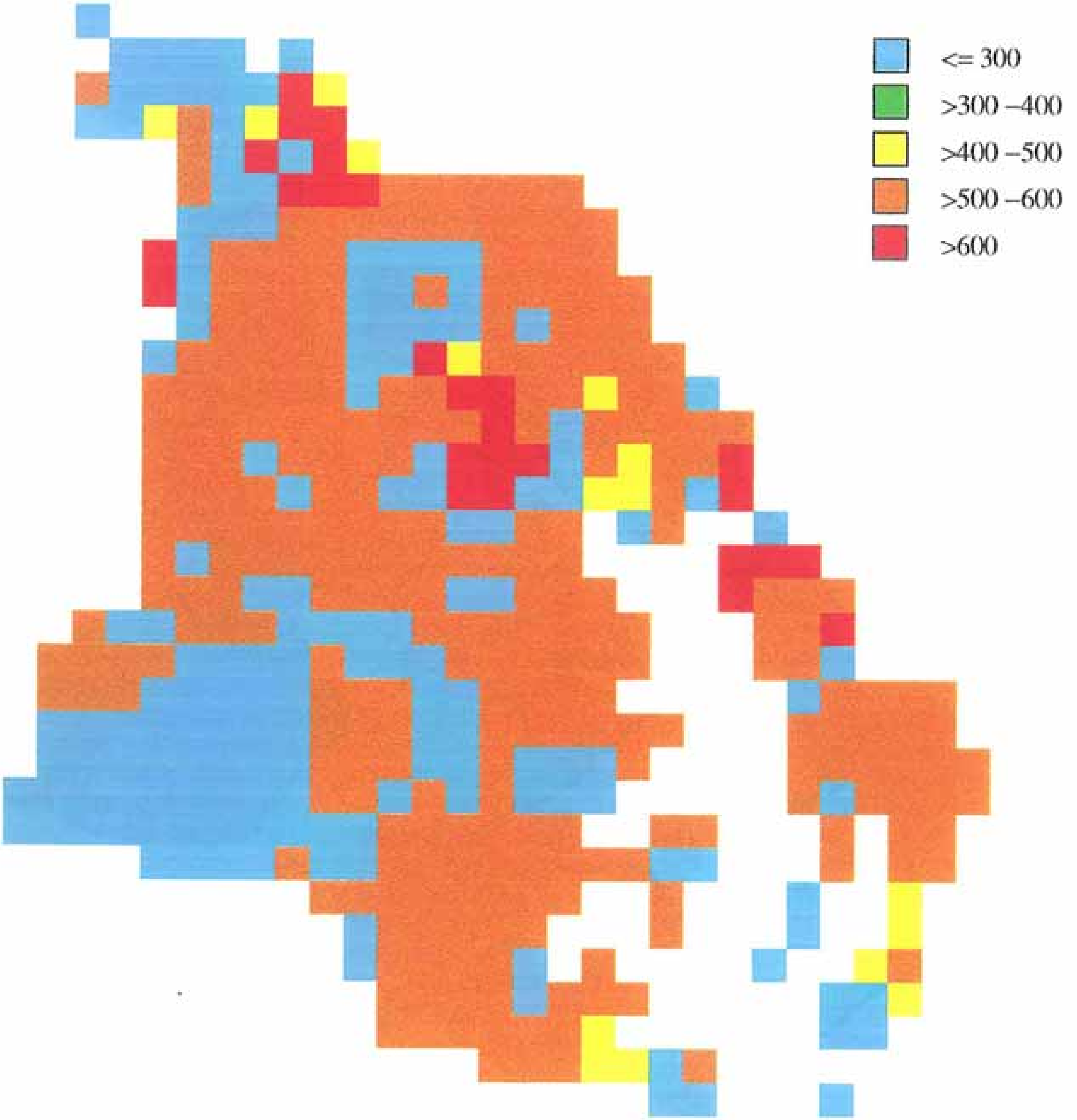

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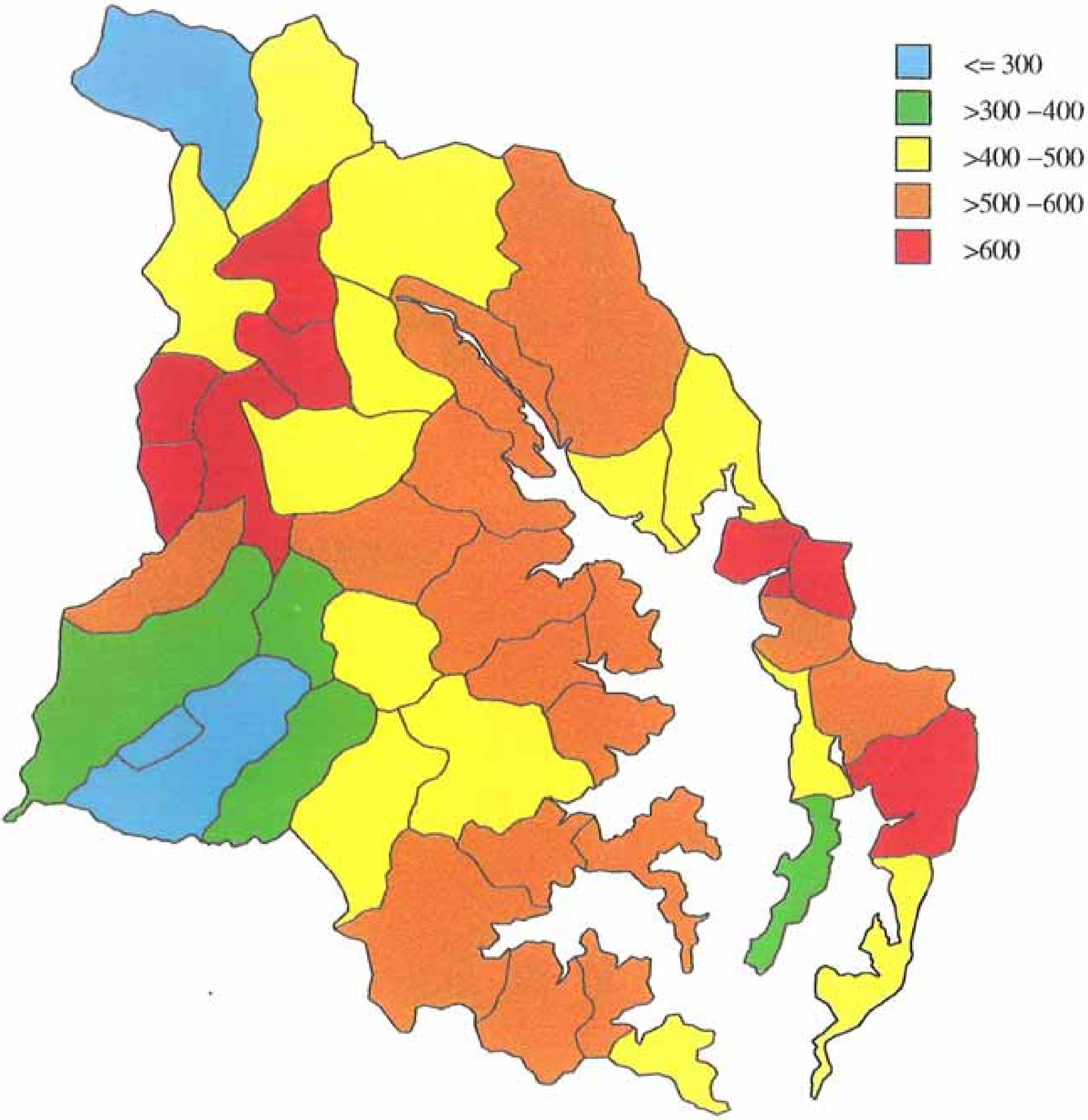


Figure 13: Model predicted sub-catchment runoff (mm).

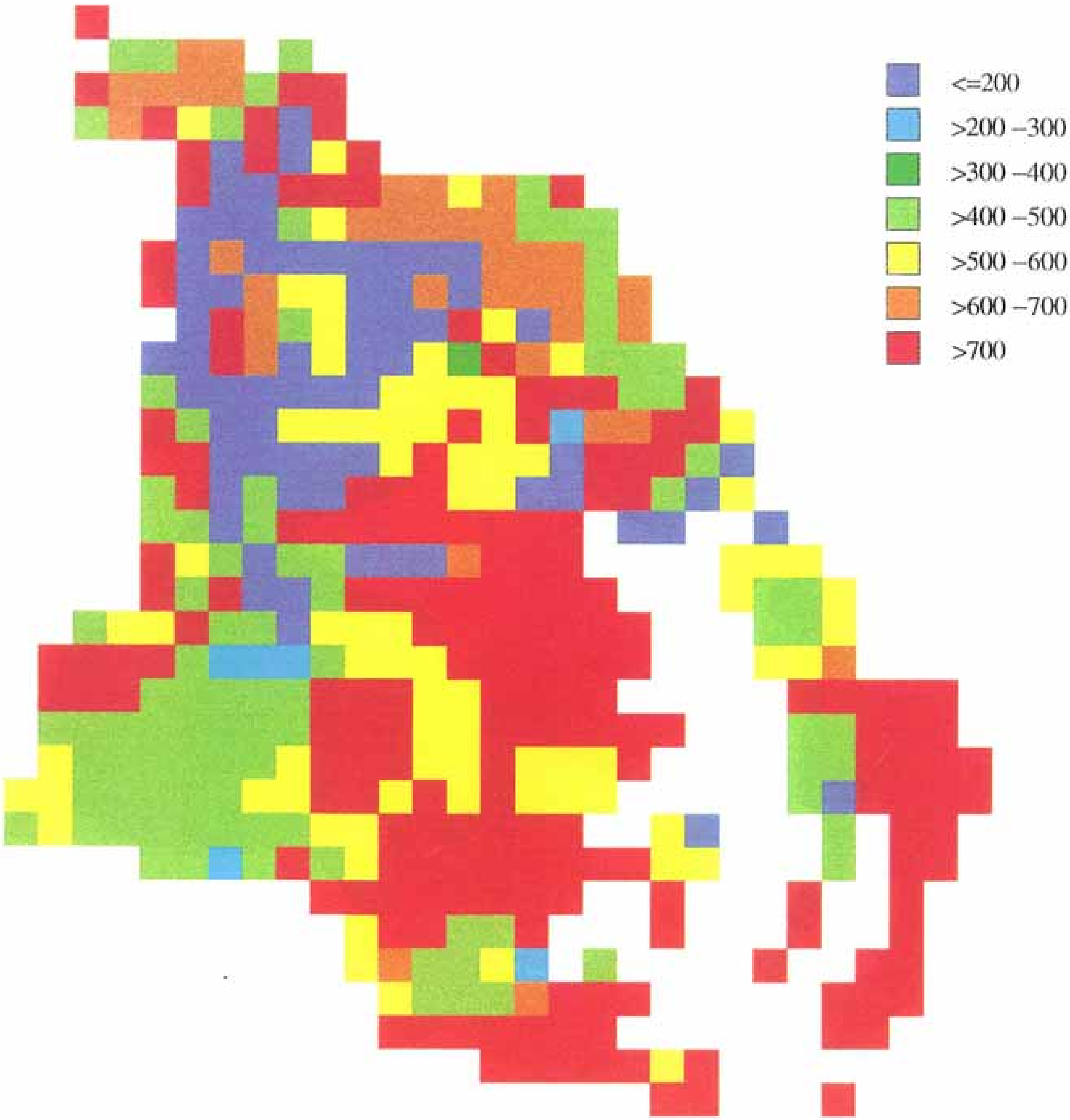


Figure 14: Model predicted cell sediment load (tonnes km^{-2} $year^{-1}$)

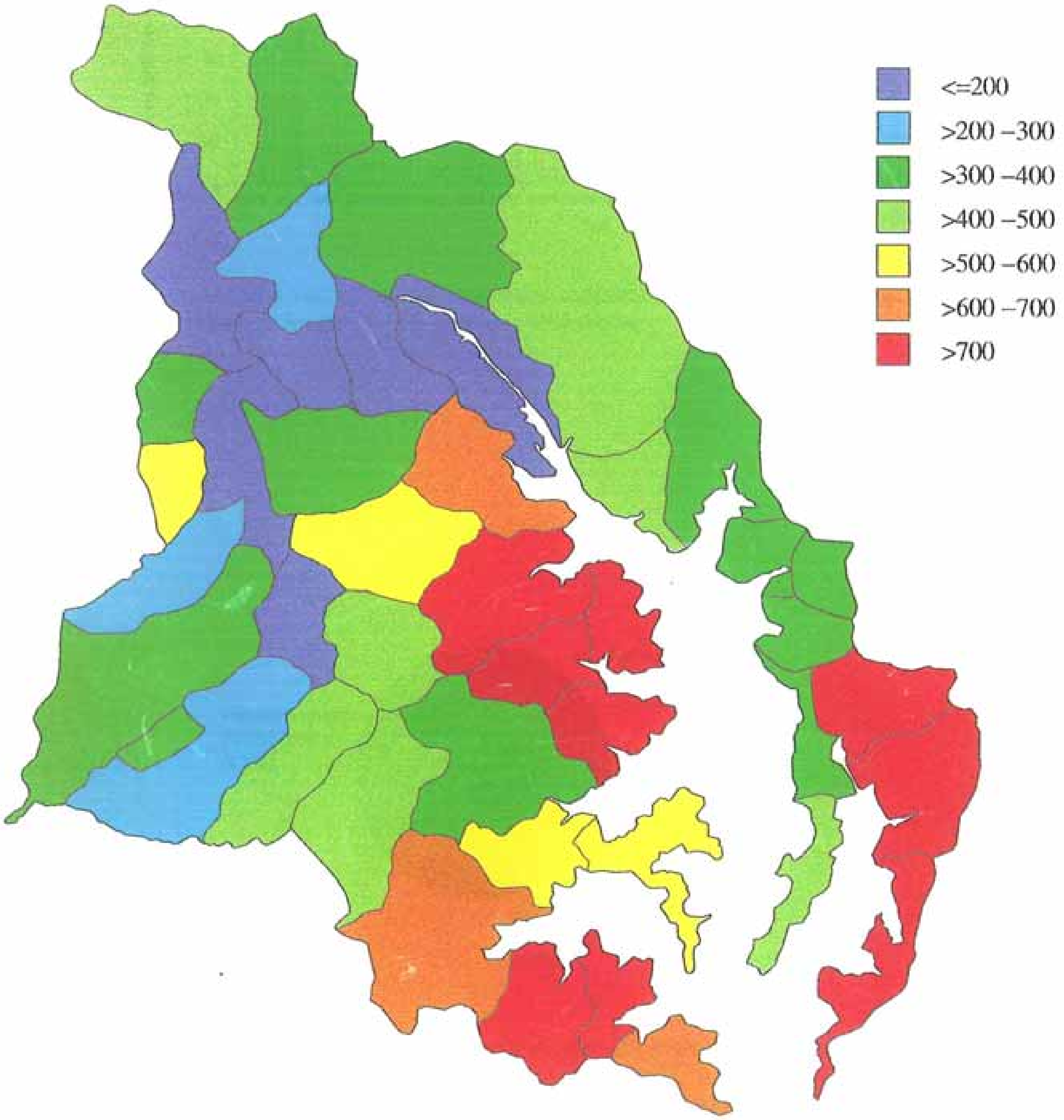
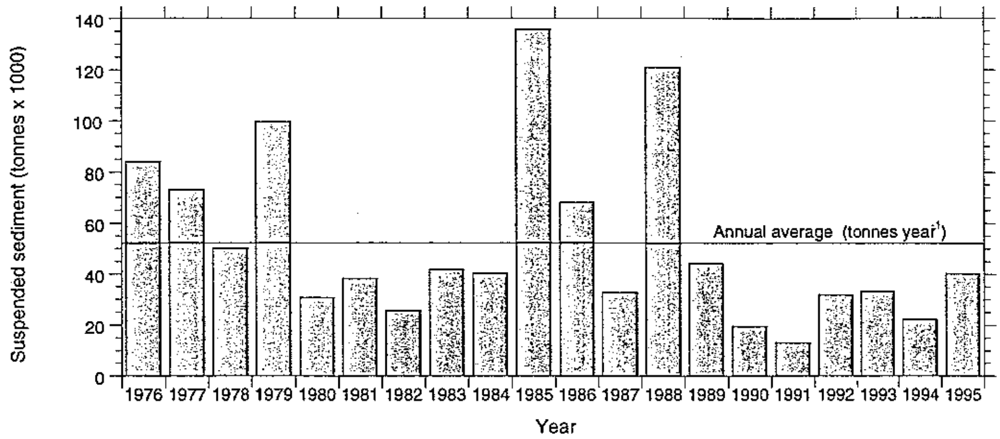


Figure 15: Model predicted sub catchment sediment load (tonnes km^{-2} $year^{-1}$)



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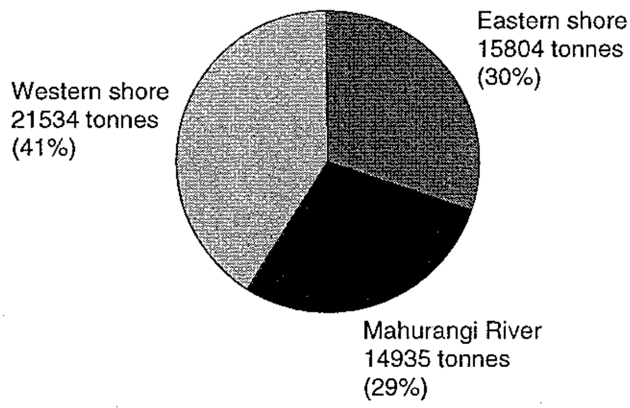

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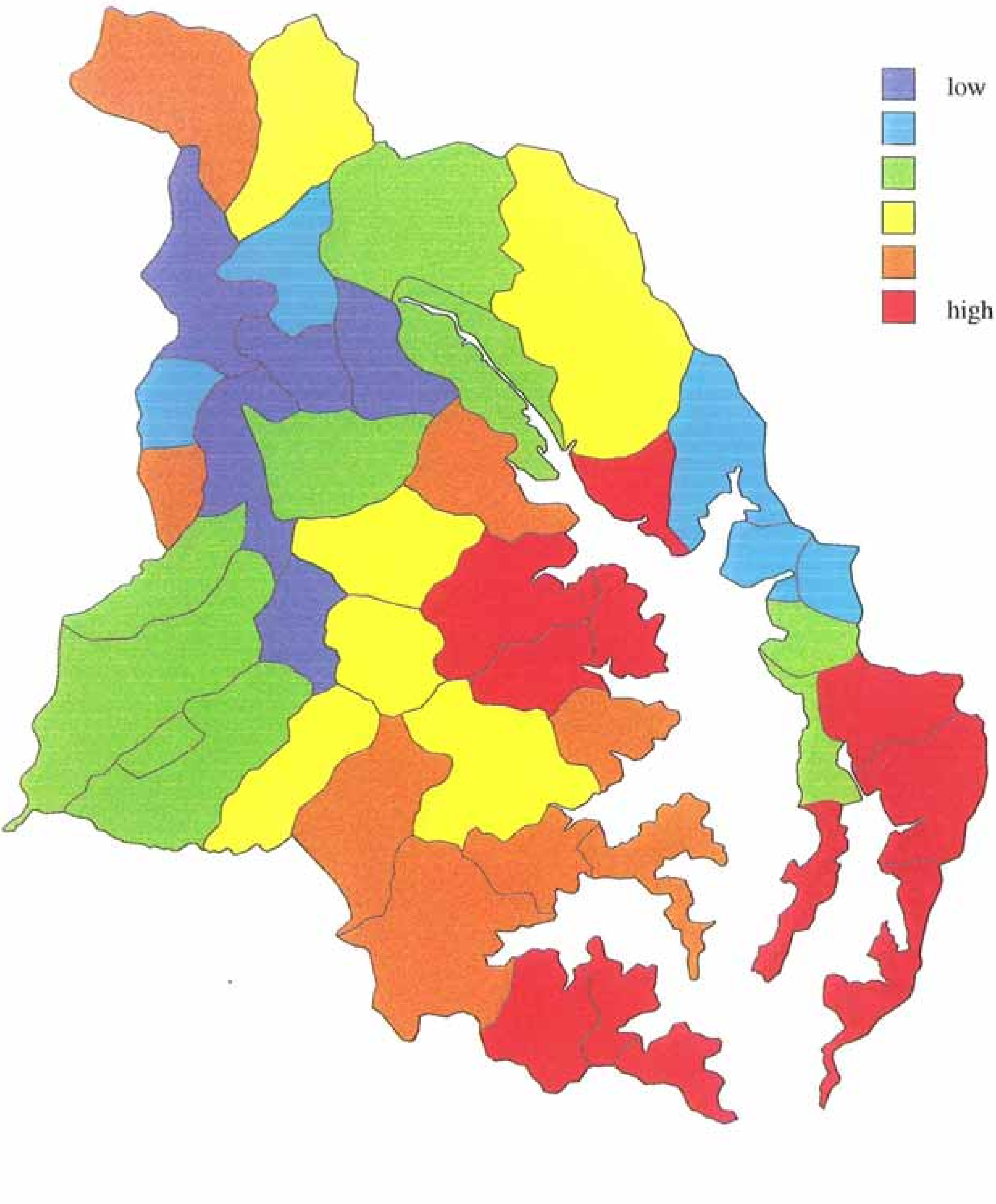

Figure 18: Model predicted relative sub-catchment loads of sediment phosphorus.

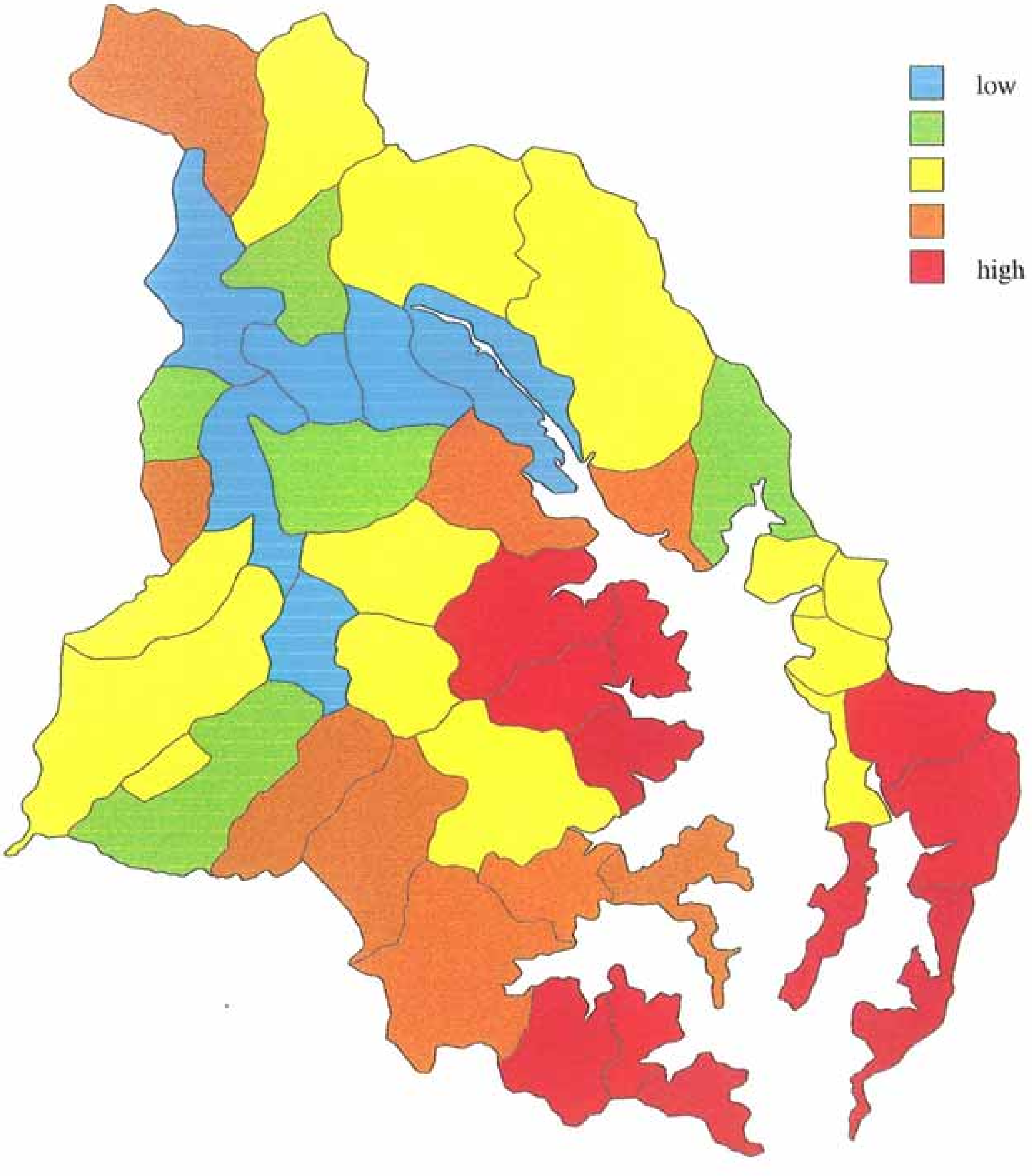

Figure 19: Model predicted relative sub-catchment loads of sediment nitrogen.

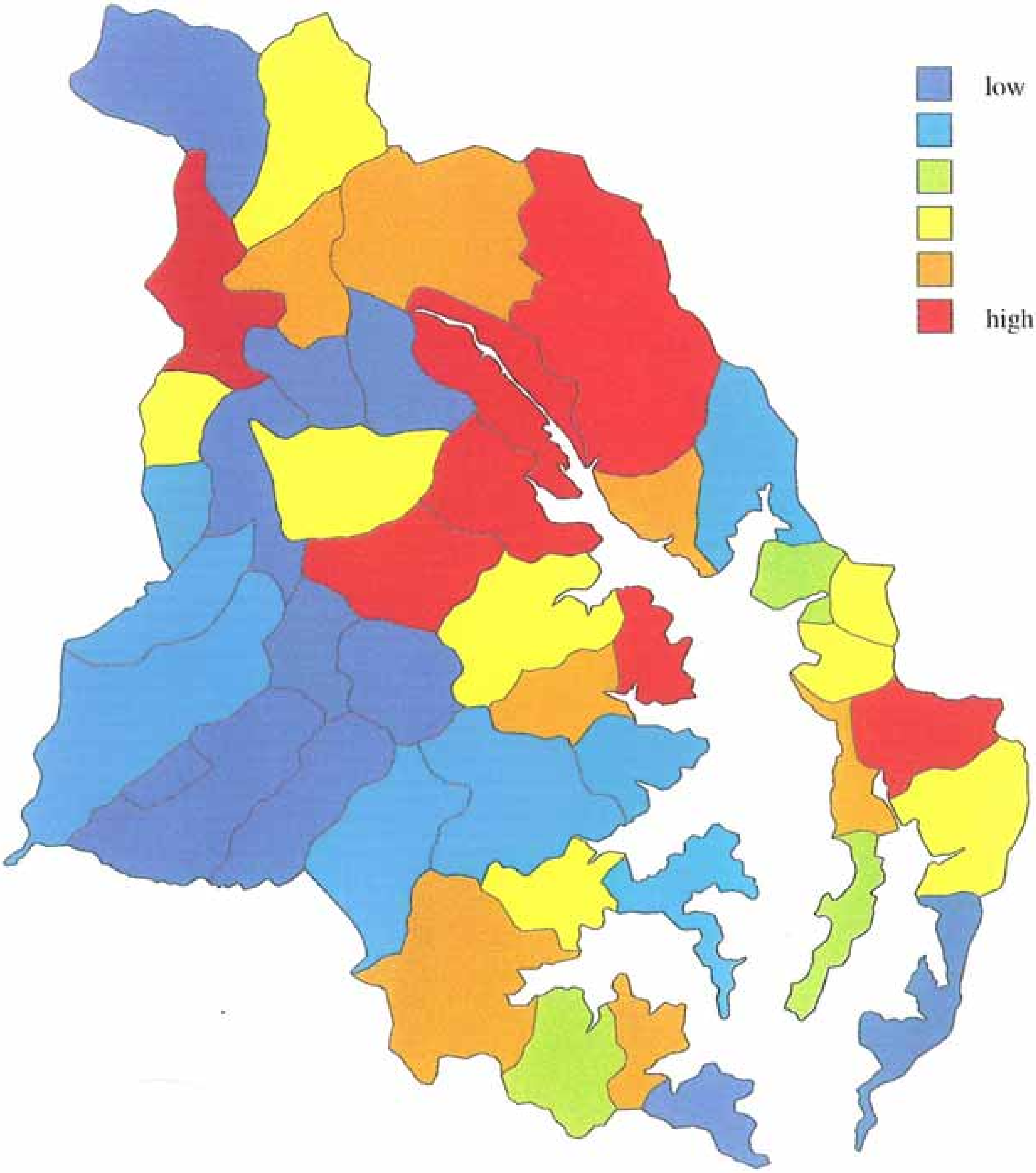

Figure 20: Model predicted relative sub-catchment loads of soluble phosphorus

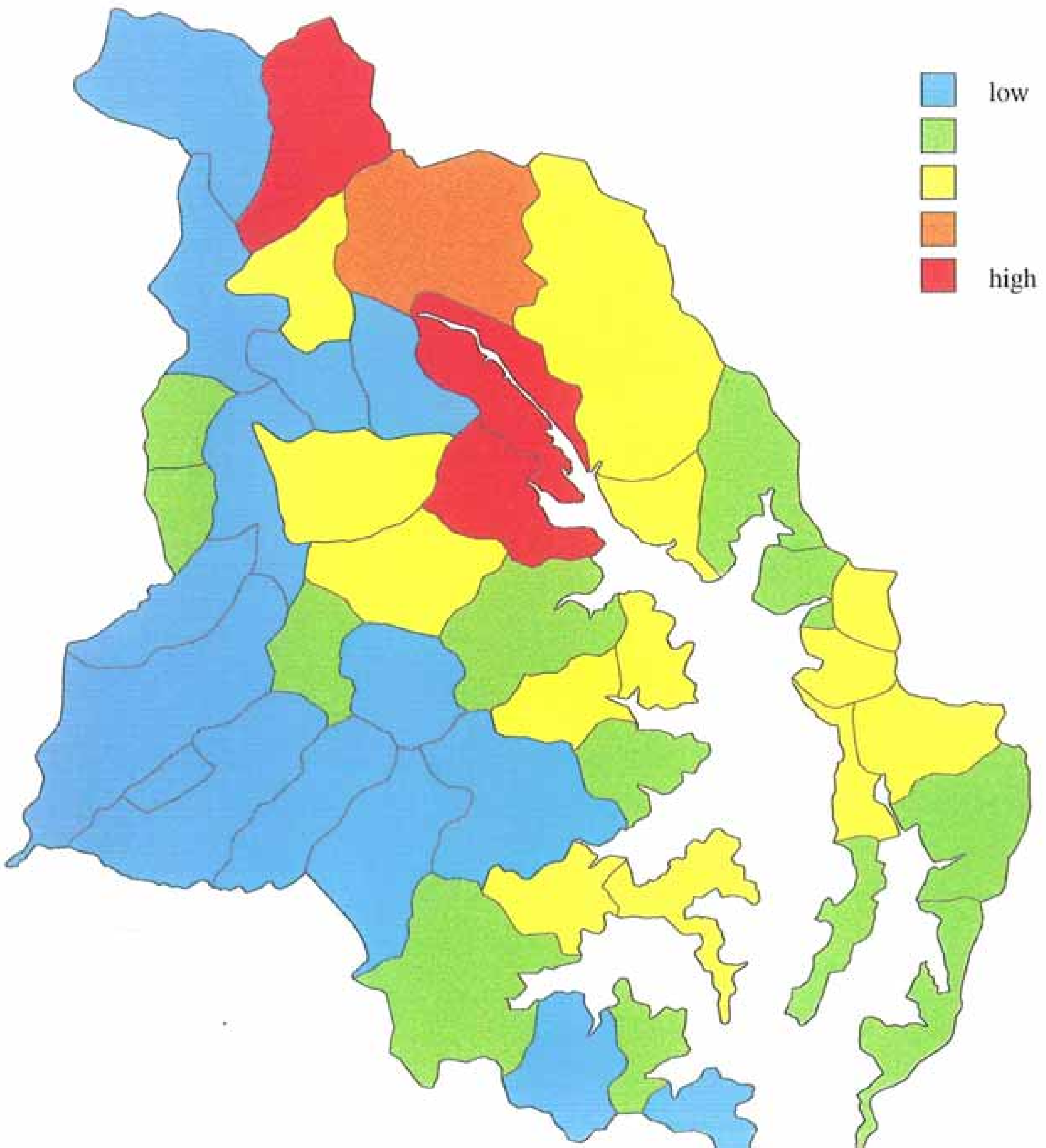

Figure 21: Model predicted relative sub-catchment loads of soluble nitrogen