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Prediction of subsurface redox status for Hauraki and Coromandel Catchments

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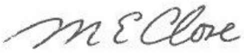

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EXECUTIVE SUMMARY

Waikato Regional Council contracted the Institute of Environmental Science and Research Ltd (ESR) to apply regional models for predicting subsurface redox status in the Waikato region to the sub-catchments of the Hauraki and Coromandel areas. These models had been developed as GIS layers as part of the Groundwater Assimilative Capacity research programme. The overlay GIS maps of predicted redox status on the sub-catchments was used as a basis for assessing the likely amount of denitrification for each of the sub-catchments.

A brief summary of the method development is provided together with figures giving the overlay of the sub-catchment boundaries on the predicted subsurface redox status for the shallow (<25 m) and medium (25 to 100 m) depth groundwater. The percentages of predicted reducing, mixed and oxidising redox status for the shallow and medium depth groundwater are given in the report, together with some comments about the likely degree of nitrate attenuation for each sub-catchment.

The amount of missing data, excluded from the predictive model either from the presence of mountainous land or lakes, was 26% (on an area-weighted basis). Overall the shallow and medium depth predictions indicated similar patterns of oxic, mixed and reduced groundwater, with the overall amounts being approximately 40%, 10%, and 25% for the oxic, mixed and reduced redox state groundwater, respectively.

In general, nitrate-rich shallow groundwater is likely to encounter reducing conditions in the Hauraki catchment and will mostly encounter oxic conditions in the Coromandel area. The actual amount of attenuation due to denitrification for a particular catchment depends on the amount of reducing and mixed redox state groundwater there is and may also depend somewhat on how the reducing zones are distributed in each sub-catchment.

1. BACKGROUND

The Groundwater Assimilative Capacity research programme, led by ESR, has developed, as part of its research, a method for the prediction of the redox status of groundwater systems. Groundwater chemistry data from wells are used to classify the redox status of groundwater at that location and then a model for predicting the redox status is developed using a suite of geological, soil and topographical spatial variables. This results in a series of models for predicting subsurface redox status in the Waikato region which can be output as GIS maps (Geographical information system). ESR has been requested to apply those maps to the sub-catchments being used for the Hauraki and Coromandel areas, carry out checks on the overlay of the sub-catchments on the regional redox maps with respect to the distribution of well data (used to develop the models), and provide some interpretation of the results.

The following aspects are covered in this report:

- Brief summary of the method development and how the results can be applied to assist with estimates of sub-catchment attenuation used to inform policy,
- Figures for the overlay of the sub-catchment boundaries with the most appropriate maps of predicted subsurface redox status,
- Summary of the likely degree of nitrate attenuation and a brief explanation for each sub-catchment in the Hauraki and Coromandel areas.

2. SUMMARY OF METHOD DEVELOPMENT

The method for predicting redox status in groundwater systems has been developed as part of the Groundwater Assimilative Capacity research programme (MBIE funded) and is described in detail by Close et al. (2016). A non-technical summary of the method is given below.

Reducing conditions are necessary for denitrification, thus the groundwater redox status can be used to identify subsurface zones where potentially significant nitrate reduction can occur. Groundwater chemistry was classified with respect to redox status and related to mappable factors, such as geology, topography and soil characteristics using discriminant analysis. The models from the discriminant analysis were used in GIS to predict the redox status for the whole Waikato region. Then the sub-catchment boundaries as defined for the Hauraki and Coromandel catchments were overlain on the predicted redox map and the percentage of oxidised (oxic), mixed and reduced groundwater in each sub-catchment was calculated. Comments are provided regarding the likely amount of nitrate attenuation in each sub-catchment based on those percentages.

2.1 REDOX ASSIGNMENT

There is a series of redox reactions that occur in groundwater systems that successively utilise O_2, NO_3, Mn(IV), Fe(III), SO_4, and CO_2 as electron acceptors. There is a decrease in energy available to the microbes from each successive electron acceptor so they will generally be utilised in the above order. As we were concerned about the reduction of NO_3, we focused on the first 3 parameters, O_2, NO_3, and Mn. For reducing conditions concentrations of O_2 will be low, NO_3 will be low and Mn will be high. McMahon and Chapelle (2008) have developed a more comprehensive system for assignment of redox status and their procedure was largely followed in this study. They derived thresholds for each parameter based on concentrations typically found for particular redox environments for a range of studies and the thresholds were designed to be broadly applicable to a range of different hydrologic conditions at the regional scale. The thresholds used in this study were 1.0 mg/L for O_2, 0.5 mg/L for NO_3-N, and 0.05 mg/L for Mn. Mean concentrations for NO_3-N, O_2, and Mn were calculated from the groundwater data for 554 wells for the period from 1990 to 2011, and the wells were classified as having reduced, mixed or oxidised water. The mixed class were used when the nitrate, Mn and O_2 parameters provided a mixed indication of redox status. In the situation when the NO_3–N levels were low (<0.5 mg/L) but the DO and Mn values indicated oxic conditions then the data was assigned to be oxic, as the water was likely to be oxic but old groundwater or derived from low land use intensity, which resulted in low nitrate levels rather than the low nitrate concentration indicating reduced groundwater conditions existed. Otherwise wells with mixed indicators were assigned to the mixed class. These wells probably reflect a system that is not in redox equilibrium, or where there are well screens that draw water from two redox environments, or where concentrations are close to threshold values. More discussion of this is provided in Close et al. (2016).

2.2 SELECTION OF PREDICTIVE VARIABLES

A predictive model was developed using linear discriminant analysis (LDA) so that we could then predict subsurface redox status across a region. Hence, parameters (spatial GIS layers) with complete or nearly complete coverage across a region were required. Ten predictive parameters were chosen from the fields of geology, land use, topography, and soil that discriminated between the groundwater redox states.

The geological parameters included the main_rock and sub_rock categories from QMAP (Rattenbury and Heron 1997) and the geological age of the formation. The land use parameter was sourced from the New Zealand Land Use Map (Newsome et al. 2013). The topography parameters included the elevation, slope and aspect. These were taken from an 8m DEM supplied by Geographx (Geographx 2012). Aspect did not contribute to any of the discriminant models and so was not considered further. The soil parameters were taken from a combination of the Fundamental Soil Layers (Newsome et al. 2008) and the S-map database (Lilburne et al. 2012) and included soil carbon (minimum and maximum), the drainage class, and New Zealand Soil Order, which is the highest level in the New Zealand Soil Classification (Hewitt 2010). Some of these parameters had numerical values such as soil carbon, elevation and slope. Soil carbon (percent organic matter content of the top 20 cm) min and max is provided as the lower and upper thresholds, respectively of the relevant soil carbon classes. Elevation and slope are continuous variables and were assigned into ranges (bins) to ensure that all variables were compatible with a vector GIS model development and to simplify the spatial processing. Both the slope and elevation data were skewed distributions so were log transformed before determination of bin thresholds using the Jenks natural breaks methods (Jenks, 1963). The geological age data were also skewed so were log-transformed and binned using the Jenks natural breaks method. The Jenks natural breaks method provided better resolution of the flatter slopes, lower elevations and younger geological ages for those parameters. Ten groups or bins were created for the 3 parameters and the thresholds are given in Table 1. The bin numbers were used as the parameter values for development of the LDA models.

Other parameters were categorical and required that numerical values be assigned to each class or category. The assignments for the geological rock type and soil order were carried out by giving a low score to categories that tended to be inert or retain oxidising conditions and giving a higher score to categories that were more reactive with respect to oxygen and nitrate and thus likely to promote more reducing conditions. The scales ranged between 1 and 5. For example, geological units such as gravels were given a score of 1, whereas peats were given a score of 5 (Table 2). The Land Use Classification parameter provided a very rough measure of potential nitrate inputs, with high nitrate inputs associated with cropland and high productivity grassland given scores of 1 and 2, respectively, compared to low nitrate inputs associated with forest and wetlands given scores of 4 and 5, respectively. The values for the predictive parameters at each well location were obtained by doing a sptaial query in GIS.

Table 1 Bin thresholds for elevation, slope and Geological age. Bin 1 contains the data from zero to the threshold value. The bin numbers are used in the LDA modelling.

Bin number	Upper threshold value		
	Elevation (m)	Slope (degrees)	Age (Ka)
1	3	0.20	7
2	6	0.34	37
3	9	0.53	103
4	16	0.85	251
5	28	1.42	500
6	53	2.44	1,550
7	104	4.16	3,549
8	220	6.96	11,585
9	429	11.18	35,327
10	1308	19.00	275,271

Table 2 Scores for Categorical Predictive Parameters

Parameter	1	2	3	4	5
Geology: Rock Type[a]	Dacite Gravel Limestone Quartz Sand	Ash Basalt Ignimbrite Pumice Rhyolite Sandstone Tephra	Schist Silt Siltstone	Clay Mud Mudstone	Lignite Peat
NZ Soil Order	Allophanic Brown Oxidic Pumice Raw Recent Semiarid	Melanic Pallic Ultic	Granular Podzol	Gley Organic	
Land Use Classification	Cropland	High producing grassland	Low producing & woody grassland; Settlements[b]	Forest	Wetlands

[a] Only the more common rock types are shown in Table 2 as examples.
[b] Settlements were assigned a value of 2.5

2.3 DEVELOPMENT OF PREDICTIVE MODELS USING LINEAR DISCRIMINANT ANALYSIS

Discriminant analysis seeks to statistically distinguish between two or more groups of cases, using a set of discriminating variables that measure characteristics on which the groups are expected to differ. Discriminant analysis attempts to do this by forming one or more linear combinations of the discriminating variables. These discriminant functions are of the form

$$D_i = d_{i1}Z_1 + d_{i2}Z_2 + \ldots + d_{ip}Z_p \quad (1)$$

where Di is the score on the discriminant function i, the d's are weighting coefficients, and the Z's are the standardised values of the p discriminant variables used in the analysis. The functions are formed in such a way as to maximise the separation of the groups. Once a set of variables is found which provides satisfactory discrimination for cases with known group memberships, a set of classification functions can be derived which permits the classification of new cases with unknown memberships. The procedure for classification uses a separate linear combination of the discriminating variables for each group. These produce a probability of membership in the respective group and the case is assigned to the group with the highest probability. The discriminant analysis was carried out using all 10 parameters and then the least significant (using the F statistic) parameters were removed until the discriminating success (% classified correct) decreased and all parameters had F >1.

The analysis was performed for three different well depths, shallow (<25 m), medium (25 to 100 m) and deep (>100 m), but only the shallow and medium depth models were used for this project as these depths are where most of the flow of nitrate-contaminated groundwater occurs. There were 54% of wells in the shallow depth class, 32% in the medium depth class, and 14% in the deep depth class for the Waikato region. The discriminant models were derived on a random selection of 67% of the well data and then tested on the remaining 33% of the data to test the robustness of the models, as well as being developed from the full dataset. Some wells had missing data for the predictive parameters meaning that a total of 435 wells was used to develop the predictive models.

GIS layers for each of the model variables throughout the region were prepared. Each layer was recoded as described in the previous section. The raster topography parameters were converted to vector and intersected with the other parameter layers. Mountainous terrain (i.e., land with a land use capability class of 8 or class 7 land with a slope greater than 19 degrees) was excluded from the models and maps. A composite layer containing all the model variables was collated and the results from the discriminant analyses (performed using SYSTAT) were implemented in the ARCMap GIS framework to extrapolate the results thoroughout the region. Each polygon within the intersected layer was assigned the redox status that had the highest probability, as indicated by the LDA model, for each depth layer.

3. REDOX STATUS FOR EACH SUB-CATCHMENT

The sub-catchments for the Hauraki and Coromandel areas are labelled in Figure 1, with the key for the labels given in Table 3 (labels were avoided in redox maps as they obscured too much of the predicted redox information). The maps of predicted redox status are given in Figures 2 and 3 for the shallow (<25 m) and medium (25 to 100 m) depth groundwaters overlaid with the sub-catchment boundaries for the Hauraki and Coromandel catchments. In the Waikato region, the geology is dominated by large volcanic events that deposited material over wide areas, which were then reworked by alluvial processes in catchments and sub-catchments to form the current groundwater systems. Organic material was often buried by these eruptions and incorporated into the shallow (<25 m) subsurface environment. In the Hauraki Plains, which are alluvial plains built up by sediment deposited by the current Piako and Waihou Rivers and the ancestral Waikato River, the environment consists of flat, peaty, and partly swampy land, with predominantly reduced redox conditions in the groundwater.

Figure 4 shows the distribution of the wells for the whole Waikato region that were used to develop the predictive models. The distribution is reasonably even at a regional scale but there is significant variability at the sub-catchment scale with some sub-catchments having up to 15 wells within the sub-catchment boundary and other sub-catchments having no wells. Figure 4 indicates that there is generally good coverage of the region and highlights the value of a predictive model that can predict redox status for sub-catchments where there are no wells with suitable data. The variability in wells coverage is greatest in the Coromandel Peninsula where the catchments are very steep, particularly in the centre of the Peninsula, and most of the wells in the Coromandel are located adjacent to the coast where there are flatter slopes and most of the development has occurred.

The models for both the shallow and medium depth groundwaters (Figures 2 and 3) predict predominantly reduced conditions in the Hauraki Plains and mostly oxic conditions in the Coromandel Peninsula. The models for the shallow and medium depth groundwater differ in the south of the area, where the shallow depth is mainly a mixed redox state and the medium depth is mainly oxic redox state. The difference between shallow and medium depths is consistent with the volcanic history of the area over the past few thousand years. This caused burial of topsoils (paleosols), with high levels of organic material within the shallow (<25 m) subsurface environment compared to the deeper groundwaters.

The percentages of predicted oxic, mixed and reducing redox status for the shallow and medium depth groundwater are given in Table 3, together with some comments about the likely degree of nitrate attenuation for each sub-catchment. A ranking of attenuation, equivalent to the description given in Table 3, is provided for the purposes of examining the distribution of attenuation conditions. The ranking value does not imply any quantitative value for attenuation. The ranking values used in Table 3 are: high attenuation 6; moderate to high attenuation 5; moderate attenuation 4; minor to moderate attenuation 3; minor attenuation 2; little attenuation 1; and no attenuation 0.

The amount of missing data, excluded from the predictive model either from the presence of mountainous land or lakes, was 26% (on an area-weighted basis), which is much higher than the 6% noted for the Waikato and Waipa catchments (Close, 2015). Overall the shallow and medium depth predictions indicated similar patterns of oxic, mixed and reduced groundwater

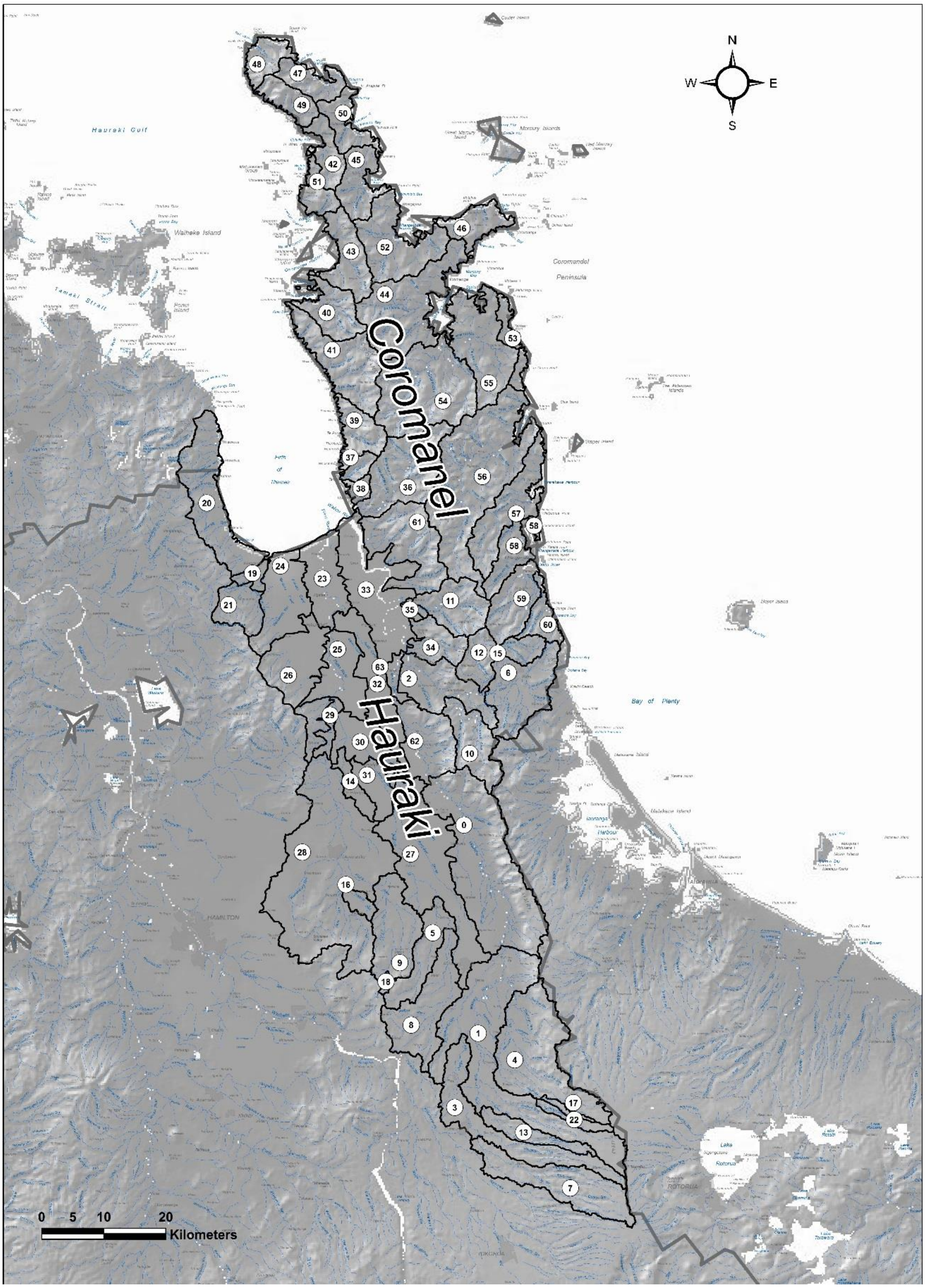

Figure 1: Map of sub-catchment labels for Hauraki and Coromandel catchments.

(Figures 2 and 3; Table 3), with the general amounts being approximately 40%, 10%, and 25% for the oxic, mixed and reduced redox state groundwater, respectively.

The significant amounts of missing data in the predicted maps are mainly due to the amount of steep and mountainous land. The percentage of missing area for each sub-catchment is noted in Table 3 and the sub-catchment where the percentage of missing area is >30% is commented as this indicates more uncertainty in the predicted redox status. It is possible that the steep and mountainous land will have low levels of organic carbon and other factors likely to induce reducing conditions but this has not been studied at all due to the lack of wells available in these areas. The maximum amount of missing area was 70% for the Waiaro and Port Jackson sub-catchments which are both located near the top of the Coromandel Peninsula.

The distribution of likely attenuation descriptions was reasonably well-spread with 27% of the sub-catchments having moderate to high attenuation (ranks 4 to 6), 34% of the sub-catchments having minor to moderate attenuation (ranks 2 and 3), and 40% having little to no attenuation (ranks 0 and 1). While there is a well-spread distribution for the Hauraki and Coromandel regions as a whole, there are large areas that are dominated by either oxic or reducing conditions.

The distribution of reducing zones has implications for the nitrate load to come and the time distribution of the load moving through the Hauraki and Coromandel catchments. Nitrate-rich shallow groundwater is likely to encounter reducing conditions in the Hauraki catchment and will mostly encounter oxic conditions in the Coromandel area

The actual amount of attenuation due to denitrification for a particular catchment depends on the amount of reducing and mixed redox state groundwater there is and may also depend somewhat on how the reducing zones are distributed in each sub-catchment. A number of sub-catchments in the Coromandel Peninsula, particularly on eastern side, had small areas (<10%) of reducing groundwater located in the lower catchment or stream channel. In this situation more nitrate could pass through those zones and be attenuated than would be expected on the basis of only the small percentage of reduced zones present , but this depends on how much of the groundwater actually flowed through these zones. Where the reducing zones are in the upper reaches of the catchment a lower flux of nitrate would be expected to pass through those zones and be attenuated.

In the portion at the southern end of the study area which may be influenced by the Taupo and possibly Rotorua eruptions, slow nitrate leakage, via longer, deeper flow pathways will less likely encounter reducing conditions. Hence the likelihood for attenuation is lower and the time for contamination of deeper aquifers will be longer as will the time to remediate them. The overall time distribution of nitrate discharge in these areas might be multi-modal, a nitrate pulse via short, shallow pathways following land development possibly with some attenuation; followed by a slow, gradual increase of nitrate as the nitrate concentrations rise in deeper aquifers over time.

The maps of subsurface redox status were developed using data for the whole Waikato region and are, thus, regional scale models. Regions with different characteristics require LDA models with different coefficients to reflect to those characteristics (Close et al. 2016). As the Waikato region is large (25,000 km^2), this raises the question of the appropriate scale for the development of these regional prediction models. It is likely that models developed for sub-regions may provide more accurate predictions of redox status provided that a sufficient number of input data (wells) are available for model development. This has not been done at present but could be carried out in a future study.

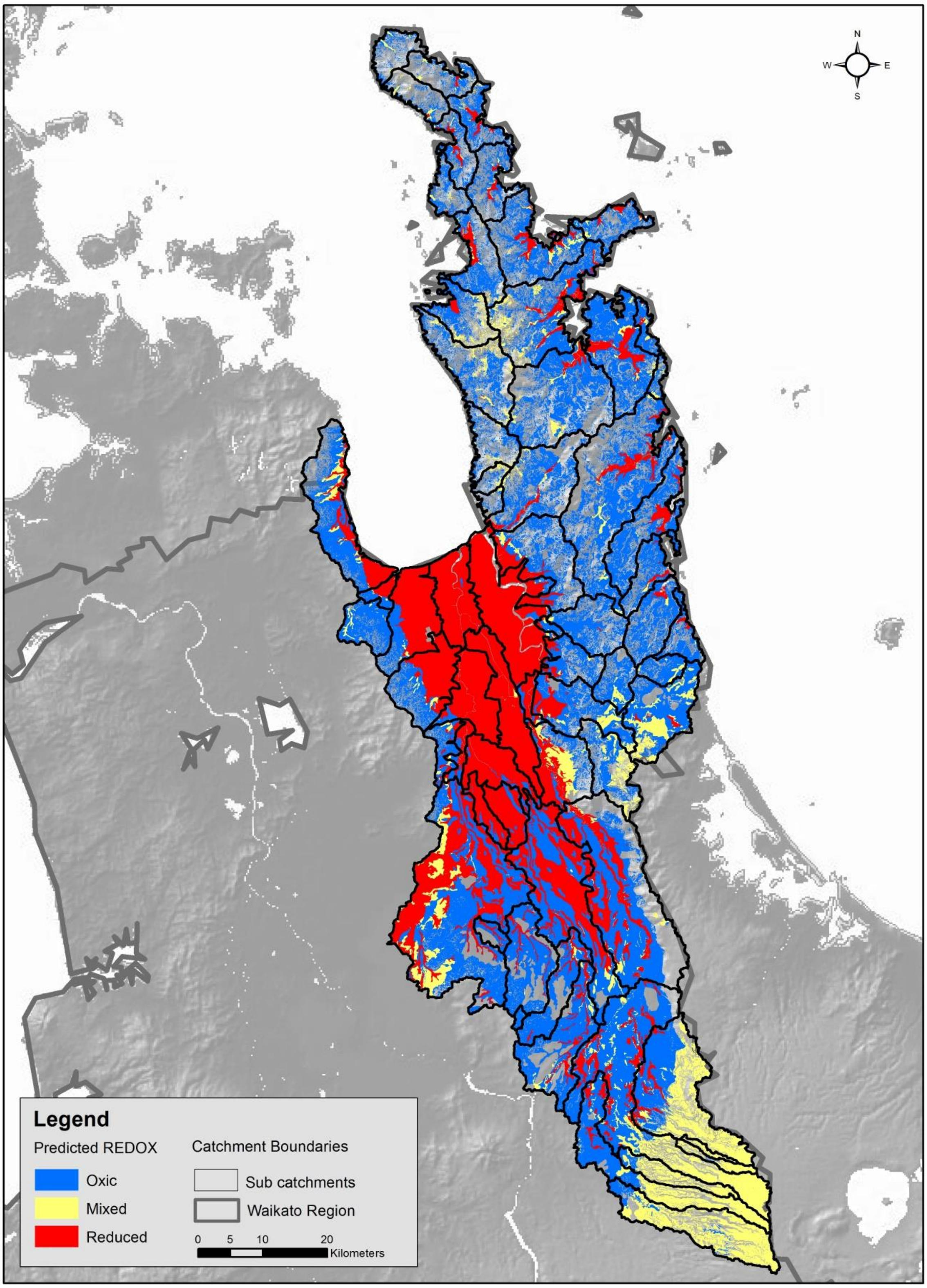

Figure 2: Map of predicted redox status for shallow (<25 m bgl) groundwater overlaid on sub-catchment boundaries for Hauraki and Coromandel catchments.

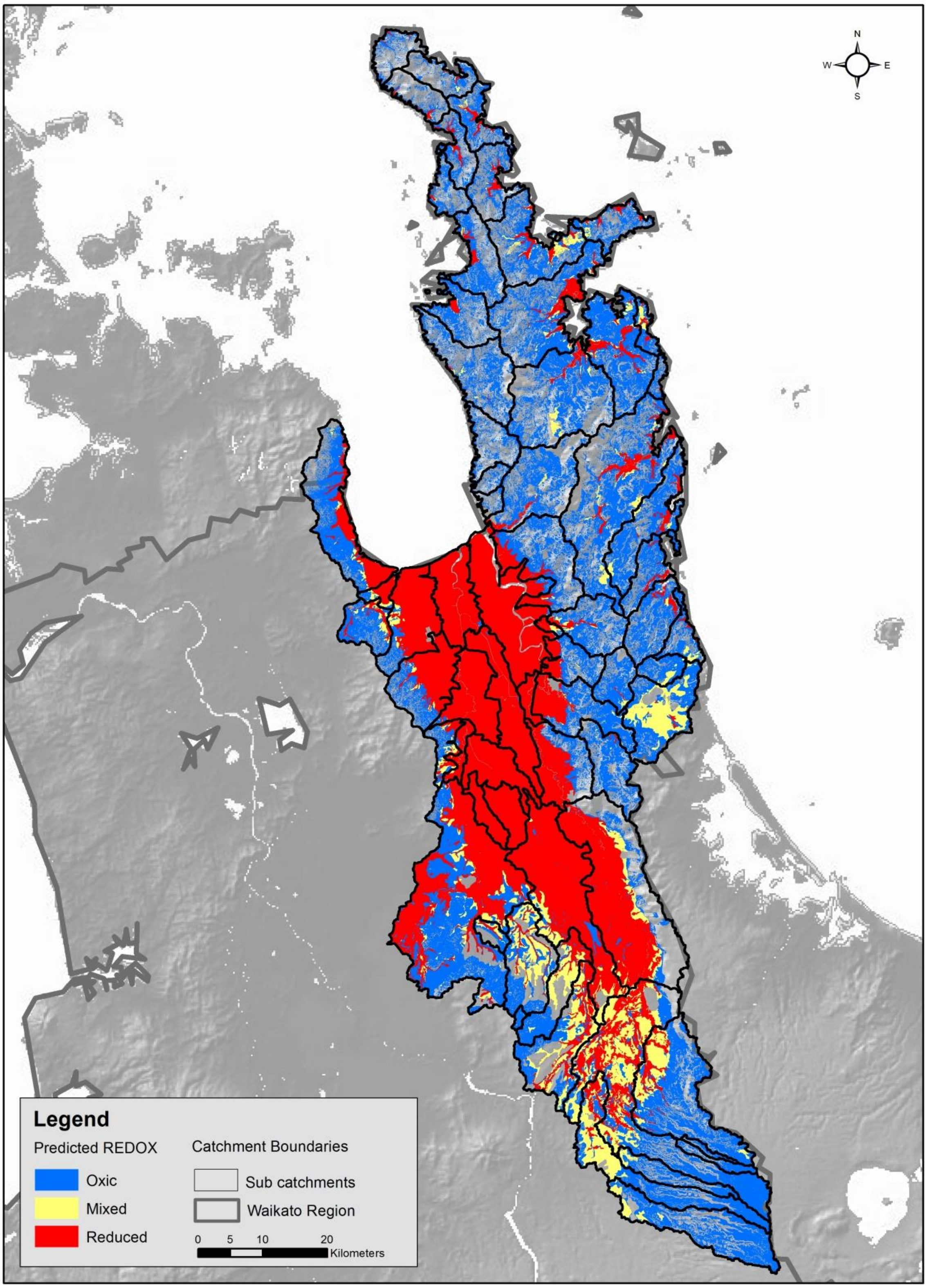

Figure 3: Map of predicted redox status for medium depth (25 - 100 m bgl) groundwater overlaid on sub-catchment boundaries for Hauraki and Coromandel catchments.

Table 3 Predicted percentages of sub-catchment area of oxidised, mixed and reduced groundwater for shallow (<25 m) and medium (25 – 100 m) groundwater for each sub-catchment, including likely implications for nitrogen attenuation. GW = groundwater.

Catchment name	Sub-catchment label	Area (ha)	Shallow Oxic %	Shallow Mixed %	Shallow Reduced %	Medium Oxic %	Medium Mixed %	Medium Reduced %	Missing %	Implications for attenuation	Attenuation ranking
Awaiti canal	32	9311	1	1	97	0	0	99	1	Shallow 97% reduced; medium 99% reduced; attenuation high	6
Colville Bay	42	4153	42	3	8	43	1	8	48	48% missing=steep/mountain; Shallow & medium mostly oxic with some reduced around bottom of catchment; attenuation little to minor	1.5
Coromandel	43	7166	44	5	9	51	1	6	42	42% missing=steep/mountain; shallow and medium mostly oxic with a little reduced in lower part of catchment; attenuation little to minor	1.5
Hikutaia Lower	35	645	65	7	20	12	16	65	7	Shallow mostly oxic; medium 12% oxic, 65% reduced; Attenuation minor to moderate	3
Hikutaia Upper	11	7368	59	1	0	53	3	5	39	39% missing=steep/mountain; shallow 59% oxic; medium mostly oxic, a little reducing around stream channel; little attenuation	1.0
Hot Water Beach-Hahei	53	2922	64	9	4	59	9	8	24	Both shallow & medium have mostly oxic with some mixed	1.5

Catchment name	Sub-catchment label	Area (ha)	Shallow Oxic %	Shallow Mixed %	Shallow Reduced %	Medium Oxic %	Medium Mixed %	Medium Reduced %	Missing %	Implications for attenuation	Attenuation ranking
										and reduced; little to minor attenuation	
Kaimarama	44	15820	45	10	9	52	2	10	36	36% missing=steep/mountain; shallow and medium mostly oxic with a little reduced in lower part of catchment; some mixed in shallow gw; attenuation little to minor	1.5
Karaka	38	1301	24	6	0	30	0	1	69	69% missing=steep/mountain; Shallow is mainly oxic with some mixed at top of catchment; medium is all oxic; attenuation =little to none	0.5
Kauaeranga	36	12913	45	3	4	48	1	3	48	48% missing=steep/mountain; Shallow & medium nearly all oxic except around stream channel; Attenuation dependant on how much gw goes thru reducing zone before entering stream; probably little to minor	1.5
Kennedy Bay	45	5955	38	3	4	38	1	6	54	54% missing=steep/mountain; shallow and medium mostly oxic with a little reduced in lower part of catchment; attenuation little to minor	1.5
Komata	34	5056	58	2	12	45	0	26	29	Shallow mostly oxic; medium 45% oxic, 26% reduced (29% missing); Attenuation minor	2

Catchment name	Sub-catchment label	Area (ha)	Shallow Oxic %	Shallow Mixed %	Shallow Reduced %	Medium Oxic %	Medium Mixed %	Medium Reduced %	Missing %	Implications for attenuation	Attenuation ranking
Kuhatahi @ Feierabends Weir	22	1606	1	71	0	72	0	0	28	shallow is all mixed; medium is all oxic; atten dependant on gw flow path but prob minor to moderate (assume most goes thru shallow)	3
Lower Piako	23	8175	1	0	95	1	0	95	5	Both shallow and medium reduced; high attenuation	6
Lower Waihou Flood plain	33	16491	5	1	85	3	0	88	9	Shallow 85% reduced; medium 88% reduced; attenuation high	6
Manaia Harbour	40	6276	38	13	4	50	1	4	46	46% missing=steep/mountain; shallow and medium is mostly oxic; a little reducing near bottom of catchment; some mixed at top of catchment; atten prob little to minor	1.5
Mangawhero	26	12841	39	3	44	31	6	49	14	Both shallow & medium have 30-40% oxic gw in upper half of catchment but 40-50% of catchment in lower half is reduced; attenuation moderate to high	5
Maukoro & Pouarua	24	10046	21	1	71	13	4	75	7	Both shallow & medium have some oxic gw in top of catchment but most of catchment is reduced; attenuation moderate to high	5
Ohine stream	31	4073	15	0	85	0	0	100	0	Shallow 85% reduced; medium 100% reduced; attenuation high	6

Catchment name	Sub-catchment label	Area (ha)	Shallow Oxic %	Shallow Mixed %	Shallow Reduced %	Medium Oxic %	Medium Mixed %	Medium Reduced %	Missing %	Implications for attenuation	Attenuation ranking
Ohinemuri	2	9269	53	11	16	48	1	30	21	Both depths are oxic in east near top of catchment; medium is all reduced near bottom of catchment; shallow half reduced near bottom; minor to mod attenuation	3
Ohinemuri @ Queens Head	6	11011	55	26	2	46	35	1	18	shallow is mainly oxic with some mixed; medium is about even oxic and mixed with mixed in middle of basin; minor attenuation	2
Ohinemuri @ SH25 Bridge	15	2621	71	11	0	70	11	0	19	Both shallow & medium mostly oxic with a little mixed near stream channel; little attenuation	1.0
Opito Peninsula	46	4636	51	4	6	50	4	7	39	39% missing=steep/mountain; shallow and medium mostly oxic with a little reduced in lower part of catchment; attenuation little to minor	1.5
Oraka @ Lake Rd	3	12515	43	38	5	51	28	8	14	Shallow is mixed at top of catchment; mainly oxic at bottom; medium is oxic at top; mainly mixed with some reduced at bottom; minor to moderate attenuation	3
Oraka @ Pinedale	7	13017	9	63	0	65	7	0	28	shallow is nearly all mixed; medium is nearly all oxic; atten dependant on gw flow path but prob minor to	3

Catchment name	Sub-catchment label	Area (ha)	Shallow Oxic %	Shallow Mixed %	Shallow Reduced %	Medium Oxic %	Medium Mixed %	Medium Reduced %	Missing %	Implications for attenuation	Attenuation ranking
										moderate (assume most goes thru shallow)	
Otahu River	59	7160	62	1	3	59	1	5	35	35% missing=steep/mountain; shallow and medium nearly all oxic with a little reduced in lower part of catchment; Little attenuation	1.0
Piako @ Kiwitahi	9	10346	65	1	7	38	28	7	27	shallow nearly all oxic; medium more mixed in bottom half of catchment and around stream channels; attenuation prob minor assuming most geos thru shallow	2
Piako @ Paeroa-Tahuna Rd	28	41469	46	11	35	43	5	44	8	Shallow is 45% oxic, 35% reduced - oxic thru centre on catchment thru to lower end; Medium is evenly oxic and reduced also with oxic thru centre; Attenuation moderate	4
Piako Kopouatai	25	8056	5	0	93	2	0	96	2	Both shallow & medium have a little oxic gw in top of catchment but nearly all catchment is reduced; attenuation high	6
Piako Middle	29	1886	32	3	62	7	4	86	2	Shallow mostly reduced; medium nearly all reduced; Attenuation moderate to high	5
Piakonui	18	463	96	0	0	95	0	0	4	Both shallow and medium all oxic; no attenuation	0.0

Catchment name	Sub-catchment label	Area (ha)	Shallow Oxic %	Shallow Mixed %	Shallow Reduced %	Medium Oxic %	Medium Mixed %	Medium Reduced %	Missing %	Implications for attenuation	Attenuation ranking
Port Charles	47	4455	27	4	2	29	1	2	67	67% missing=steep/mountain; shallow and medium mostly oxic with a little reduced in lower part of catchment; little attenuation	1.0
Port Jackson	48	3888	27	4	0	28	0	2	70	70% missing=steep/mountain; shallow and medium nearly all remaining is oxic with a little mixed or reduced in lower part of catchment; little attenuation	1.0
Tairua Harbour	56	28086	50	2	6	48	4	7	42	42% missing=steep/mountain; shallow and medium mostly oxic with some reduced in lower part of catchment; Little to minor attenuation	1.5
Tararu	37	1562	23	17	0	39	0	0	61	61% missing=steep/mountain; Shallow is mainly oxic with some mixed at top of catchment; medium is all oxic; attenuation =little	1.0
Te Puru	39	5369	33	5	0	38	0	0	62	62% missing=steep/mountain; Shallow is mainly oxic with some mixed at top of catchment; medium is all oxic; attenuation =little to none	0.5
Toenepi @ Tahuroa Rd	16	1614	54	0	14	41	17	11	31	31% missing=steep/mountain; shallow mostly oxic with reduced by the stream; medium mostly oxic with	3

Catchment name	Sub-catchment label	Area (ha)	Shallow Oxic %	Shallow Mixed %	Shallow Reduced %	Medium Oxic %	Medium Mixed %	Medium Reduced %	Missing %	Implications for attenuation	Attenuation ranking
										mixed and reduced near stream; minor to moderate attenuation	
Waiaro	49	4164	23	6	1	24	1	5	70	70% missing=steep/mountain; shallow and medium nearly all remaining is oxic with a little mixed or reduced in lower part of catchment; little attenuation	1.0
Waihou @ Okauia	1	29180	51	26	10	35	29	23	13	Shallow is mixed at top of catchment; mainly oxic at bottom; medium is oxic at top; mixed & reduced at bottom; moderate attenuation	4
Waihou @ Te Aroha	0	30052	46	2	22	8	6	56	30	30% missing=steep/mountain; shallow gw is 46% oxic; 22% reduced; evenly spread; medium gw is mostly reduced; moderate attenuation	4
Waihou @ Tirohia	62	9165	23	21	33	23	0	53	23	Shallow fairly evenly spread with more reducing gw; medium about 2/3 reducing cf 1/3 oxic; reducing in lower part of catchment; moderate to high attenuation	5
Waihou @ Whites Rd	13	4204	12	56	0	60	8	0	32	32% missing=steep/mountain; shallow is nearly all mixed; medium is nearly all oxic;	3

Catchment name	Sub-catchment label	Area (ha)	Shallow Oxic %	Shallow Mixed %	Shallow Reduced %	Medium Oxic %	Medium Mixed %	Medium Reduced %	Missing %	Implications for attenuation	Attenuation ranking
										atten dependant on gw flow path but prob minor to moderate (assume most goes thru shallow)	
Waihou above Ohinemuri	63	1577	25	5	66	1	0	95	4	Shallow mainly reduced with some oxic; medium is virtually all reduced; high attenuation	6
Waikawau Bay	50	4585	52	2	7	52	2	8	39	39% missing=steep/mountain; Shallow & medium mostly oxic with some reduced around bottom of catchment; attenuation little to minor	1.5
Waikawau-Tapu	41	11531	36	9	0	44	1	0	55	55% missing=steep/mountain; shallow mainly oxic with some mixed at top of catchment; medium nearly all oxic; Little attenuation	1.0
Waiohotu	17	742	0	79	0	79	0	0	21	shallow is all mixed; medium is all oxic; atten dependant on gw flow path but prob minor to moderate (assume most goes thru shallow)	3
Waiomou @ Matamata-Tauranga Rd	4	19372	33	40	6	57	15	7	21	Shallow is mixed at top of catchment; mainly oxic at bottom; medium is oxic at top; mainly mixed with some reduced at bottom; minor to moderate attenuation	3

Catchment name	Sub-catchment label	Area (ha)	Shallow Oxic %	Shallow Mixed %	Shallow Reduced %	Medium Oxic %	Medium Mixed %	Medium Reduced %	Missing %	Implications for attenuation	Attenuation ranking
Waitakaruru Lower	19	1476	47	2	46	21	18	57	4	Both shallow & medium have over half the catchment as reduced, all in lower end; moderate to high attenuation	5
Waitakaruru Upper	21	5011	80	5	0	64	9	11	15	Shallow nearly all oxic; medium mostly oxic but more mixed & reduced around stream channels; prob little attenuation assuming most geos thru shallow	1.0
Waitawheta	10	7521	35	23	0	57	1	1	42	42% missing=steep/mountain; shallow mixed in top of catchment, oxic in lower catchment; Medium all oxic; little attenuation	1.0
Waitekauri	12	4313	59	8	0	64	2	1	32	32% missing=steep/mountain; flow N to S; Shallow mostly oxic with a little mixed near catchment outlet; medium = oxic; little attenuation	1.0
Waitete Bay	51	3381	43	3	1	44	1	2	54	39% missing=steep/mountain; shallow and medium mostly oxic with a little reduced in lower part of catchment; attenuation little to minor	1.5
Waitoa @ Mellon Road	27	21659	51	2	45	4	9	85	2	Shallow is about 50% oxic, 45% reduced evenly spread; medium is 85% reduced. Atten moderate	4

Catchment name	Sub-catchment label	Area (ha)	Shallow Oxic %	Shallow Mixed %	Shallow Reduced %	Medium Oxic %	Medium Mixed %	Medium Reduced %	Missing %	Implications for attenuation	Attenuation ranking
Waitoa @ Waharoa	8	12292	62	5	9	28	27	20	24	Shallow mainly oxic; little bit reducing around stream channel; medium evenly split between all 3 states; more red and mixed around catchment outlet; prob minor assuming most goes thru shallow	2
Waitoa @ Walton Road	5	6944	65	2	9	33	25	17	24	Shallow is mainly oxic for whole catchment (65 out 76%); medium is oxic at top; mainly mixed & reduced at bottom; depends on gw flow paths; minor to moderate attenuation depending on prop that goes thru shallow gw	3
Waitoa Lower	30	6388	10	0	90	0	0	100	0	Shallow 90% reduced; medium 100% reduced; attenuation high	6
Waiwawa River	54	19162	48	3	3	48	3	3	46	46% missing=steep/mountain; shallow and medium mostly oxic with a little reduced in lower part of catchment; Little attenuation	1.0
Warahoe Puriri	61	12561	42	3	19	44	0	20	36	36% missing=steep/mountain; shallow and medium 2/3 oxic with 1/3 reduced in lower part of catchment; minor to moderate attenuation	3

Catchment name	Sub-catchment label	Area (ha)	Shallow Oxic %	Shallow Mixed %	Shallow Reduced %	Medium Oxic %	Medium Mixed %	Medium Reduced %	Missing %	Implications for attenuation	Attenuation ranking
Western Firth	20	14194	49	7	20	50	2	24	23	Both shallow & medium have mostly oxic conditions in upper catchment but reduced near the coast; moderate attenuation	4
Whakahoro	14	2683	14	0	86	0	0	100	0	Both shallow & medium nearly all reduced; high attenuation	6
Whangamata Harbour	58	4862	61	1	4	59	1	6	34	34% missing=steep/mountain; shallow and medium nearly all oxic with a little reduced in lower part of catchment; Little attenuation	1.0
Whangapoua Harbour	52	11635	48	5	9	47	8	7	38	38% missing=steep/mountain; shallow and medium mostly oxic with a little reduced in lower part of catchment; little attenuation	1.0
Wharekawa River	57	10105	62	0	9	61	4	6	29	Both shallow & medium have mostly oxic with some reduced around catchment outlet; little to minor attenuation	1.5
Whenuakite	55	12836	66	3	13	69	3	10	18	Both shallow & medium have mostly oxic with some reduced around catchment outlet; little to minor attenuation	1.5
Whiritoa	60	3302	62	1	4	56	7	3	33	33% missing=steep/mountain; shallow and medium nearly all	1.0

Catchment name	Sub-catchment label	Area (ha)	Shallow Oxic %	Shallow Mixed %	Shallow Reduced %	Medium Oxic %	Medium Mixed %	Medium Reduced %	Missing %	Implications for attenuation	Attenuation ranking
										oxic with a little reduced in lower part of catchment; Little attenuation	
Overall area-weighted %			42	10	22	38	7	29	26		

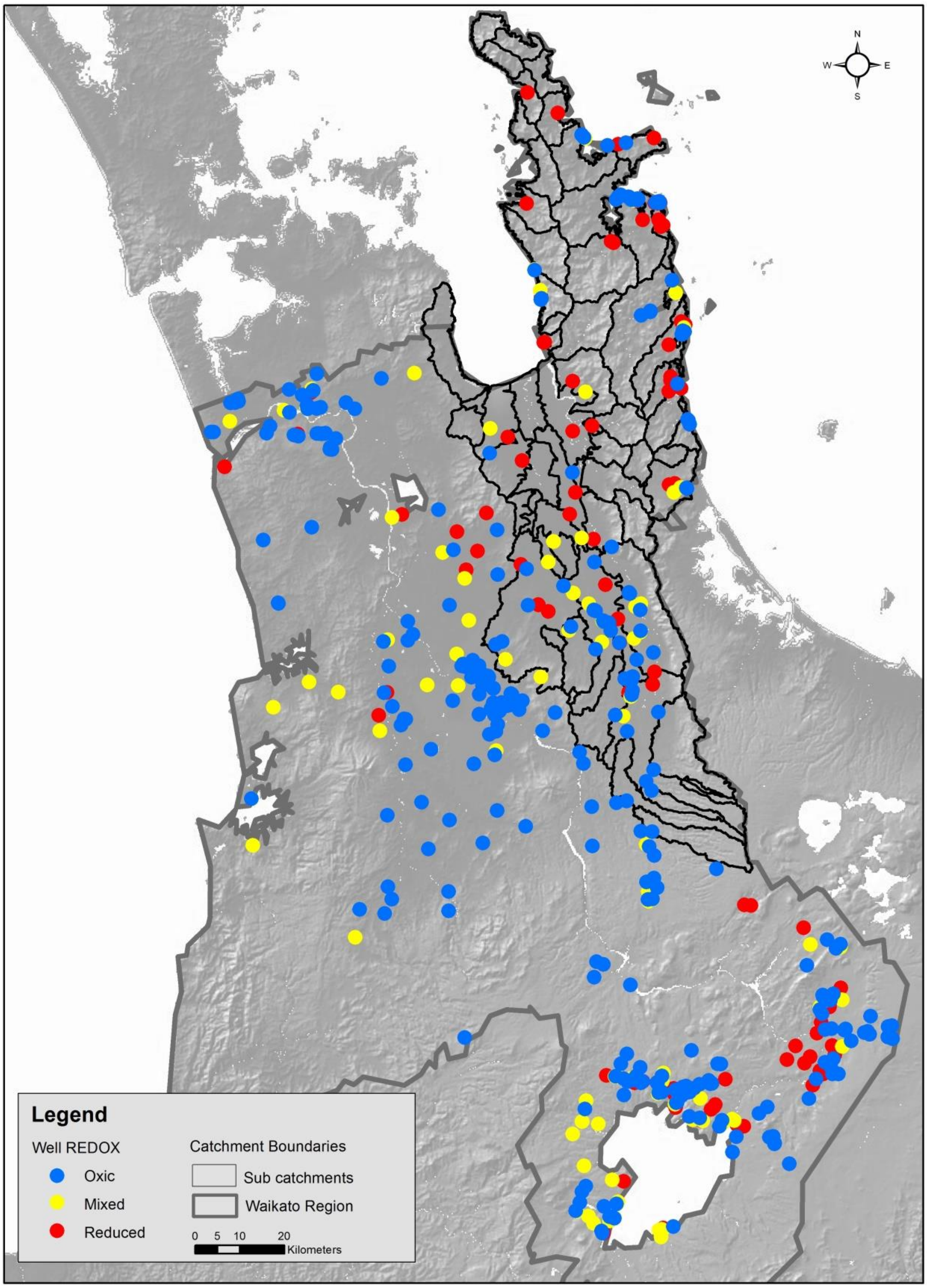

Figure 4: Location of wells used for developing models for prediction of groundwater redox status overlaid on sub-catchment boundaries for Hauraki and Coromandel catchments.

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