Healthy Rivers
PLAN FOR CHANGE
Wai Ora
HE RAUTAKI WHAKAPAIPAI

Draft for discussion purposes

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Prediction of Subsurface Redox Status for Waikato Healthy Rivers - Plan for Change: Waiora He Rautaki Whakapaipai Project

This report was commissioned by the Technical Leaders Group for the Healthy Rivers Wai Ora Project

The Technical Leaders Group approves the release of this report to Project Partners and the Collaborative Stakeholder Group for the Healthy Rivers Wai Ora Project.

Signed by:

Date: 13 November 2015

Prediction of Subsurface Redox Status for Waikato Healthy Rivers - Plan for Change: Waiora He Rautaki Whakapaipai Project

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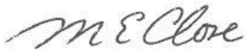
July 2015

PREPARED FOR:	**Waikato Regional Council**
CLIENT REPORT No:	**CSC 15010**
PREPARED BY:	**Murray Close**
REVIEWED BY:	**Phil Abraham**

Manager	Peer reviewer	Authors
		
Dr Chris Litten	**Phil Abraham**	**Murray Close**
Group Manager, Water		

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EXECUTIVE SUMMARY

Waikato Regional Council contracted the Institute of Environmental Science and Research Ltd (ESR) to apply models for predicting subsurface redox status in the Waikato region to the sub-catchments being used for the Healthy Rivers - Plan for Change: Waiora He Rautaki Whakapaipai project. These models had been developed as part of the Groundwater Assimilative Capacity research programme. The overlay of the maps of predicted redox status on the sub-catchment boundaries 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 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, averaged 6% per sub-catchment (on an area-weighted basis). There were approximately equal amounts by area of predicted reducing and oxidising conditions for the shallow groundwater but about three times as much oxidising groundwater compared with reducing conditions for the medium depth groundwater.

1. BACKGROUND

The Groundwater Assimilative Capacity research programme, led by ESR, has produced, as part of its research programme, a series of models for predicting subsurface redox status in the Waikato region which can be output as maps. ESR has been requested to apply those maps to the sub-catchments being used for the Healthy Rivers project, 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.

A summary of likely attenuation (low, medium, high) and a short comment contained in an Excel spreadsheet was supplied by Murray Close for a meeting on Friday 22nd May 2015 for the sub-catchments in the Healthy Rivers project.

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 and used to inform policy,
- Figures for the overlay of the sub-catchment boundaries with the most appropriate maps of subsurface redox status,
- Summary of the likely degree of nitrate attenuation and a brief explanation will be provided for each sub-catchment in the Healthy Rivers project.

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. (2015). 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 "Healthy Rivers" project were overlain on the predicted redox map and the percentage of reduced and oxidised (oxic) water 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 or oxidised water.

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 (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 geological age was highly skewed so was log transformed before using it in the development of the LDA models. The land use parameter was sourced from the New Zealand Land Use Map (LUM) (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 to ensure that all variables were compatible with a vector GIS model development to simplify the spatial processing. The elevation data were assigned the midpoint value for each 10 m interval (eg, an elevation of 16.7 was assigned a value of 15). The slope data were split into 7 groups using the Jenks natural breaks methods (Jenks 1963) and assigned the midpoint value for each range. The slope classes were 0 – 1.0; 1.0 – 2.4; 2.4 – 3.4; 3.4 – 6.9; 6.9 – 11.2; 11.2 – 19; >19. The Jenks natural breaks method provided for more resolution of the flatter slopes, which were most prevalent where the wells that were sampled existed.

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 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 1). 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 were obtained by doing a GIS overlay analysis.

Table 1 Scores for Categorical Predictive Parameters

Parameter	1	2	3	4	5
Geology: Rock Type[a]	Andesite Basalt Gravel Limestone Sand	Ash Hawaiite Ignimbrite Pumice Rhyolite Sandstone Tephra	Schist Silt Siltstone	Clay Mud Mudstone Olivine Basalt	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

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

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 is to the group with the highest probability. The discriminant analysis was carried out using all 10 initial 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 the Healthy Rivers 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.

Results from the discriminant analyses (performed using SYSTAT) were implemented in the GIS framework to extrapolate the results to each region. GIS layers for each of the model parameters for each 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. Each polygon within the intersected layer was assigned the redox status with the highest probability for each depth layer and redox category model. 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.

3. REDOX STATUS FOR EACH SUB-CATCHMENT

The maps of predicted redox status are given in Figures 1 and 2 for the shallow (<25 m) and medium (25 to 100 m) depth groundwaters overlaid with the sub-catchment boundaries for the Healthy Rivers project. 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.

The predictions of redox status around Lake Taupo are mainly reduced for the shallow depth and are oxic for the medium depth (Figs 1 & 2). The difference between shallow and medium depths is consistent with the history of volcanic eruptions centred on Taupo over the past few thousand years that caused burial of old topsoils, with higher levels of organic material within the shallow (<25 m) subsurface environment compared to the deeper groundwaters.

This predicted result, and the associated groundwater chemistry from the shallow and medium depth wells, around Lake Taupo contrasts with what is usually observed in groundwater systems, with reducing conditions usually being more likely in deeper flow paths with longer residence times (other things being equal). Elsewhere in the Waikato region the models predict predominantly reduced conditions in the Hauraki Plains (although outside the Healthy Rivers project area) and around the Hamilton city area, and reducing conditions would be expected to increase with depth.

Figure 3 shows the distribution of the wells in the whole Waikato region that were used to develop the predictive models. The distribution is reasonably even at a regional scale but there is some variability at the sub-catchment scale with some sub-catchments having up to 14 wells within the sub-catchment boundary and other sub-catchments having no wells. Figure 3 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 percentages of predicted reducing and oxidising redox status for the shallow and medium depth groundwater are given in Table 2, 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, averaged 6% per sub-catchment (on an area-weighted basis). There were approximately equal amounts of predicted reducing and oxidising conditions for the shallow groundwater but about three times as much oxidising groundwater compared to reducing conditions for the medium depth groundwater.

The distribution of reducing zones has implications for the nitrate load to come and the time distribution of the load entering Healthy Rivers catchments. Nitrate-rich shallow groundwater is likely to encounter reducing conditions in about 50 per cent of the catchment area. This depends somewhat on how the reducing zones are distributed in each sub-catchment. 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 (eg, Table 2 comments for Mangamingi sub-catchment). Where the reducing zones are in the lower portion of the catchment more nitrate would be expected to pass through those zones and be attenuated (eg, Table 2 comments for Awaroa @ Waiuku sub-catchment). In the southern portion of the Healthy Rivers catchments influenced by the Taupo 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.

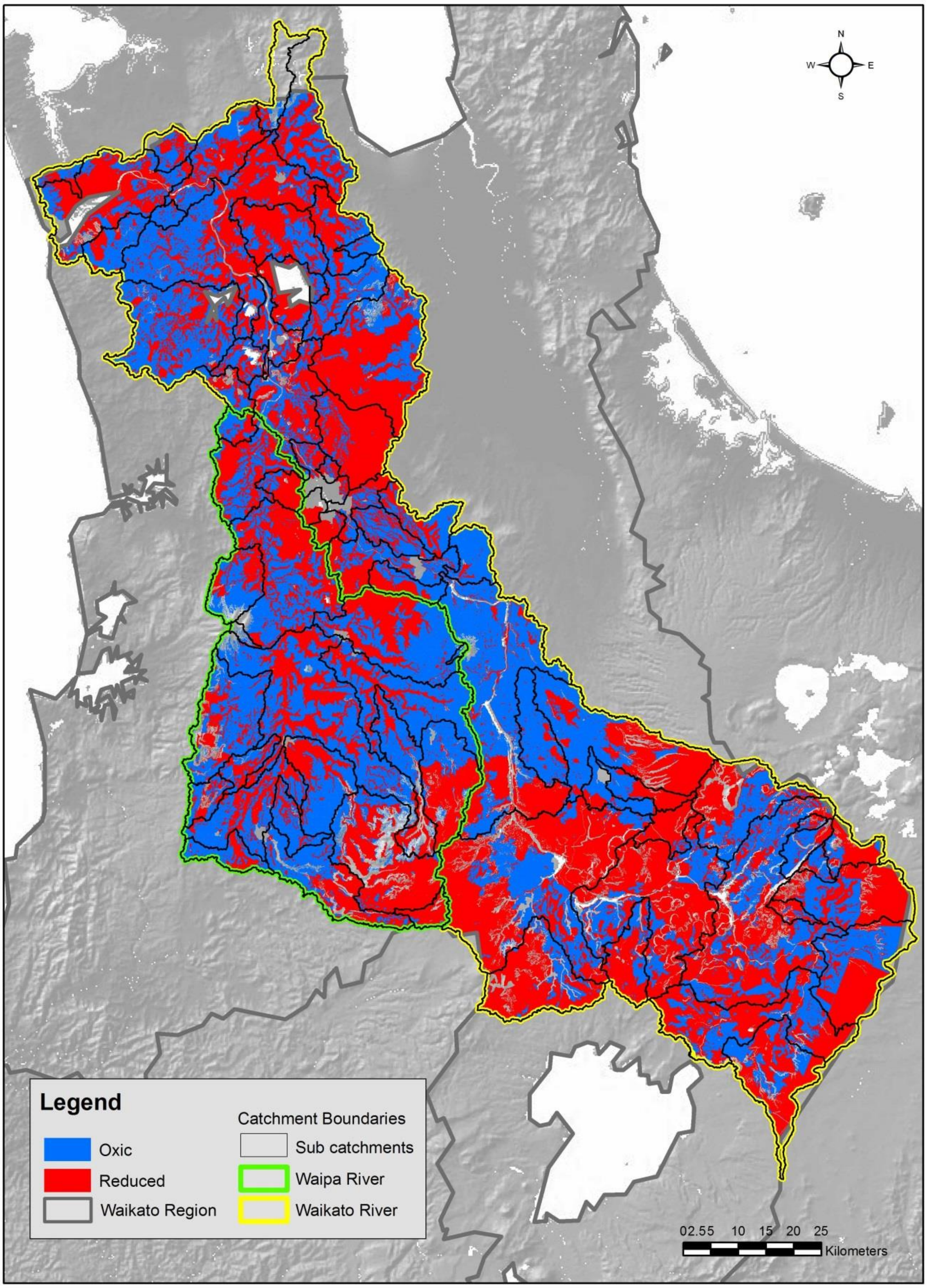

Figure 1: Map of predicted redox status for shallow (<25 m bgl) groundwater overlaid on sub-catchment boundaries for Waikato catchment.

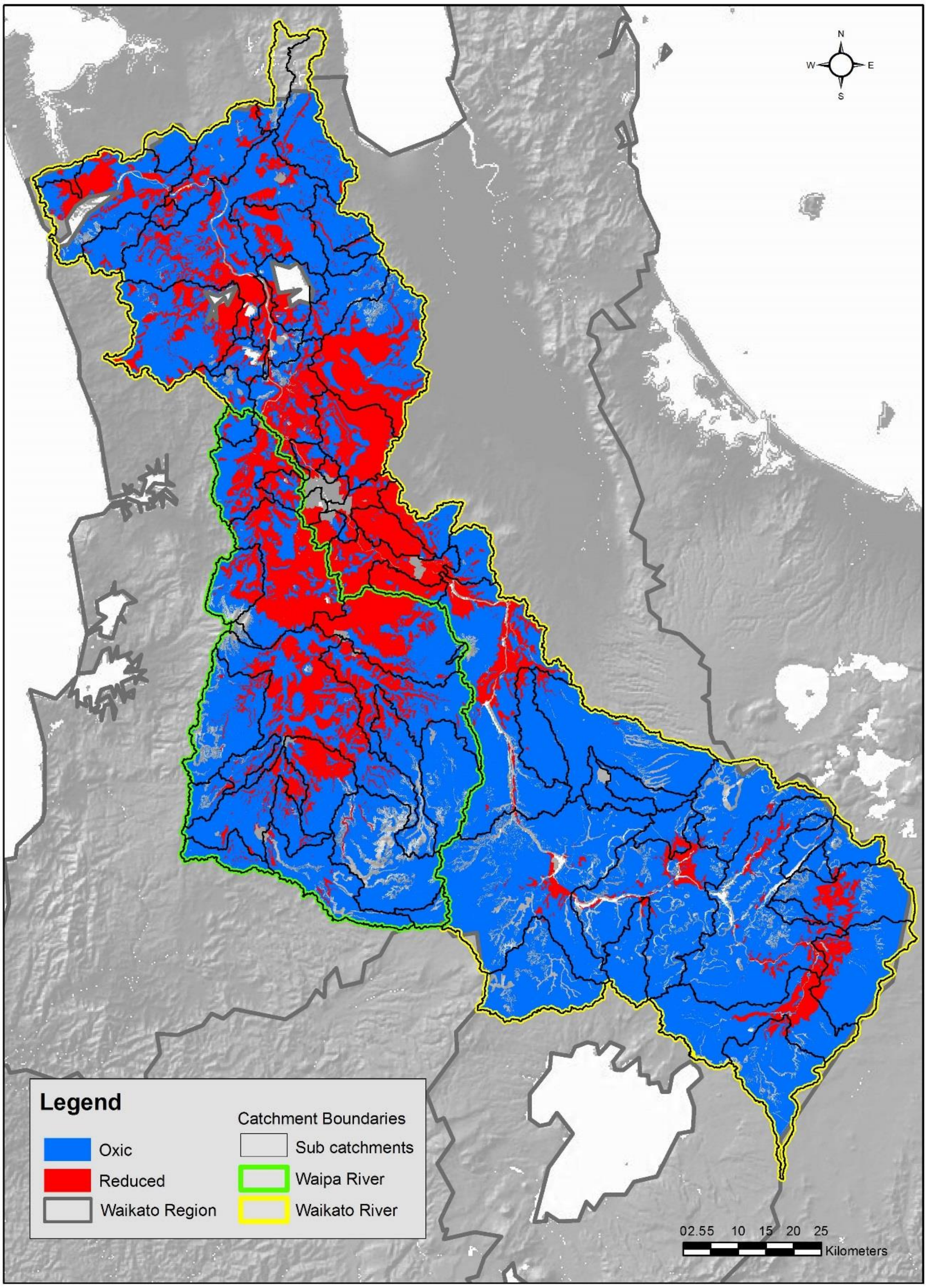

Figure 2: Map of predicted redox status for medium depth (25 - 100 m bgl) groundwater overlaid on sub-catchment boundaries for Waikato catchment.

Table 2 Predicted percentages of sub-catchment area of reduced and oxidised groundwater for shallow (<25 m) and medium (25 – 100 m) groundwater for each sub-catchment, including likely implications for nitrogen attenuation. RZ = reducing zones; OX = oxic zones; gw = groundwater; * = done at workshop.

Catchment name	NZ Reach	Shallow Oxic	Shallow Reduced	Medium Oxic	Medium Reduced	Missing	Implications for attenuation
Awaroa (Rotowaro) at Harris/Te Ohaki Br	3012631	48	38	65	21	14	Lake in catchment. Reducing zones (RZ) around 20% of area. Attenuation likely to be low to moderate
Awaroa (Rotowaro) at Sansons Br	3013581	47	40	73	14	13	Minor RZ for medium depth; more RZ in shallow depths near bottom of catchment. Depends if gw flow goes thru these zones before entering stream. Attenuation likely to be low to moderate.
Awaroa (Waiuku)	3007434	49	46	69	27	4	Looks like RZ mainly in lower part of catchment for both medium and shallow depths. If gw enters stream at bottom of catchment then attenuation high; if gw enters stream above this zone then attenuation could be moderate (or even low)
Firewood	3015451	59	41	83	17	0	Mainly Ox for medium depth; some RZ in shallow around lower end of catchment. Attenuation likely to be low to moderate depending if gw goes thru these zones before entering stream.
Kaniwhaniwha	3019566	56	37	61	32	8	Oxic in upper catchment for both shallow and medium depths; some RZ for both depths in lower catchment. Attenuation likely to be moderate
Karapiro	3020352	94	5	89	10	1	About 90% Ox for both depths. Attenuation likely to be low
Kawaunui	3034452	66	25	89	2	9	Oxic for medium depth; some RZ for shallow depth. Attenuation likely to be low to moderate
Kirikiriroa	3016924	34	47	20	62	18	Mainly RZ for medium depth; less RZ at shallow depth. Attenuation likely to be moderate. (N concs probably more influenced by dairy going to urban?)

Catchment name	NZ Reach	Shallow Oxic	Shallow Reduced	Medium Oxic	Medium Reduced	Missing	Implications for attenuation
Komakorau	3014466	12	88	25	75	0	High RZ for both medium and shallow depths but less at lower end of catchment. Attenuation likely to be moderate to high.
Little Waipa	3023862	88	12	94	6	0	Mostly oxic with some RZ near catchment outlet. However stream incised and attenuation likely to be low. *
Mangaharakeke	3032678	9	85	82	12	5	Medium depth is largely Ox with some RZ near outlet; shallow has much more RZ. Attenuation will depend on gw flow paths and is likely to be low to moderate.
Mangakara	3037027	21	68	83	5	12	Medium depth is largely Ox with some RZ near outlet; shallow has much more RZ. Attenuation will depend on gw flow paths and is likely to be low to moderate.
Mangakino	3036710	20	75	95	0	5	Medium depth is all Ox; shallow depth has much more RZ. Attenuation will depend on gw flow paths and is likely to be low to moderate. (Measured N load indicates low).
Mangakotukutuku	3018237	6	78	17	67	16	Both medium and shallow are largely RZ. Attenuation is likely to be moderate to high.
Mangamingi	3027230	67	23	90	0	10	Medium depth is all OX; Shallow depth has a little RZ in upper catchment. Attenuation will be low.
Mangaohoi	3023476	74	1	75	0	25	Medium and Shallow depths are all OX. Attenuation should be low. (Mainly forest with low inputs)
Mangaokewa	3031564	48	41	86	4	10	Medium depth is mainly OX; Shallow has some RZ in upper catchment. Attenuation is likely to be low.
Mangaone	3018213	63	37	5	95	1	Medium depth is mainly RZ; shallow is a reasonably even mixture. Attenuation will depend on gw flow paths and is likely to be moderate.
Mangaonua	3017726	62	38	54	46	0	Medium depth is Ox in upper catchment and RZ in

Catchment name	NZ Reach	Shallow Oxic	Shallow Reduced	Medium Oxic	Medium Reduced	Missing	Implications for attenuation
							lower catchment; Shallow is similar but less RZ in lower catchment. Attenuation will depend on gw flow paths and is likely to be moderate.
Mangapiko	3022010	57	42	45	53	2	Medium depth is Ox in upper catchment and RZ in lower catchment; Shallow is similar but slightly less RZ in lower catchment. Attenuation will depend on gw flow paths and is likely to be moderate.
Mangapu	3027166	62	35	80	18	3	Both depths are Ox in most of the catchment; some RZ in lower catchment towards outlet. Geomorphology indicates incised river valleys so attenuation likely to be low (gw doesn't enter stream just at bottom of catchment).
Mangarama	3031371	64	33	94	4	3	Medium depth is Ox in most of the catchment; Shallow has some RZ in lower catchment towards outlet. Geomorphology indicates incised river valleys so attenuation likely to be low (gw doesn't enter stream just at bottom of catchment).
Mangarapa	3028468	76	23	85	14	1	Both depths are Ox in most of the catchment; some RZ in lower catchment towards outlet for shallow depths. Geomorphology indicates incised river valleys so attenuation likely to be low (gw doesn't enter stream just at bottom of catchment).
Mangatangi	3006132	49	49	89	8	2	Medium depth is mostly OX; Shallow depth is mixture. Attenuation is likely to be moderate. (Note upper catchment cut off by RC boundary)
Mangatawhiri	3005110	40	32	57	15	28	Both depths are mostly OX. Attenuation is likely to be low. (Note upper catchment cut off by RC boundary)
Mangatutu	3024473	55	35	78	12	10	Medium depth is mostly OX with some RZ near bottom

Catchment name	NZ Reach	Shallow Oxic	Shallow Reduced	Medium Oxic	Medium Reduced	Missing	Implications for attenuation
							of catchment; Shallow depth has some RZ along valley bottom near stream. Depending on GW flow paths attenuation is likely to be moderate to low.
Mangauika	3023179	35	18	53	0	47	Both depths look OX (some of the map is steep mountain so is omitted). Attenuation is likely to be low.
Mangawara	3013137	31	65	48	49	4	Both depths are 50-60% RZ both the RZ is focused in lower catchment. Attenuation is likely to be moderate to high.
Mangawhero	3020102	47	52	11	88	0	Medium depth is mainly RZ; Shallow is OX is lower half of catchment and RZ is upper half. Attenuation will depend on gw flow paths and is likely to be moderate.
Matahuru	3010952	71	24	86	9	5	Stream flow chem rapidly equilibrates with landuse (~ 5 yr). TN conc at outlet stable, intensification of landuse steady. Limited denitrification likely. Likely to be in approx equilibrium with landscape. Little evidence for attenuation. Apparent attenuation expressed by current chemistry. Attenuation = current. *
Moakurarua	3023962	62	26	81	7	12	Both depths mostly OX. Attenuation likely to be low.
Ohaeroa	3007733	87	13	67	33	0	Shallow mainly OX; Medium has some RZ towards outlet. Attenuation likely to be low to moderate depending on the gw flow paths.
Ohote	3017348	19	79	47	51	2	Both depths slightly more RZ than OX. Attenuation likely to be moderate to high.
Opuatia	3008985	73	26	92	6	1	Both depths mostly OX. Attenuation likely to be low.
Otamakokore	3031549	71	24	95	0	5	Both depths mainly OX with some RZ in Shallow depth but in upper catchment. Attenuation likely to be low. Note that loads indicate Att Factor = 0.65. I suspect this

Catchment name	NZ Reach	Shallow Oxic	Shallow Reduced	Medium Oxic	Medium Reduced	Missing	Implications for attenuation
							means significant load to come - check with age data if any.
Pokaiwhenua	3023849	48	49	96	1	3	Oxidised medium gw, reduced shallow gw(?). Denitrification potential in medium gw, low, in shallow gw possible, but to be confirmed. *
Pueto	3042044	30	62	88	4	8	Denitrification - mixed shallow gw, denitrification occurring. Overall moderate attenuation expected. *
Puniu at Bartons Corner Rd Br	3023180	75	24	66	33	1	Both depths mostly OX with some RZ at shallow depths along valley floor. Depending on gw flow paths attenuation is likely to be low to moderate.
Puniu at Wharepapa	3025988	36	56	92	0	8	Medium depth is all OX; Shallow depth has 50% RZ located in upper catchment. Attenuation is likely to be low to moderate.
Tahunaatara	3032435	46	48	91	2	7	Both depths mainly OX with some RZ in Shallow depth but in upper catchment. Attenuation likely to be low. Note that loads indicate Att Factor = 0.58. I suspect this means significant load to come - check with age data if any.
Torepatutahi	3038300	45	53	83	15	2	Redox indicates most medium depth oxidised, Low end of denitrification potential. *
Waerenga	3009556	89	11	93	7	0	Likely to be little attenuation, available attenuation currently seen. *
Waikare	3010071	32	62	62	32	6	Lake Waikare in middle of catchment. Both medium and shallow depths have mixture of OX and RZ with shallow having more RZ. Attenuation likely to be moderate to high.
Waikato at Bridge St Br	3017901	35	48	16	67	17	Medium depth has nearly all RZ; Shallow has mostly RZ. Bottom 20% of catchment is urban so

Catchment name	NZ Reach	Shallow Oxic	Shallow Reduced	Medium Oxic	Medium Reduced	Missing	Implications for attenuation
							haven't extended prediction to that area. Attenuation is likely to be moderate to high.
Waikato at Horotiu Br	3015830	22	38	21	39	40	70% urban in this catchment which is excluded from my model. Would suspect that attenuation is similar to Waikato at Bridge St (upstream catchment) and is moderate to high
Waikato at Huntly-Tainui Br	3013160	39	53	35	57	8	Medium is mostly RZ; Shallow is more OX. Attenuation probably depends on gw flow paths and is likely to be moderate.
Waikato at Karapiro	3020656	67	26	73	20	7	Medium depth is mostly OX with some RZ at lower end of catchment and along river in middle section; Shallow is ~80% OX with some RZ in upper end of catchment. Attenuation is likely to be low but will depend of gw flow paths.
Waikato at Mercer Br	3006806	51	47	68	30	2	Both depths have a mixture of OX and RZ with the medium depth having less RZ. The RZ for the shallow depth is concentrated in the east of the catchment. Attenuation is likely to be moderate to low.
Waikato at Narrows	3018977	48	45	16	77	7	The medium depth is nearly all RZ; the shallow depth is about 50:50, with the RZ concentrated in the west. Attenuation is likely to be moderate.
Waikato at Ohaaki	3039804	37	60	81	15	4	The medium depth is nearly all OX except for some RZ along the river at the lower end of the catchment. The shallow depth is about 60:40 RZ:OX throughout the catchment. Attenuation is likely to be low to moderate depending on the gw flow path.
Waikato at Ohakuri	3035123	40	50	83	8	10	The medium depth is nearly all OX; the shallow depth is a mixture of RZ and OX. Attenuation is likely to be

Catchment name	NZ Reach	Shallow Oxic	Shallow Reduced	Medium Oxic	Medium Reduced	Missing	Implications for attenuation
							low to moderate depending on the gw flow paths.
Waikato at Port Waikato	3009006	33	60	60	33	7	The medium depth is a mixture of RZ and OX with most of the RZ on the north side of the river. The shallow depth has a similar pattern but with more RZ throughout the catchment. Attenuation is likely to be moderate.
Waikato at Rangiriri	3010604	45	40	47	38	15	Medium depth is about 50:50 with most of the RZ is the lower part of catchment; The shallow is a bit more OX. Attenuation is likely to be moderate to low depending on the gw flow paths.
Waikato at Tuakau Br	3007421	50	48	80	19	1	Medium depth is nearly all OX; Shallow depth is about 50:50. Attenuation will depend on gw flow paths but is likely to be low to moderate.
Waikato at Waipapa	3030247	27	64	88	3	8	Medium depth is nearly all OX with a little RZ around the river; shallow depth is mostly RZ. Attenuation will depend on gw flow path and is likely to be moderate.
Waikato at Whakamaru	3035301	26	63	81	7	12	Medium depth is nearly all OX with a little RZ around the river; shallow depth is mostly RZ. Attenuation will depend on gw flow path and is likely to be moderate.
Waiotapu at Campbell	3034280	26	65	88	2	10	Low denitrification likely. Shallow gw potential for denitrification through paleosols, deeper gw relatively limited potential for denitrification. Attenuation low, short residence time, load to come = low, OR moderate residence time with little attenuation = current trend could be evidence of conversion from 1960s and intensification. *
Waiotapu at Homestead	3037105	28	65	76	17	7	Redox status - medium depth = oxidised, band of

Catchment name	NZ Reach	Shallow Oxic	Shallow Reduced	Medium Oxic	Medium Reduced	Missing	Implications for attenuation
							reducing material through catchment (along river course). Much reduced gw at shallow depth, peat pockets, reducing conditions in shallow pumice sediments, and reducing conditions adjacent to stream. *
Waipa at Mangaokewa Rd	3036214	3	96	100	0	0	The medium depth is all OX; the shallow depth is all RZ. Attenuation will depend on gw flow paths but is likely to be low to moderate.
Waipa at Otewa	3029370	20	62	80	1	18	Medium depth gw oxidised, shallow indicates some reducing conditions, but may not intercept gw. Apparent attenuation zero. *
Waipa at Otorohanga	3027129	63	34	55	41	3	Medium depth is about 50:50 RZ:OX with RZ mostly in lower part of catchment; shallow depth has more OX but RZ is at catchment outlet. Attenuation is likely to be moderate.
Waipa at Pirongia-Ngutunui Rd Br	3022669	60	36	56	40	4	Both depths have more OX than RZ reasonably distributed through the catchment. Attenuation will depend on gw flow paths but is likely to be low to moderate.
Waipa at SH23 Br Whatawhata	3017829	47	51	35	64	1	Medium depth has more RZ than OX; Shallow has more OX than RZ. Attenuation will depend on gw flow paths but is likely to be low to moderate.
Waipa at Wainaro Rd Br	3015066	41	56	54	43	3	Both depths have about 50:50 RZ:OX. Attenuation will depend on gw flow paths but is likely to be low to moderate.
Waipapa	3035556	29	69	96	2	2	Medium depth is nearly all OX; Shallow depth is mostly RZ. Attenuation is likely to be low to moderate depending on gw flow paths.
Waitawhiriwhiri	3017487	0	50	2	48	50	Both depths are all RZ but have about 50% of the

Catchment name	NZ Reach	Shallow Oxic	Shallow Reduced	Medium Oxic	Medium Reduced	Missing	Implications for attenuation
							catchment as urban (excluded from the model). Attenuation is likely to be moderate to high.
Waitomo at SH31 Otorohanga	3026779	53	44	82	15	3	Redox conditions mixed, largely inferred from limited data. Overall summary of attenuation - expect low to moderate attenuation anticipated. *
Waitomo at Tumutumu Rd	3028966	52	38	85	5	10	Medium depth is all OX; Shallow depth has some RZ (perhaps 25%). Attenuation is likely to be low. Note that Att Factor is calc as 1.9 - could be flow coming from outside catchment???
Whakapipi	3006346	53	47	96	3	1	Medium depth is all OX; Shallow depth has some RZ (~30%). Attenuation is likely to be low.
Whakauru	3027821	40	57	97	0	3	Medium depth is all OX; Shallow is about 50% RZ which is located in the upper half of catchment. Attenuation likely to be low.
Whangamarino at Island Block Rd	3007681	39	61	73	27	0	Medium denitrification potential, but limited flow through gw, therefore surface TN increasing. Overall summary of attenuation - limited attenuation (quickflow bypass, ie timing issue). *
Whangamarino at Jefferies Rd Br	3008369	46	54	94	6	0	Redox conditions - medium depth oxidised, shallow mixed, more reduced. Reasonable denitrification expected. Overall summary of attenuation - moderate attenuation likely. *
Whangape	3010847	67	31	66	32	2	Medium depth is mainly OX with some RZ located at outlet of catchment; Shallow depth has slightly more OX with some RZ located near outlet. Attenuation will depend on gw flowpaths but is likely to be low to moderate.
Whirinaki	3031392	42	44	87	0	13	Medium depth is all OX; Shallow depth has some RZ

Catchment name	NZ Reach	Shallow Oxic	Shallow Reduced	Medium Oxic	Medium Reduced	Missing	Implications for attenuation
							in upper catchment (~30-40%). Attenuation is likely to be low.

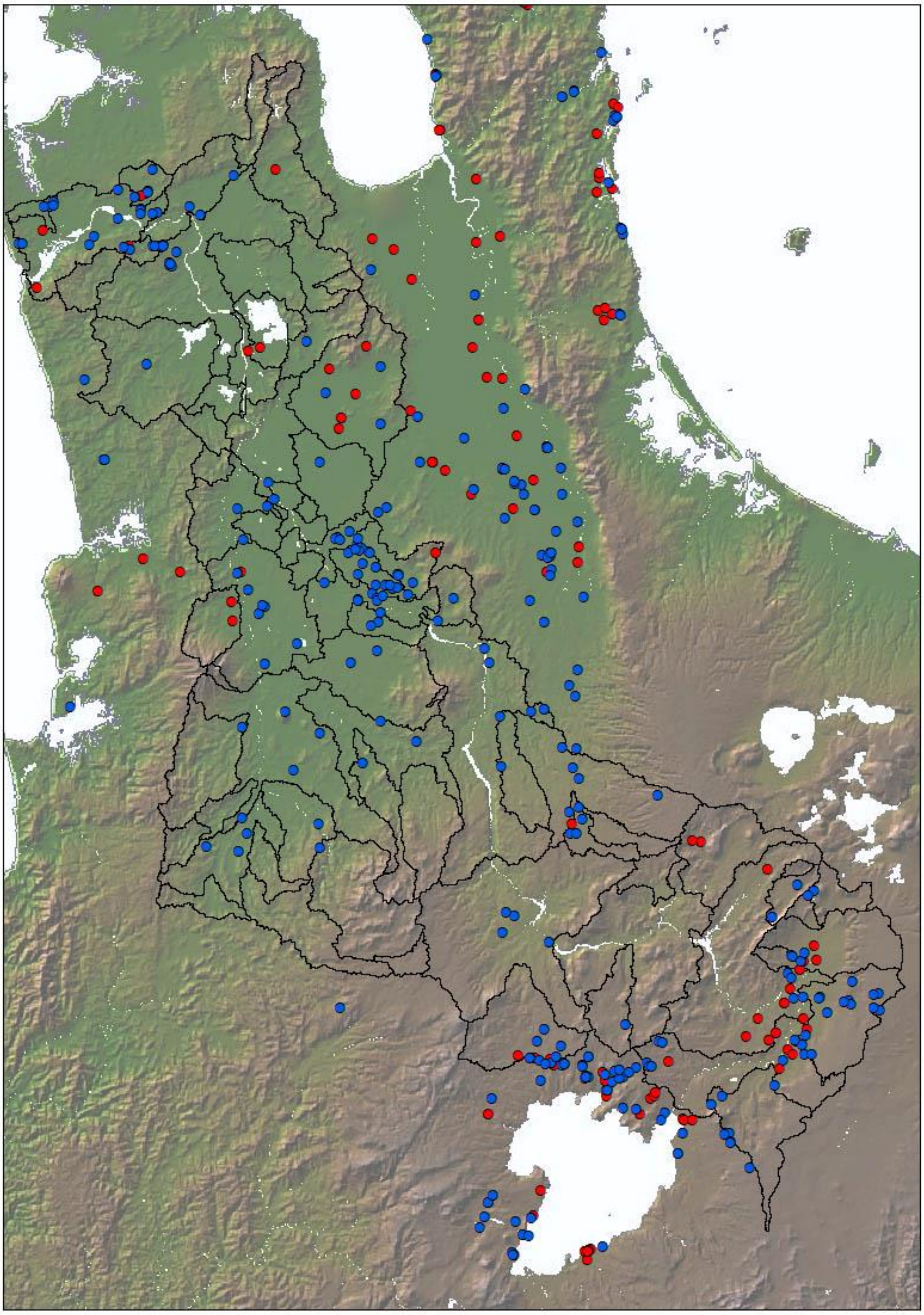

Figure 3: Location of wells used for developing models for prediction of groundwater redox status overlaid on sub-catchment boundaries for Waikato catchment. Blue circles are wells with oxidised groundwater; red circles are wells with reduced groundwater

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INSTITUTE OF ENVIRONMENTAL SCIENCE AND RESEARCH LIMITED

Kenepuru Science Centre
34 Kenepuru Drive, Kenepuru, Porirua 5022
PO Box 50348, Porirua 5240
New Zealand
T: +64 4 914 0700 **F:** +64 4 914 0770

Mt Albert Science Centre
120 Mt Albert Road, Sandringham, Auckland 1025
Private Bag 92021, Auckland 1142
New Zealand
T: +64 9 815 3670 **F:** +64 9 849 6046

NCBID – Wallaceville
66 Ward Street, Wallaceville, Upper Hutt 5018
PO Box 40158, Upper Hutt 5140
New Zealand
T: +64 4 529 0600 **F:** +64 4 529 0601

Christchurch Science Centre
27 Creyke Road, Ilam, Christchurch 8041
PO Box 29181, Christchurch 8540
New Zealand
T: +64 3 351 6019 **F:** +64 3 351 0010

www.esr.cri.nz