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Prediction of water quality within the Waikato and Waipa River catchments in 1863

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Prediction of water quality within the Waikato and Waipa River catchments in 1863

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"Tooku awa koiora me oona pikonga he kura tangahia o te maataamuri"

"The river of life, each curve more beautiful than the last."

King Tawhiao

1. Introduction

The Healthy Rivers Plan for Change: Waiora He Rautaki Whakapaipai (HRWO) Project[1] will establish targets and limits for nutrients (N and P), sediment, and *E. coli* in water bodies across the Waikato/Waipa catchment. The need for this process is established by the *Vision and Strategy for the Waikato River/Te Ture Whaimana o Te Awa o Waikato* and the *National Policy Statement for Freshwater Management 2014*. The *Vision and Strategy for the Waikato River* focuses on restoring and protecting the health and wellbeing of the Waikato and Waipa Rivers for current and future generations. It recognises that water quality and other natural resources have deteriorated since the onset of extensive settlement and agricultural development in the catchments of the Waikato and Waipa Rivers (Davies-Colley, 2013). Nevertheless, there has been no structured assessment of the state of water quality within these catchments when the *New Zealand Settlements Act 1863* was passed and substantial tracts of land were confiscated from local iwi. This is problematic since it increases the uncertainty around how successful current actions will be in restoring and protecting the water ways of the Waikato Basin, as outlined within the *Vision and Strategy for the Waikato River*.

The primary objective of this report is to provide evidence around the state of water quality in the Waikato and Waipa River catchments in 1863. Three secondary objectives are used to focus this research:

1. Estimate the state of water quality in the Waikato and Waipa River catchments in 1863 using predictive modelling.
2. Discuss the findings with respect to historical records and previous research.
3. Indicate the effect that future policy actions—derived from the HRWO process—are likely to have on surface water quality.

The report is structured as follows. Section 2 describes the method used to predict water quality in 1863, while Section 3 presents and discusses model output in the context of other research.

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[1] www.waikatoregion.govt.nz/healthyrivers

Section 3 includes a comparison of the water-quality outcomes predicted to have existed in 1863 with the current stateand with the established long-term goal for water quality established within the HRWO process—known broadly as "Scenario 1". Scenario 1 defines goals of substantial improvement in water quality throughout the catchment for swimming, taking food, and healthy biodiversity.

2. Methods

2.1 Process of research

The development and application of empirical models to estimate water-quality outcomes in 1863 is difficult because of a lack of data. To overcome this deficiency, a structured participatory process was utilised around the modelling application to help isolate deficiencies in the analysis and highlight ways that these could be overcome (Doole and Pannell, 2013). In this regard, the generation of model output consisted of seven key stages:

1. Literature review to identify the intensity and scale of agricultural and point sources of contaminants in the Waikato and Waipa River catchments in 1863.
2. Generation of draft predictions using hydrological models that incorporate source loads, attenuation, flow between key sites, and the calculation of associated contaminant concentrations. These models are described in detail by Semadeni-Davies et al. (2015a, b) and Yalden and Elliott (2015).
3. Presentation of draft results to the HRWO Collaborative Stakeholder Group (CSG), with a focus on gaining guidance for further refinement.
4. Collection of further data to justify the inputs used to generate the water-quality predictions.
5. Updated prediction of contaminant levels using the hydrological models, given the assumed level of agricultural intensification and point-source loadings arising within the catchment.
6. Review and refinement of the models and model output, in response to individual feedback from members of the Technical Leaders Group (TLG). This iterative step necessitated returning to Step #5 a number of times.
7. Presentation of the predictions in a draft report, with further review by the TLG and other experts motivating further refinement (i.e. a return to Step #5).

Within Steps #2 and #5, the models predicted how a change in source load affects the concentration of *E. coli* (Semadeni-Davies et al., 2015a), sediment (Yalden and Elliott, 2015), nitrogen (Semadeni-Davies et al., 2015b), and phosphorus (Semadeni-Davies et al., 2015b) across the present network of monitoring sites in the catchments. These models were developed by the National Institute for Water and Atmospheric Research (NIWA) and are based on the Catchment Land Use for Environmental Sustainability (CLUES) model (Semadeni-Davies et al., 2007), which has been applied throughout New Zealand to represent the flows of a range of contaminants through a catchment network, in both environmental (e.g. Monaghan et al., 2010; Palliser and Elliott, 2013; Elliott et al., 2014) and economic (e.g. Doole, 2013) studies.

The modelling process has helped to provide detailed insight regarding the state of water quality within the Waikato and Waipa River catchments in 1863. However, like all modelling analyses, it is necessarily subject to a number of key assumptions—these are required because of data scarcity, as well as technical limitations of the empirical models used. For the latter, one issue is of key concern. A number of models were developed for the HRWO process to represent the concentration of contaminants in the water as a function of management decisions on the land (Semadeni-Davies et al., 2015a, b; Yalden and Elliott, 2015). Retrodiction[2] of water-quality outcomes in 1863 through the application of these models is inherently difficult because these models were constructed to represent the current state and adjustments relative to the current state, such as changes in water quality arising from the introduction of mitigation measures. The consequences of this are minor when the departures from current conditions are modest. However, 1863 conditions represent a significant departure from current conditions. The impacts of this disparity are minimised through careful comparison of predicted water-quality outcomes with data from other sources and various stages of iterative review. Such issues are common in modelling studies that seek to estimate past natural conditions (Fildes and Kourentzes, 2011), and it is important to remain aware of these constraints when interpreting the results outlined in this report.

[2] The process of estimating conditions that have occurred in the past.

2.2 Research methods

A broad literature review and consultation with stakeholders highlighted that contaminant loading to the Waikato and Waipa River catchments was likely to have been extremely low in 1863. The population was primarily Maori, and was very small relative to the present-day population. For example, the Maori population in the Waikato area was probably around 12,500 in 1863, of a total of around 61,500 Maori and 50,000 Europeans across the whole of New Zealand at that time (Pool, 1991). There is strong evidence that the impacts of the resident Maori population on the waters of the Waikato region were minimal, largely as a result of their low population density and the nature of their traditional practices. For example, a document provided to the TLG on behalf of iwi involved in the HRWO process by Poto Davies (Ngati Koroki Kahukara Trust) outlines the following:[3]

> *Māori were very aware of their responsibility to the whole environment. Food was grown and harvested in harmony with a lunar calendar, cleansing the body was always done downstream of drinking water collection and cultural activity sites. The ngāhere (bush), provided clothing, kai, shelter, resources for waka, tools, weapons etc. It was widespread and sprinkled with the many walking tracks of the people. Ablution areas were purposely established away from waterways.*

Traditional agricultural practices involved limited nutrient application, and no intensive livestock grazing. Indeed, practices were based primarily on soil amelioration through physical amendment, use of fertilisers with modest nutrient concentrations, such as ash, and shifting cultivation (Gumbley et al., 2003; Appendix 1). Additionally, evidence suggests that although wide-scale deforestation may have occurred throughout the Waikato with Maori settlement (Lowe et al., 2000), a mosaic of forest types remained that were heavily utilised by Maori

[3] The full document is provided in Appendix 1.

(McGlone, 1989; Nicholls, 2002; Gumbley et al., 2003; Appendix 1). This is consistent with data presented in Figure 1, in which McGlone (1989) outlines the historical extent of various forms of vegetation across the North Island. These forest areas would almost certainly have retained the low environmental footprint that is evident for undisturbed native-forest assemblages today (Larned et al., 2004). Overall, these factors suggest that Maori settlement would have had minimal impact on water quality in the region in 1863.

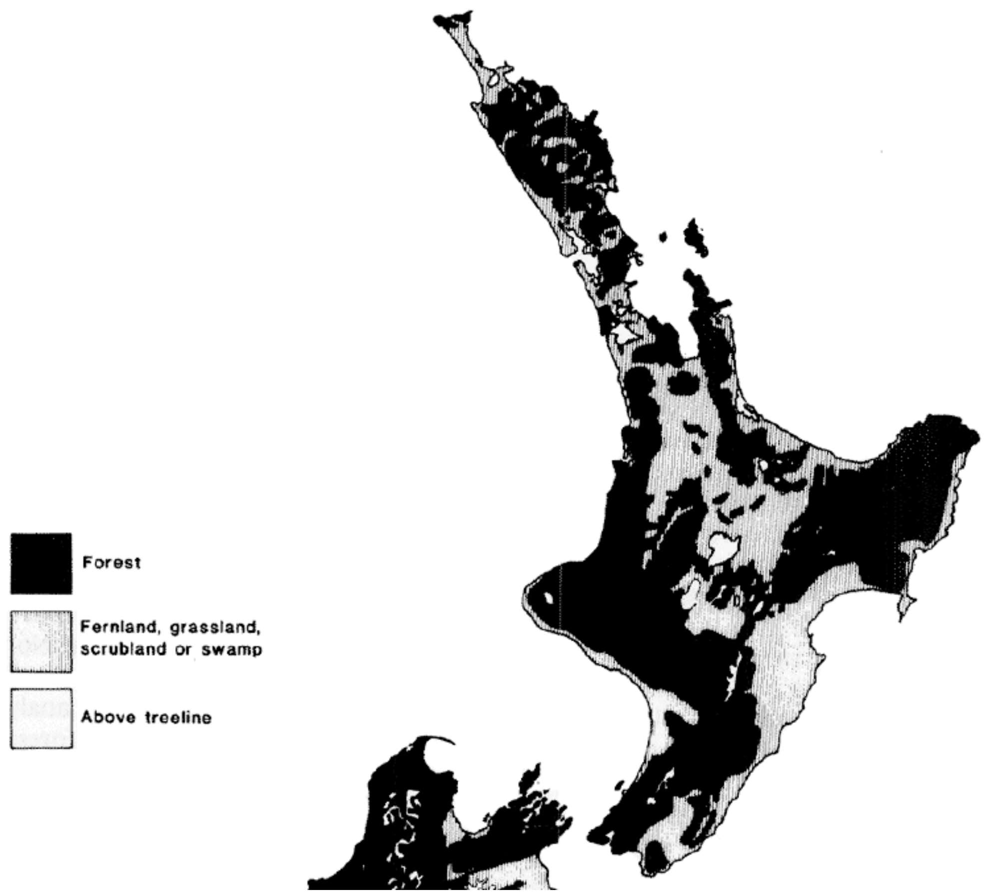

Figure 1. Extent of various vegetation types in the North Island during the time of the first European surveys (1840–1860) (altered from McGlone, 1989).

Based on these insights, it is assumed in this modelling study that equivalent nutrient, sediment, and microbial losses occurred from land in 1863 to what occurs currently from native forest, and that no losses occur from point sources. Not all areas would have been covered by native forest, though. Figure 1 shows that a substantial part of the Waikato region would have consisted of other natural landscapes such as fernland, grassland, scrubland, or swamp during the 1840–1860 period. Further, Rutherford (2001) identified that in the 1920s, around sixty years after 1863, the catchment remained largely undeveloped from Lake Taupo to the Pokaiwhenua Stream (mainly due to soil trace-nutrient limitations), and development increased to around 40% pasture from the confluence with the Pokaiwhenua Stream to Port Waikato. The Upper Waikato at that stage was dominated by sparse scrub, primarily due to coarse soil textures with low nutrient status and low water-holding capacity (Nicholls, 2002). Additionally, information held by the Waikato Regional Council shows that more than 90% of the Lower Waikato River catchment would likely have consisted of wetlands, scrubland, *or* native forest in 1863. Nevertheless, the assumption that contaminant losses are equivalent to native forest is retained, both for consistency and given that the contaminant loads arising from these diverse natural land types would have generally been very low, especially relative to intensive agriculture, and close in absolute magnitude. Indeed, this assumption is consistent with the overall consensus that low-intensity Maori settlement would only have had minor impacts on water quality.

Given these arguments, the following assumptions were utilised in the modelling:

Nutrient losses are assumed to be 4 kg N ha^{-1} and 0.3 kg P ha^{-1}, consistent with typical nutrient losses measured from native forest. Additional phosphorus losses associated with mass erosion—as described in Semadeni-Davies et al. (2015b)—are included, as well.

Sediment losses are estimated for each parcel of land in the study region through the use of the New Zealand Empirical Erosion Model (NZEEM) (Dymond, 2014).[4] Loss rates for land parcels that are not forested currently were reduced by 90% to account for the significant reduction in erosion rates observed in native forest (Dymond et al., 2010).

Modelling the linkage between the source loads and concentrations of microbes observed in water ways is difficult because knowledge regarding the sources and transport of faecal microbes is limited, particularly relative to that for nutrients and sediment (Muirhead, 2015).

[4] NZEEM is an empirical model that estimates the erosion rate present on a given piece of land, as determined by rainfall, slope, parent material, and vegetation cover (Dymond et al. 2010).

Modelling becomes substantially more complex when estimating loads and concentrations in 1863. For example, current losses of *E. coli* from forested areas include contributions from feral animals that are unlikely to have been as prevalent in 1863. Accordingly, the catchment model developed by NIWA for *E. coli* (Semadeni-Davies et al. 2015a) was not utilised to predict concentrations across the catchments in 1863 – it was deemed that it would extend the model too far. Rather, evidence was collected from several sources to estimate likely faecal indicator bacteria (FIB) losses, using data derived from native catchments. These are deemed to provide the best available information into the microbial loads associated with natural landscapes across the Waikato and Waipa River catchments in 1863.

Wetland coverage of the Lower Waikato catchment was extensive in 1863. Waikato Regional Council records show that wetland coverage in the Waikato region in 1840 was around 108,620 ha, including 76,839 ha in the catchments studied in the HRWO process (Figure 2). This area did not change to any significant degree before 1863, given that a low Maori population was still resident there at that time (Pool, 1991). Additionally, Rutherford (2001) highlighted that the development of peat land between 1840 and the 1920s was limited to the Gordonton and Orini areas.

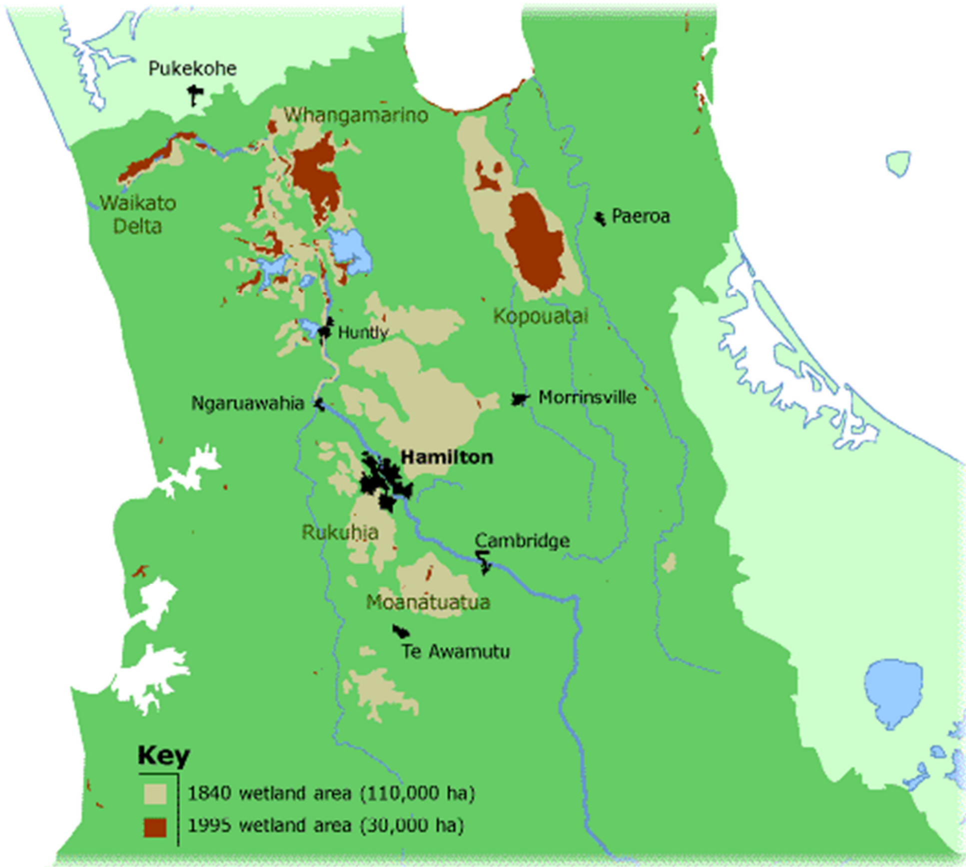

Figure 2. Areas of wetland present in the Lower Waikato River region in 1840 and 1995. (Source: Waikato Regional Council.)

The total area of wetland for each sub-catchment studied in the HRWO process (Semadeni-Davies et al. 2015a, b) was estimated by the Waikato Regional Council using Geographical Information Systems (GIS). These data are summarised in Table 1.

Table 1. The sub-catchments in the HRWO study region that contained areas of wetland in 1863 and the size of those wetland areas. (Source: Waikato Regional Council.)

Sub-catchment	Wetland area (ha)
Awaroa (Rotowaro) at Harris/Te Ohaki Br	713
Waipa at Waingaro Rd Br	622
Awaroa (Rotowaro) at Sansons Br	156
Kirikiriroa	9
Komakorau	13,024
Mangakotukutuku	1,484

Mangapiko	4,968
Mangawara	12,645
Mangawhero	1,708
Matahuru	635
Ohote	1,284
Waikato at Horotiu Br	348
Waikato at Huntly-Tainui Br	3,756
Waikato at Mercer Br	10,752
Waikato at Narrows	2,802
Waikato at Tuakau Br	1,972
Waipa at Mangaokewa Rd	136
Waipa at Pirongia-Ngutunui Rd Br	3,380
Waitawhiriwhiri	1,190
Whangamarino at Island Block Rd	5,309
Whangape	1,571
Waikare	1,318
Waipa at SH23 Br Whatawhata	4,210
Waikato at Bridge St Br	858
Waikato at Rangiriri	393
Waikato at Port Waikato	1,596
Total	**76,839**

These wetland areas are included in the models used to predict water quality in 1863. Rutherford (2001) highlighted that wetlands in the Lower Waikato would have generated nutrient losses at equivalent rates to those of undisturbed native forest. However, in addition, wetlands have a significant capacity to remove contaminants from the water that flows through them. For consistency, the modelling of 1863 water-quality outcomes included this capacity of wetlands to abate the four contaminants (nitrogen, phosphorus, faecal microbes, and sediment) that are the focus of the HRWO program. The assumed levels of reduction are (Doole, 2016):

- An 80% reduction for sediment,
- A 40% reduction for nitrogen,
- A 70% reduction for phosphorus, and
- A 90% reduction for faecal microbes.

3. Results and Discussion

This section presents the results of the modelling study, discusses the output in the context of past research, and compares water quality at current state, in 1863, and under the policy for water-quality improvement generated by the CSG.

One key piece of information must be considered in the following. In the *National Policy Statement for Freshwater Management 2014*, the attribute bands generated for Total Nitrogen and Total Phosphorus relate to levels of eutrophication in lakes. Within the HRWO process, the TLG has recommended extending the use of these bands to the Waikato River main stem, a lake-fed river with impoundments (hydroelectric dams) that increase residence time and provide opportunity for algal growth. Therefore, Total Nitrogen, Total Phosphorus and chlorophyll attributes are discussed for main stem Waikato river sites but are not relevant to tributaries and the Waipa River due to their short residence times; that is, because phytoplankton do not have time to grow.

3.1 Total Phosphorus concentrations

Table 2 presents the model estimated concentrations of Total Phosphorus (TP) for 1863 and currently. These concentrations are presented only for the main stem sites for the reason discussed above (see Doole et al., 2016a, b).

The TP concentrations currently increase five-fold along the Waikato River moving downstream from Lake Taupo towards the mouth, reflecting the cumulative inputs of phosphorus from agriculture and point sources within the catchment area (Table 2). The levels predicted to occur in 1863 also increase in a downstream direction, though the concentrations are significantly lower than those observed currently. The increase in these levels down the river network is unsurprising in both 1863 and at current state. The Waikato River is fed by very low-concentration water (<5 mg/m^3) from Lake Taupo that has a long residence time, allowing the removal of phosphorus—these conditions would have applied in 1863, as well. Those flows pass down the Waikato River, becoming progressively enriched with nutrients. However, the TP levels predicted to have been observed in 1863 at the majority of sites are still not within the “A” attribute band; rather, most fit within the “B” attribute band outlined in the Waikato Objectives Framework (Scarsbrook, 2016).

It is difficult to compare these median-flow results to those estimated for the 1920s by Rutherford (2001) since that author only presents low-flow values for summer. Nevertheless, the reported values for 1863 are very similar to those reported for waterways present in native catchments throughout New Zealand. The average TP concentration drawn from the field studies of Cooper et al. (1987), Davies-Colley and Nagels (2002), and Davis (2005) is 13 mg m^{-3}, and the predicted concentrations reported for 1863 in Table 2 are either side of this mean value. Mean TP concentrations observed in catchments dominated by native forest in the lower catchment are 50 mg m^{-3} for Mangaohoi, 19–21 mg m^{-3} for Mangatawhiri, and 9 mg m^{-3} for Mangauika. Cooper et al (1987) measured a median concentration of 18 mg m^{-3} in a small catchment—dominated by pine forest on pumice soils—and the mean concentration is likely to be larger than that. Furthermore, McDowell et al. (2013) estimated 'reference' TP concentrations of 19 mg/m^3 for the WWL[5] stream category, that of most relevance to the Waikato basin. The outcomes estimated for 1863 (Table 2) are also in close agreement with those presented by Hamilton (2011). This work shows that the 75% of lakes in naturalised catchments will have TP levels below 18 mg m^{-3}, a range that bounds the estimates provided in Table 2 and that is broadly consistent with "A" and "B" bands within the Waikato Objectives Framework. Overall, it can be seen that there is close agreement between the estimated TP levels in 1863 and those found in field studies of native catchments throughout New Zealand.

[5] WWL is the abbreviation used for "Warm, Wet, Lowland" sites in McDowell et al. (2013). This is one of the attributes used to describe the "Source of flow" in the New Zealand River Environment Classification system (REC, http://www.mfe.govt.nz/sites/default/files/environmental-reporting/about-environmental-reporting/classification-systems/rec-user-guide-2010.pdf)

Table 2. Total phosphorus levels for sites down the Waikato River in 1863 and at current state, as predicted by the HRWO model.

Site	FMU	TP concentration (mg m^{-3})		Attribute band for TP	
		1863	Current	1863	Current
Waikato at Ohaaki	Upper	8	11	A	B
Waikato at Ohakuri	Upper	9	18	A	B
Waikato at Whakamaru	Upper	10	20	A	B
Waikato at Waipapa	Upper	11	26	B	C
Waikato at Narrows	Central	11	29	B	C
Waikato at Horotiu Br	Central	12	38	B	C
Waikato at Huntly-Tainui Br	Lower	14	47	B	C
Waikato at Mercer Br	Lower	16	54	B	D
Waikato at Tuakau Br	Lower	16	56	B	D

3.2 Concentrations of nitrogen species

Table 3 reports Total Nitrogen (TN) levels for the nine main-stem sites at which this attribute has been studied within the HRWO process. As outlined for TP above, the current TN concentration also increases in a downstream direction from Lake Taupo (Table 3), reflecting the cumulative contribution of nitrogen inputs from agriculture and point sources within the catchment area. In contrast, TN concentrations predicted for 1863 stay at low levels along the entire Waikato River main stem, solely representing levels consistent with the "A" attribute band in the Waikato Objectives Framework. This represents the low nitrogen inputs (losses) associated with large areas of native forest, as well as substantial capacity for the attenuation of this nutrient across the 1863 landscape.

High rates of nitrogen attenuation would have been expected in the extensive wetlands that dominated the Lower Waikato region in 1863 (Table 1). Wetlands can help to mitigate nitrogen through denitrification and plant uptake (Tanner and Sukias, 2011). They can also help to mitigate phosphorus through plant uptake and phosphorus becoming bound to soils as water passes through (McDowell et al., 2008).

The concentrations of TN predicted for 1863 (Table 3) are consistent with those reported for catchments dominated by native forest (Cooper et al., 1987; Davies-Colley and Nagels, 2002; Davis, 2005; McDowell et al., 2013). McDowell et al. (2013) provided a reference TN concentration of 178 mg m^{-3} and a reference nitrate (NO_3-N) concentration of 39 mg m^{-3} for WWL classes. The adequacy of these predictions are further confirmed by their consistency with the values predicted for summer low-flow conditions in the Waikato River main stem in the 1920s (Rutherford, 2001). Indeed, Rutherford identified a low-flow median value of 178 mg TN m^{-3} that is quite close to the values reported here. The TN concentrations at the outlet of Lake Taupo were about 85 mg m^{-3} in the report of Rutherford (2001), but the concentrations increase substantially by the time they reach the Waikato River at Ohaaki site due to the influence of geothermal and intervening catchment sources. Additionally, the outcomes estimated for 1863 (Table 3) are in close agreement with those presented by Hamilton (2011). This work shows that the 75% of lakes in catchments with native vegetation will have TN levels below 380 mg m^{-3}, with a median of 175 mg m^{-3}. The data presented for 1863 in Table 3 are entirely consistent with these estimates. Overall, it can be seen that there is close agreement between the estimated TN levels in 1863 and those found in field studies of catchments with native vegetation throughout New Zealand.

Table 3. Total Nitrogen (TN) levels for sites down the Waikato River in 1863 and at current state, as predicted by the HRWO model.

Site	**FMU**	**TN concentration ($mg\ m^{-3}$)**		**Attribute band for TN**	
		1863	**Current**	**1863**	**Current**
Waikato at Ohaaki	Upper	127	138	A	A
Waikato at Ohakuri	Upper	154	215	A	B
Waikato at Whakamaru	Upper	147	271	A	B
Waikato at Waipapa	Upper	153	336	A	B
Waikato at Narrows	Central	147	410	A	C
Waikato at Horotiu Br	Central	141	441	A	C
Waikato at Huntly-Tainui Br	Lower	145	585	A	C
Waikato at Mercer Br	Lower	158	662	A	C
Waikato at Tuakau Br	Lower	143	595	A	C

Table 4 and Table 5 present the median and 95th percentile NO_3-N concentrations for 1863 conditions and at current state, respectively, for each monitoring site studied in the HRWO process. These concentrations vary broadly under current state, but overall indicate reasonable water quality. For example, 80% of sites achieve an "A" attribute grade in the Waikato Objectives Framework for median NO_3-N concentration in current state, while around 65% of sites achieve an "A" attribute grade for 95th percentile NO_3-N concentration in current state.

The model predicts much better water quality would have existed in 1863. Indeed, all sites are predicted to satisfy the "A" attribute grade for both median and 95th percentile NO_3-N concentrations in 1863. This is expected given:

- The existing high level of water quality with respect to NO_3-N concentration at most sites (Table 4 and Table 5). For example, around 80% of sites are currently in the "A" band for median nitrate concentration.
- The prevalence of forest—that has a very low rate of nitrogen loss, relative to intensive agriculture (Davis, 2014)—in the catchment in 1863.
- The prevalence of wetlands—that have a significant capacity to attenuate nitrogen through plant uptake and denitrification (Rutherford, 2001; McDowell et al., 2008; Tanner and Sukias, 2011; Doole, 2016)—in the catchment in 1863.

Additionally, these observed NO_3-N concentrations are consistent with those reported for catchments dominated by native forest in previous studies (Cooper et al. 1987; Davies-Colley and Nagels 2002; Davis, 2005; McDowell et al., 2013). For example, McDowell et al (2013) give a reference NO_3-N concentration of 0.39 mg L^{-3} for WWL classes.

Table 4. Median NO_3-N levels for sites in the Waikato and Waipa River catchments in 1863 and at current state as predicted by the HRWO model.

Site	FMU	Median nitrate concentration (mg L^{-3})		Attribute band for median nitrate	
		1863	Current	1863	Current
Pueto	Upper	0.28	0.45	A	A
Waikato at Ohaaki	Upper	0.03	0.04	A	A
Waikato at Ohakuri	Upper	0.05	0.08	A	A

Torepatutahi	Upper	0.38	0.50	A	A
Mangakara	Upper	0.36	1.30	A	B
Waiotapu at Homestead	Upper	0.46	1.29	A	B
Kawaunui	Upper	0.53	2.60	A	C
Waiotapu at Campbell	Upper	0.40	0.92	A	A
Otamakokore	Upper	0.18	0.74	A	A
Whirinaki	Upper	0.25	0.77	A	A
Waikato at Whakamaru	Upper	0.05	0.10	A	A
Waipapa	Upper	0.40	1.21	A	B
Tahunaatara	Upper	0.17	0.56	A	A
Mangaharakeke	Upper	0.24	0.53	A	A
Waikato at Waipapa	Upper	0.07	0.16	A	A
Mangakino	Upper	0.17	0.65	A	A
Mangamingi	Upper	0.33	2.80	A	C
Whakauru	Upper	0.04	0.26	A	A
Pokaiwhenua	Upper	0.29	1.76	A	B
Little Waipa	Upper	0.27	1.58	A	B
Waikato at Karapiro	Upper	0.08	0.22	A	A
Karapiro	Central	0.15	0.52	A	A
Waikato at Narrows	Central	0.08	0.24	A	A
Mangawhero	Central	0.33	2.10	A	B
Waikato at Bridge St Br	Central	0.08	0.24	A	A
Mangaonua	Central	0.38	1.51	A	B
Mangakotukutuku	Central	0.08	0.80	A	A
Mangaone	Central	0.62	2.60	A	C
Waikato at Horotiu Br	Central	0.08	0.26	A	A
Waitawhiriwhiri	Central	0.10	0.88	A	A
Kirikiriroa	Central	0.18	0.82	A	A
Waipa at Mangaokewa Rd	Waipa	0.17	0.38	A	A
Waipa at Otewa	Waipa	0.08	0.23	A	A
Mangaokewa	Waipa	0.14	0.53	A	A
Mangarapa	Waipa	0.17	0.88	A	A
Mangapu	Waipa	0.17	0.86	A	A

Mangarama	Waipa	0.17	0.86	A	A
Waipa at Otorohanga	Waipa	0.10	0.37	A	A
Waipa at Pirongia-Ngutunui Rd	Waipa	0.11	0.57	A	A
Waitomo at Tumutumu Rd	Waipa	0.21	0.63	A	A
Waitomo at SH31 Otorohanga	Waipa	0.15	0.52	A	A
Moakurarua	Waipa	0.17	0.64	A	A
Puniu at Bartons Corner Rd Br	Waipa	0.12	0.65	A	A
Puniu at Wharepapa	Waipa	0.20	0.88	A	A
Mangatutu	Waipa	0.12	0.38	A	A
Mangapiko	Waipa	0.20	1.41	A	B
Mangaohoi	Waipa	0.17	0.23	A	A
Waipa at SH23 Br Whatawhata	Waipa	0.13	0.68	A	A
Mangauika	Waipa	0.12	0.21	A	A
Kaniwhaniwha	Waipa	0.12	0.35	A	A
Waipa at Waingaro Rd Br	Waipa	0.13	0.67	A	A
Ohote	Waipa	0.10	0.50	A	A
Firewood	Waipa	0.17	0.52	A	A
Waikato at Huntly-Tainui Br	Lower	0.09	0.36	A	A
Komakorau	Lower	0.04	1.31	A	B
Mangawara	Lower	0.07	0.77	A	A
Waikato at Rangiriri	Lower	0.09	0.36	A	A
Awaroa (Rotowaro) at Harris Br	Lower	0.00	0.01	A	A
Awaroa (Rotowaro) at Sansons	Lower	0.23	0.70	A	A
Waikato at Mercer Br	Lower	0.09	0.37	A	A
Whangape	Lower	0.00	0.00	A	A
Whangamarino at Island Block	Lower	0.02	0.07	A	A
Whangamarino at Jefferies Rd	Lower	0.14	0.63	A	A
Waerenga	Lower	0.24	0.82	A	A
Matahuru	Lower	0.17	0.72	A	A
Waikare	Lower	0.00	0.00	A	A
Opuatia	Lower	0.20	0.74	A	A
Mangatangi	Lower	0.04	0.11	A	A
Waikato at Tuakau Br	Lower	0.08	0.32	A	A

Ohaeroa	Lower	0.27	1.53	A	B
Mangatawhiri	Lower	0.01	0.01	A	A
Whakapipi	Lower	0.42	3.50	A	C
Awaroa (Waiuku)	Lower	0.28	1.41	A	B
Waikato at Port Waikato	Lower	0.08	0.33	A	A

Table 5. 95th percentile nitrate levels for sites in the Waikato and Waipa River catchments in 1863 and at current state, as predicted by the HRWO model.

Site	**FMU**	**95th percentile nitrate concentration (mg L-3)**		**Attribute band for 95th percentile nitrate**	
		1863	**Current**	**1863**	**Current**
Pueto	Upper	0.33	0.54	A	A
Waikato at Ohaaki	Upper	0.06	0.08	A	A
Waikato at Ohakuri	Upper	0.10	0.17	A	A
Torepatutahi	Upper	0.63	0.83	A	A
Mangakara	Upper	0.47	1.68	A	B
Waiotapu at Homestead	Upper	0.60	1.67	A	B
Kawaunui	Upper	0.63	3.10	A	B
Waiotapu at Campbell	Upper	0.50	1.14	A	A
Otamakokore	Upper	0.32	1.36	A	A
Whirinaki	Upper	0.29	0.89	A	A
Waikato at Whakamaru	Upper	0.13	0.25	A	A
Waipapa	Upper	0.51	1.56	A	B
Tahunaatara	Upper	0.26	0.85	A	A
Mangaharakeke	Upper	0.36	0.80	A	A
Waikato at Waipapa	Upper	0.15	0.32	A	A
Mangakino	Upper	0.23	0.88	A	A
Mangamingi	Upper	0.40	3.40	A	B
Whakauru	Upper	0.07	0.46	A	A
Pokaiwhenua	Upper	0.37	2.20	A	B
Little Waipa	Upper	0.37	2.15	A	B

Waikato at Karapiro	Upper	0.19	0.51	A	A
Karapiro	Central	0.51	1.76	A	B
Waikato at Narrows	Central	0.19	0.54	A	A
Mangawhero	Central	0.43	2.72	A	B
Waikato at Bridge St Br	Central	0.20	0.58	A	A
Mangaonua	Central	0.53	2.10	A	B
Mangakotukutuku	Central	0.23	2.35	A	B
Mangaone	Central	0.77	3.20	A	B
Waikato at Horotiu Br	Central	0.18	0.54	A	A
Waitawhiriwhiri	Central	0.14	1.27	A	A
Kirikiriroa	Central	0.43	1.98	A	B
Waipa at Mangaokewa Rd	Waipa	0.33	0.71	A	A
Waipa at Otewa	Waipa	0.17	0.50	A	A
Mangaokewa	Waipa	0.29	1.06	A	A
Mangarapa	Waipa	0.29	1.53	A	B
Mangapu	Waipa	0.29	1.43	A	A
Mangarama	Waipa	0.30	1.55	A	B
Waipa at Otorohanga	Waipa	0.32	1.15	A	A
Waipa at Pirongia-Ngutunui Rd	Waipa	0.30	1.54	A	B
Waitomo at Tumutumu Rd	Waipa	0.28	0.83	A	A
Waitomo at SH31 Otorohanga	Waipa	0.27	0.93	A	A
Moakurarua	Waipa	0.26	1.02	A	A
Puniu at Bartons Corner Rd Br	Waipa	0.24	1.31	A	A
Puniu at Wharepapa	Waipa	0.29	1.30	A	A
Mangatutu	Waipa	0.28	0.91	A	A
Mangapiko	Waipa	0.37	2.65	A	B
Mangaohoi	Waipa	0.30	0.42	A	A
Waipa at SH23 Br Whatawhata	Waipa	0.30	1.60	A	B
Mangauika	Waipa	0.17	0.29	A	A
Kaniwhaniwha	Waipa	0.34	1.00	A	A
Waipa at Waingaro Rd Br	Waipa	0.30	1.58	A	B
Ohote	Waipa	0.29	1.39	A	A
Firewood	Waipa	0.30	0.90	A	A

Waikato at Huntly-Tainui Br	Lower	0.24	1.00	A	A
Komakorau	Lower	0.15	5.30	A	C
Mangawara	Lower	0.31	3.35	A	B
Waikato at Rangiriri	Lower	0.23	0.96	A	A
Awaroa (Rotowaro) at Harris Br	Lower	0.12	0.48	A	A
Awaroa (Rotowaro) at Sansons	Lower	0.46	1.39	A	A
Waikato at Mercer Br	Lower	0.21	0.89	A	A
Whangape	Lower	0.19	0.80	A	A
Whangamarino at Island Block	Lower	0.20	0.87	A	A
Whangamarino at Jefferies Rd Br	Lower	0.57	2.50	A	B
Waerenga	Lower	0.42	1.42	A	A
Matahuru	Lower	0.44	1.91	A	B
Waikare	Lower	0.07	0.25	A	A
Opuatia	Lower	0.29	1.08	A	A
Mangatangi	Lower	0.52	1.29	A	A
Waikato at Tuakau Br	Lower	0.21	0.88	A	A
Ohaeroa	Lower	0.34	1.92	A	B
Mangatawhiri	Lower	0.34	0.40	A	A
Whakapipi	Lower	0.64	5.35	A	C
Awaroa (Waiuku)	Lower	0.49	2.50	A	B
Waikato at Port Waikato	Lower	0.21	0.90	A	A

3.3 Visual clarity and black disk sighting distance

Table 6 reports median visual clarity. This is measured as the horizontal sighting distance of a 100 mm diameter black disc—the so-called "black disk measurement" (BDM, measured in units of metres). The Waikato Objectives Framework outlines that an "A" grade for clarity requires a BDM above or equal to 3 m, a "B" grade for clarity requires a BDM above or equal to 1.6 m and below 3 m, a "C" grade for clarity requires a BDM above or equal to 1 m and below 1.6 m, and a "D" grade involves a BDM of less than 1 m (Scarsbrook, 2016). Overall, clarity at current state within the water bodies of the Waikato Basin is generally poor, though highly variable across sites (Table 6). Indeed, 15% of sites record a "B" grade, 33% record a "C" grade, and 52% record a "D" grade in terms of the attribute levels for clarity outlined in the Waikato Objectives Framework. This trend is unsurprising and represents a strong link between pastoral farming and sediment delivery to water ways in the region (Ritchie, 2012).

In comparison, the clarity predicted at sites throughout the catchment in 1863 is much greater. Here, 22% of sites record an "A" grade, 51% record a "B" grade, 22% record a "C" grade, and 5% record a "D" grade in terms of the attribute levels for clarity outlined in the Waikato Objectives Framework. McDowell et al. (2013) provided a reference/baseline level of clarity of 1.78 m for WWL REC stream reaches. This is consistent with a "B" band outcome. We can expect, however, that there will be variation about this—as observed in Table 6—with greater clarity in spring-fed, pumice streams (e.g. Pueto) and lower clarity in streams draining areas with clay or peat soils (e.g. Waitomo at Tumutumu Road).

Some extreme responses are also recorded. For example, the black disc measurement improves by more than five times at the Pueto site in 1863, relative to the current state (Table 6). The estimated 1863 value of 9.1 m at Pueto is extreme, but is comparable to the highest value identified by Rutherford (2001) (8.5 m) in the vicinity of this site.

These outcomes are similar to results from previous research. Rutherford (2001) predicted that under summer low-flow conditions in the 1920s, 3% of sites were an "A" grade, 39% recorded a "B" grade, 32% recorded a "C" grade, and 26% recorded a "D" grade in terms of the attribute levels for clarity outlined in the Waikato Objectives Framework. These outcomes indicate that while land use was substantially less-intensive in the 1920s than it is currently, the clarity of water bodies throughout the catchment was still not outstanding, relative to criteria outlined in the Waikato Objectives Framework. More information provides further context to this outcome. The average BDM estimated by Rutherford (2001) for all sites in the catchment in the 1920s was 1.6 m, with a standard deviation of 1.2 m. In comparison, the average BDM at current state is 1 m, with a standard deviation of 0.52 m. In contrast, the predicted levels for 1863 presented in Table 6 have a mean of 2.44 m and a standard deviation of 1.6 m. Thus, the clarity predicted for 1863 (Table 6) is greater than what is predicted to have existed in the 1920s and currently, and exhibited greater variability.

This trend is also evident in monitoring data collected in the catchment. The Waipa at Mangaokewa Road site contains a high proportion of native and plantation forest currently. However, the median BDM in this sub-catchment is currently around 1.5 m, placing it in the "C" band. Model output indicates that greater clarity was likely in 1863, but only sufficient to lift it to a "B" band within the Waikato Objectives Framework (Table 6). This is consistent with results from NIWA (2010), which highlight that sedimentary rocks in parts of the Waipa catchment (particularly around Te Kuiti and Waitomo) are associated with low clarity, even when covered with undisturbed native forest. Similarly, the forested Mangahoi and Mangatawhiri catchments both have a current BDM of 1.6 m. Clarity levels consistent with outcomes in the "D" band are predicted in some sub-catchments—such as Waitawhiriwhiri and Kirikiriroa—under 1863 conditions. This primarily reflects contributions from dissolved organic matter associated with swampy/peat soils. In line with this result, using an empirical approach based on the regression modelling of current concentrations, Rutherford (2001, Table 24) estimated a BDM of 0.26 m at mean flow for tributaries draining undeveloped wetlands. Rob Davies-Colley (NIWA, pers. comm.) has also noted that visual clarity in Westland streams covered with a mosaic of flax swamps, other wetlands, and kahikatea swamp-forest was approximately 0.47 m. [This is further supported by the results reported in Davies-Colley and Nagels (2008).] Dr Davies-Colley considers that this is unexpectedly low and related to the amount of dissolved organic matter (possibly due to humic detritus), and this could well hold for the Waikato too, suggesting that lowland peat-dominated stream catchments would also have low clarity (~1m), even under 1863 conditions.

Table 6. Estimates of visual clarity quantified by black disc measurement (BDM), and associated attribute bands, for sites in the Waikato and Waipa River catchments in 1863 and at current state (denoted "Cur."), as predicted by the HRWO model.

Site	**FMU**	**BDM (m)**		**BDM attribute band**	
		1863	**Cur.**	**1863**	**Cur.**
Pueto	Upper	9.1	1.6	A	B
Waikato at Ohakuri	Upper	5.3	2	A	B
Waiotapu at Homestead	Upper	1.1	0.7	C	D
Kawaunui	Upper	3.3	1.3	A	C
Waiotapu at Campbell	Upper	1.8	1.2	B	C
Otamakokore	Upper	3.2	1.1	A	C
Whirinaki	Upper	7.8	2.7	A	B
Waipapa	Upper	2.8	1.1	B	C
Tahunaatara	Upper	2.1	1.2	B	C

Mangaharakeke	Upper	1.3	1.1	C	C
Waikato at Waipapa	Upper	2.6	1.6	B	B
Mangakino	Upper	2.6	1.6	B	B
Mangamingi	Upper	1.7	0.8	B	D
Whakauru	Upper	1.7	0.8	B	D
Pokaiwhenua	Upper	2.5	1.3	B	C
Little Waipa	Upper	5.9	1.5	A	C
Karapiro	Central	3.5	0.9	A	D
Waikato at Narrows	Central	3.8	1.6	A	B
Mangawhero	Central	1.6	0.3	B	D
Waikato at Bridge St Br	Central	4.3	1.4	A	C
Mangaonua	Central	3.2	0.9	A	D
Mangakotukutuku	Central	1.1	0.4	C	D
Mangaone	Central	2.4	1	B	C
Waikato at Horotiu Br	Central	3.8	1.4	A	C
Waitawhiriwhiri	Central	0.6	0.4	D	D
Kirikiriroa	Central	0.5	0.4	D	D
Waipa at Mangaokewa Rd	Waipa	2.0	1.5	B	C
Waipa at Otewa	Waipa	3.4	2.2	A	B
Mangaokewa	Waipa	2.4	1	B	C
Mangapu	Waipa	2.9	0.8	B	D
Waipa at Otorohanga	Waipa	2.0	1.1	B	C
Waipa at Pirongia-Ngutunui Rd Br	Waipa	2.1	0.8	B	D
Waitomo at Tumutumu Rd	Waipa	1.7	1	B	C
Waitomo at SH31 Otorohanga	Waipa	1.1	0.6	C	D
Puniu at Bartons Corner Rd Br	Waipa	2.6	0.9	B	D
Mangatutu	Waipa	2.7	1.5	B	C
Mangapiko	Waipa	2.3	0.6	B	D
Mangaohoi	Waipa	1.8	1.6	B	B
Waipa at SH23 Br Whatawhata	Waipa	1.6	0.6	B	D
Waikato at Huntly-Tainui Br	Lower	2.5	0.9	B	D
Mangawara	Lower	1.2	0.3	C	D
Waikato at Rangiriri	Lower	2.2	0.8	B	D

Awaroa (Rotowaro) at Sansons Br	Lower	1.5	0.8	C	D
Waikato at Mercer Br	Lower	1.8	0.6	B	D
Whangamarino at Island Block Rd	Lower	0.5	0.2	D	D
Whangamarino at Jefferies Rd Br	Lower	1.4	0.5	C	D
Waerenga	Lower	2.1	0.8	B	D
Matahuru	Lower	1.0	0.3	C	D
Opuatia	Lower	1.3	0.5	C	D
Mangatangi	Lower	1.2	0.6	C	D
Waikato at Tuakau Br	Lower	1.4	0.5	C	D
Ohaeroa	Lower	2.6	0.8	B	D
Mangatawhiri	Lower	1.7	1.6	B	B
Whakapipi	Lower	2.0	1.1	B	C
Awaroa (Waiuku)	Lower	1.5	0.4	C	D

3.4 Chlorophyll-a concentrations

Table 7 and Table 8 report the median and maximum chlorophyll-a concentrations, respectively, for the nine main-stem sites at which these attributes apply within the HRWO process. The levels evident for the current state follow those for TN and TP, in that they generally increase with distance from Lake Taupo. This reflects the accumulation of nitrogen and phosphorus from agriculture and point sources as water moves further down the catchment and the substantial residence times associated with hydro-electric development along the Waikato River—these factors both favour greater phytoplankton growth. As a consequence, both median and maximum chlorophyll-a levels reach a "C" band—as defined in the Waikato Objectives Framework—in the Lower Waikato region at current state. The values reported for 1863 are all consistent with an outcome in the "B" band in the Waikato Objectives Framework. These findings are reasonably consistent with the findings of Rutherford (2001).[6] Rutherford

[6] Table 25 in the report of Rutherford (2001) appears to provide misleading estimates of median chlorophyll-a concentrations; thus, a regression line is instead fitted to data presented in Figure 42 of this report. It is this regression line that is used to compute the data that is discussed in the main text above.

(2001) predicted that in the 1920s sites on the Waikato River main stem up to and including Waikato at Horotiu Bridge (Table 7) had median chlorophyll-a responses within a "B" band. Median chlorophyll-a concentrations at the sites past this point were predicted to have readings consistent with a "C" band. These outcomes are estimated at being at "B" band in 1863 (Table 7). This disparity reflects differences in the core assumptions employed in the frameworks (cf. Rutherford, 2001; Yalden and Elliott, 2015). The outcomes estimated for 1863 (Table 7) are in close agreement with those presented by Hamilton (2011). This work shows that almost all lakes in naturalised catchments will typically have median chlorophyll-a levels between 0 and 6 mg m^{-3}, a range that bounds the estimates provided in Table 7 and that is broadly consistent with "A" and "B" bands within the Waikato Objectives Framework. A value denoting low median chlorophyll-a incidence in 1863 is also expected because at this time the main stem of the Waikato River would not have been subject to intermittent hydroelectric impoundment, which promotes algal growth through increasing hydrological residence time (Rutherford, 2001).

Table 7. Median chlorophyll-a levels down the Waikato River in 1863 and at current state, as predicted by the HRWO model.

Site	**FMU**	**Median chlorophyll-a concentration (mg m^{-3})**		**Median chlorophyll-a attribute band**	
		1863	**Current**	**1863**	**Current**
Waikato at Ohakuri	Upper	2.4	4.9	B	B
Waikato at Waipapa	Upper	2.6	5.7	B	C
Waikato at Narrows	Central	2.9	6.3	B	C
Waikato at Bridge St Br	Central	3.0	7.0	B	C
Waikato at Horotiu Br	Central	2.9	7.0	B	C
Waikato at Huntly-Tainui Br	Lower	2.3	8.6	B	C
Waikato at Rangiriri	Lower	2.3	9.6	B	C
Waikato at Mercer Br	Lower	3.6	13.5	B	D
Waikato at Tuakau Br	Lower	3.7	13.3	B	D

Regression analysis was performed to identify the relationship between median and maximum chlorophyll-a concentrations in the main stem of the Waikato River.[7] When median chlorophyll-a concentrations estimated for 1863 (Table 7) are used as inputs to this relationship, outputs indicate a spread for maximum chlorophyll-a concentrations across both “A” and “B” bands (Table 8). For comparison, the median chlorophyll-a values generated by Rutherford (2001) are also used as inputs into this regression model. This identified that in the 1920s, the maximum chlorophyll-a concentration was consistent with an “A” band at Waikato at Ohakuri, but was consistent with a “B” band at all other main-stem sites. Thus, overall, the predictions of both models are reasonably similar. Their similarity is reinforced by the fact that they would predict identical attribute bands along the main-stem sites, if the values estimated for two sites (Waikato River at Huntly-Tainui Bridge and Waikato River at Rangiriri) were 0.2 mg m^{-3} higher, well within the margin of error associated with this type of modelling. Nevertheless, it is important to note that the output of the regression model likely overstates the incidence of maximum chlorophyll-a in 1863. This is because the flow regime that existed at that time is highly disparate from current-state conditions; this is problematic since the regression relationship that computes maximum chlorophyll-a incidence as a function of median chlorophyll-a values is based on the flow regimes that exist at current state. The implication of this is that the maximum chlorophyll-a concentrations estimated in the model (Table 8) are likely to be the upper bound of what could be expected to have existed in 1863 (due to the short residence time for algal growth before impoundment).

[7] This work was undertaken by Dr John Quinn (NIWA), within the context of the HRWO process.

Table 8. Maximum chlorophyll-a levels down the Waikato River in 1863 and at current state, as predicted by the HRWO model.

Site	FMU	Maximum chlorophyll a concentrations (mg m^{-3})		Maximum chlorophyll a attribute bands	
		1863	Current	1863	Current
Waikato at Ohakuri	Upper	10.0	15.6	A	B
Waikato at Waipapa	Upper	10.6	17.2	B	B
Waikato at Narrows	Central	11.3	18.4	B	B
Waikato at Bridge St Br	Central	11.4	20.1	B	B
Waikato at Horotiu Br	Central	11.2	20.0	B	B
Waikato at Huntly-Tainui Br	Lower	9.8	23.5	A	B
Waikato at Rangiriri	Lower	9.8	25.6	A	C
Waikato at Mercer Br	Lower	12.7	34.1	B	C
Waikato at Tuakau Br	Lower	13.0	33.5	B	C

3.5 Faecal Microbial Indicators (FIBs)

It is tenuous to relate vast changes in land use and land management to microbial concentrations in the water throughout the catchment, given the greater uncertainty around the dynamics of microbial loss relative to those for nutrients and sediment (Muirhead, 2015). However, primary data provide insight into the conditions likely to have existed throughout the catchments of the Waikato and Waipa Rivers in 1863. Substantial evidence indicates that losses of faecal microbes from native-forest catchments are generally smaller than from those catchments dominated by pastoral land uses (Smith et al., 1993; Davies-Colley and Nagels, 2002; Larned et al. 2004; Davies-Colley, 2009). Accordingly, statistically-significant negative correlations between median *E. coli* incidence and the percentage of a catchment in forest have been found in different studies. This includes estimates of Pearson's correlation coefficients of $\rho = -0.34$ in Davies-Colley (2009) and $\rho = -0.33$ in Palliser et al. (2015). Additionally, studies done in catchments containing high levels of native forest regularly identify values consistent with the "A" band for median *E. coli* set out in the Waikato Objectives Framework (less than 260 *E. coli* per 100 ml) for secondary-contact recreation ('wading'). For example, Davies-Colley and Nagels (2002) identified mean values of 4.1 and 130 *E. coli* per 100 ml for two forested catchments in Westland. The median *E. coli* concentration in native-forest catchments analysed by Larned et al. (2004) was also below the threshold of 260 *E. coli* per 100 ml that defines an "A" band for median *E. coli* set out in the Waikato Objectives Framework for secondary contact. The median *E. coli* reference (baseline) concentration from McDowell et al. (2013) for WWL streams is 79 *E. coli* per 100 ml, which is also in the "A" band for secondary contact.

On the other hand, Palliser et al. (2015) highlighted that around 20% of Northland monitoring sites represent catchments dominated by forest, yet have higher-than-average microbial concentrations. Furthermore, Larned et al. (2004) showed that median *E. coli* concentration can vary broadly across sites that contain a majority of native forest, in some cases even breaching the National Bottom Line for secondary-contact recreation of 1,000 *E. coli* per 100 ml. A similar trend is evident in Semadeni-Davies et al. (2015a), who identified that three monitoring sites within sub-catchments in the Waikato Basin that consist primarily of forest have 95th percentile *E. coli* concentrations that are well above the Minimum Acceptable State for this swimming attribute (540 *E. coli* per 100 ml). These sub-catchments are Mangatawhiri (5,615 *E. coli* per 100 ml), Mangaohoi (1,037 *E .coli* per 100 ml), and Mangauika (1,980 per 100 ml). The native-forest site at the Whatawhata Experimental Station also has a high 95th percentile concentration of *E. coli* (~5,000 *E. coli* per 100 ml) (Donnison et al., 2004). The source of these higher-than-expected observed microbial concentrations could, in some cases, be due to small non-forested areas in the sub-catchments of interest. However, it may also arise from wildlife populations present in these forests.

In 1863, there may well have been fewer large feral animals (such as pigs) present in forests throughout the Waikato Basin, so the contamination may well have been less than is observed at present in forested catchments. On the other hand, historical reports suggest that pigs had become widespread in New Zealand by 1863, with high populations present in some places.[8] Accordingly, forested areas in 1863 may have actually had similar levels of faecal contamination from these sources than is currently observed in catchments dominated by native

[8] http://www.monteriaboarhunts.co.nz/pig-boar-hunting.php?page=91

forest throughout New Zealand. It has been postulated that *E. coli* incidence in forested areas may have less association with pathogenic organisms (e.g. *Campylobacter*, *Cryptosporidium*, and *Giardia*), relative to *E. coli* incidence observed in pasture areas (Donnison and Ross, 1999). The implication of this is that for the same *E. coli* concentrations, there may be less health risk associated with runoff from forested areas than from pasture areas. Nevertheless, the evidence for this is weak, and we know that streams draining from forested areas do contain pathogens (Till et al., 2008).

It is likely that 95th percentile *E. coli* concentrations would have been within the "A" band in 1863 in sub-catchments in the Waikato Basin dominated by pumice soils—these are mainly found in the Upper Waikato FMU. The measured FIB concentrations in forested streams draining to Lake Taupo are generally low, following analysis of unpublished water-quality data (Sandy Elliott (NIWA), pers. comm.). For example, 95th percentiles are 66 *E. coli* per 100 ml for the Waihaha River at State Highway 32 (a catchment dominated by native forest), 98 *E. coli* per 100 ml for the Waitahanui River at State Highway 1 (a catchment dominated by pine forest), and 313 *E. coli* per 100 ml for the Hinemaiaia River at State Highway 1 (a catchment consisting of both native and pine forest). Furthermore, even with the current degree of development, 95th percentile *E. coli* concentrations in pumice sub-catchments within the Waikato Basin are often within the "A" band—for example, the Pueto and Whirinaki streams (Appendix B; Semadeni-Davies and Elliott, 2015). These data suggest that 95th percentile *E. coli* concentrations in 1863 in sub-catchments in which pumice soils are broadly found were likely to have been in the "A" band for primary-contact recreation in 1863.

Several reasons also suggest that concentrations in the main-stem of the Waikato River would have been in the "A" band in 1863. These justifications are:

- Flows from Lake Taupo would have had contained very-low microbial concentrations (~10 *E. coli* per 100 ml).
- Inflows from the upper Waikato River tributaries will carry low concentrations, given the dominance of pumice soils in the Upper Waikato FMU (Doole et al., 2016c).
- Both of these flows will dilute microbial inputs from the lower catchment, which will be considerably lower than is what observed at current state.
- Wetland incidence in the Lower Waikato FMU was much higher in 1863. Wetlands can provide significant attenuation of microbial concentrations (Humphrey et al., 2014), in

the order of 80–90% (Doole, 2016). Thus, these would have acted as a filter for microbes arising from the catchments that fed them. A complication in this assessment is the unknown effect of waterfowl, which are a key source of *E. coli* (McBride et al., 2002) and may have been more prevalent in 1863.

Overall, these factors suggest that *E. coli* concentrations in 1863 would have been substantially lower throughout the catchment than what exists at present. Sites in the Upper Waikato and along the main stem were likely to have been in the "A" band for primary-contact recreation. Tributaries in the lower catchment were likely to have been in the "A" band for secondary-contact recreation, but may have been in the "B" band or around the Minimum Acceptable Standard (1000 *E. coli* per 100 ml). Even in those areas, the concentrations may have been in the "A" band due to the lower prevalence of feral animals, relative to current conditions.

3.6 Comparison of water quality under current state and 1863 conditions

Table 9 highlights the current state of the Waikato and Waipa River catchments in terms of the number of sites present in each attribute band set out in the Waikato Objectives Framework. The total number of sites present for each attribute varies according to the location where the attribute is relevant and the places where assessment is performed currently. For example, there are only nine sites where TN, TP, and median/maximum chlorophyll-a concentrations are measured, because these attributes are only relevant at main-stem sites. Overall, Table 9 highlights the deleterious impact of substantial cultural, economic, environmental, and social transition since 1863, with water-quality attributes reflecting broad-scale agricultural development, population increases, hydroelectric development, and the establishment of point-source discharges.

In comparison, Table 10 highlights the number of sites predicted to be in each attribute band in 1863. In contrast to current conditions, these data paint a picture of a relatively pristine catchment where the resident human population had an extremely-low impact on water quality. Indeed, nitrogen and phosphorus levels were unlikely to have been problematic relative to current water-quality guidelines, and phytoplankton would have been present in very-low concentrations as a consequence of low nutrient concentrations and short residence times in the main stem of the Waikato River due to an absence of hydroelectric development. Unlike current conditions, the risk of infection from zoonotic diseases was also likely to have been extremely low. Nevertheless, broad variation in water clarity was likely to have existed, reflecting broad variation in the spatial coverage of wetlands and diverse lithologies.

Table 9. The number of sites in each attribute band at current state.

Attribute	Attribute band			
	A	B	C	D
Median Chlorophyll-a	0	1	6	2
Max. Chlorophyll-a	0	6	3	0
Total Nitrogen	1	3	5	0
Total Phosphorus	0	3	4	2
Median nitrate	59	11	4	0
95th percentile nitrate	48	24	2	0
Median *E. coli*	43	21	8	2
95th percentile *E. coli*	10	4	8	52
Visual clarity	0	9	17	29

Table 10. Number of sites in each attribute band in 1863.

Attribute	Attribute band			
	A	B	C	D
Median Chlorophyll-a	0	9	0	0
Max. Chlorophyll-a	3	6	0	0
Total Nitrogen	9	0	0	0
Total Phosphorus	3	6	0	0
Median nitrate	74	0	0	0
95th percentile nitrate	74	0	0	0
Visual clarity	12	28	12	3

3.7 Comparison of water quality under conditions for current state, 1863, and Scenario 1

The long-term goal for water quality established within the HRWO process is known broadly as "Scenario 1". Scenario 1 defines goals of substantial improvement in water quality throughout the catchment for swimming, taking food, and healthy biodiversity. This involves an improvement in water quality at all sites in the catchment, even if they are already meeting the Minimum Acceptable State.

A number of key lessons are evident from comparing attribute levels in current state, 1863, and in Scenario 1.

The goal for Total Phosphorus in Scenario 1 involves improving all sites that are currently below the "B" band to the "B" band. It is entirely consistent with historical conditions that are predicted to have existed in 1863, given that the majority of sites were estimated to be in the "B" band at that time, especially in the Lower Waikato region. This goal represents a significant improvement from current state, where two-thirds of sites currently sit below this level. Nevertheless, in the *National Policy Statement for Freshwater Management 2014*, the attribute bands generated for Total Phosphorus relate to levels of eutrophication in lakes. There were no hydroelectric dams on the Waikato River in 1863; thus, Total Phosphorus loses some of its significance as a measure of water quality in this context.

The goal for Total Nitrogen in Scenario 1 involves improving all main-stem sites between Lake Taupo and the Waikato River at Waipapa site to the "A" band, with sites downstream of this being lifted to the "B" band. Total Nitrogen levels were likely to have been better than this in 1863, with all sites predicted to be in the "A" band. Goals for Total Nitrogen under Scenario 1 represent significant levels of improvement, relative to current state, given that this attribute currently goes from "A" to "C" band as it moves from Lake Taupo to the Waikato River at the Narrows site. It remains in the "C" band throughout the Lower Waikato FMU. Nevertheless, in the *National Policy Statement for Freshwater Management 2014*, the attribute bands generated for Total Nitrogen relate to levels of eutrophication in lakes. There were no hydroelectric dams on the Waikato River in 1863; thus, Total Nitrogen loses some of its significance as a measure of water quality in this context.

Scenario 1 outlines that median and 95^{th} percentile NO_3-N concentrations need to improve where they are in the "A" band, while other sites need to go up by one band. These aspirations are consistent with the low nitrate concentrations that are likely to have existed in 1863 across the Waikato and Waipa River catchments. They also represent a small, but significant, improvement relative to the current state, given that presently 80% and 65% of sites are already present in the "A" band for median and 95^{th} percentile NO_3-N concentrations, respectively.

Scenario 1 requires sites at "B" band for median chlorophyll-a to go to "A" band in the upper river and all other sites to achieve "B" band. This represents a substantial improvement relative to current conditions, where around 90% of sites are currently below the "B" band. Scenario 1 is broadly consistent with conditions in 1863, where it is predicted that all sites were likely in the "B" band, though only marginally so in the Upper Waikato FMU (Table 7). At main-stem sites in the Upper Waikato FMU, the extent of those improvements required in Scenario 1 are unlikely to be achieved, because water quality would probably have to exceed what was likely to have been observed there in 1863. However, there were no hydroelectric lakes on the Waikato River in 1863; thus, median chlorophyll-a in 1863 loses some of its relevance as a measure of water quality in this context.

Scenario 1 requires maximum chlorophyll-a levels for all main-stem sites above and including the Waikato River at Huntly-Tainui Bridge site to be in the "A" band and all sites below this on the main stem to be in the "B" band. This represents a substantial improvement relative to current conditions, given that all sites must improve by one band. Scenario 1 is quite disparate from the conditions predicted to have existed in 1863, given that four sites are predicted to have lower water quality in 1863 than what would exist if the goals for maximum chlorophyll-a set out in Scenario 1 are achieved. This highlights that it will be very difficult to achieve the high aspirational goals set out for maximum chlorophyll-a in Scenario 1.

The current state is characterised by the large majority of sites (~85%) in the catchment satisfying "A" and "B" bands for median *E. coli* concentrations. (At current state, 58% of all sites are in the "A" band and 28% are in the "B" band.) However, the large majority of sites (~80%) do not meet standards for microbial contamination required for primary-contact recreation, with 70% of sites in the "D" band. Scenario 1 outlines that median *E. coli* levels in the main stem of the Waikato River and at sites in the Upper Waikato FMU should be at the "A" level, while other sites are in the "B" band. It also states that 95th percentile *E. coli* levels in the main stem of the upper Waikato River and at sites in the Upper Waikato FMU should be at the "A" level, while other sites should be in the "B" band. Thus, overall, targets for both secondary- and primary-contact recreation in Scenario 1 reflect goals for "A" band outcomes in the upper catchment, and a B aspiration elsewhere, all to meet the swimmable criterion. It is difficult to predict the concentration of microbes present across the catchment in 1863; however, our review of existing information suggests that the aspirations set out in Scenario 1 are very consistent with those conditions that are likely to have prevailed in 1863.

Scenario 1 outlines an improvement in clarity in the main stem to "A" band at sites up to and including the Waikato River at Waipapa, "B" band in the Central Waikato FMU, and "C" in the Lower Waikato FMU. All tributaries in the Upper Waikato, Central Waikato, and Waipa FMUs need to go up one band. Also, tributaries in the Lower Waikato FMU need to achieve the "C" band. Current conditions for clarity are poor, with around 84% of sites achieving a "C" or "D" grade, with 31% of the total number of sites having a "C" grade and 53% having a "D" grade. Hence, Scenario 1 represents a substantial improvement, relative to the current state. Additionally, the proposed policy mix of the CSG achieves a marked improvement in clarity across the catchment (Doole et al., 2016c). Levels of clarity that are predicted to have existed in 1863 are mixed, with 22% of sites recording an "A" grade, 51% recording a "B" grade, 22% recording a "C" grade, and 5% recording a "D" grade in terms of the attribute levels for clarity outlined in the Waikato Objectives Framework (Table 6). Nevertheless, clarity at around 85% of them was predicted to be higher in 1863, relative to Scenario 1.

This outcome is in line with expectations. Overall, visual clarity was likely to have been much better in 1863, relative to what will be possible to achieve under Scenario 1 conditions, because of the small human population, low intensity of land use, and the widespread occurrence of wetlands in 1863. These factors would historically have reduced the input of particulate and colloidal material to surface waters. Scenario 1 conditions are unlikely to achieve similar clarity, given that they will be accompanied by continued patterns of population growth, agriculture, and the maintenance of lower areas of wetlands than what would have existed historically (Doole et al., 2016a, b, c). Furthermore, the reduction of light penetration consistent with these factors is likely to reduce photosynthetic activity and suppress algal growth slightly—relative to what occurred in 1863—contributing to lower levels of algal biomass under future conditions. This change in clarity somewhat conditions the response of median and maximum chlorophyll-a levels within the context of Scenario 1, inferring that algal growth in 1863 may have been promoted by greater clarity. Nevertheless, the positive impact of this factor on algal growth in 1863 would easily have been dominated by the negative impacts of lower nutrient inputs and much-reduced hydrological residence times.

4. Conclusions

The *Vision and Strategy for the Waikato River* focuses on restoring and protecting the health and wellbeing of the Waikato and Waipa Rivers for current and future generations. In the context of this legislation, there is substantial interest in the state of water quality within these catchments when the *New Zealand Settlements Act 1863* was passed and substantial tracts of land were confiscated from local iwi. The chief finding of this report is that the broad cultural, economic, environmental, and social changes experienced in this catchment since 1863 has led to a severe decline in water quality. Nevertheless, it also establishes that moving towards the achievement of the water-quality aspirations contained in Scenario 1—developed by the Collaborative Stakeholder Group in the context of the Healthy Rivers Plan for Change: Waiora He Rautaki Whakapaipai—represents a significant step towards restoring the water bodies of the Waikato Basin. Overall, these results reinforce the salience of working together to address the environmental impacts of previous and current activities within this catchment.

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Appendix 1. Document provided to modelling group on behalf of river iwi.

1863 Scenario for the Healthy Rivers Wai Ora Project (2015)

Poto Davies (Ngati Koroki Kahukara Trust)

He piko he taniwha he piko he taniwha

At every bend a chief

This whakataukī relates to the many chiefs and settlements located along the entire length of the Waikato River; however today it is a direct acknowledgement of the Waikato iwi. From the Ruapehu slopes to Te Pūaha o te Awa the many tribes utilised the healing properties of the wai and drew sustenance/kai for the people.

Each iwi/hapū would be associated with a particular site for fishing, food gathering and spiritual nourishment. The rivers and waterways provided access, transport, trade and identified boundary locations. Wetlands and swamps provided an abundance of resource for healing, kai, clothing, tools, and the preservation of taonga.

The availability of sand and gravels from the river beds and typically the plateaus, led to the innovative custom of modifying the soils (borrow pits) to create a fertile medium for crops such as kumara, taro, bottle gourd and tropical yam (uwhi) amongst others. It is known that fires were often purposely lit so that the ash could be mixed with the garden soils. Māori would cultivate an area then move with the seasonal harvest however, they would always return to their homelands.

In the Waipā region alone a comprehensive study (Gumbley, 2013) was commissioned to gather this information. In 1943, aerial photos and ground searches identified 2543 borrow pits; as of June 2013 there were approximately 855. I have personally witnessed the destruction and loss of at least 30 borrow pits in the last year. A current archaeology dig has revealed that 1 large borrow pit is often the result of many excavations over differing time periods[9].

From these sources we can assume that the rivers and waterways were places where Māori were more likely to live. The many paa sites that are still clearly visible from the Waikato River and highways attest to that.

Information taken from Pool (1991 & 2015) provides us with a 'guestimate' of Māori population;

1769:	90,000	p. 157
1840:	80,000	p. 157
1857/58:	61,500	p. 52

Māori were very aware of their responsibility to the whole environment. Food was grown and harvested in harmony with a lunar calendar, cleansing the body was always done downstream of drinking water collection and cultural activity sites. The ngāhere (bush), provided clothing, kai, shelter, resources for waka, tools, weapons etc. It was widespread and sprinkled with the many walking tracks of the people. Ablution areas were purposely established away from waterways.

In 1863 Tāwhiao lamented for the changes to his beloved homeland. His song of sorrow describes the abundance and richness of the whenua, the beautiful and pristine waters; this is a key driver of Te Ture Whaimana.

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