BEFORE COMMISSIONERS APPOINTED
BY THE WAIKATO REGIONAL COUNCIL

IN THE MATTER	of the Resource Management Act 1991
AND	
IN THE MATTER	of the First Schedule to the Act
AND	
IN THE MATTER	of Waikato Regional Plan Change 1- Waikato and Waipā River Catchments and Variation 1 to Plan Change 1
AND	
IN THE MATTER	of submissions under clause 6 First Schedule
BY	**BEEF + LAMD NEW ZEALAND LIMITED** **Submitter**

BRIEF OF EVDIENCE OF TIMOTHY JASON COX
15 February 2019

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BACKGROUND

1. My full name is Timothy Jason Cox.

2. I am a water resources engineer and scientist, specializing in water quality and hydrologic modelling.

3. I hold a Batchelor of Sciences degree in Civil and Environmental Engineering from Duke University (USA), a Master's degree in Water Resources Engineering from the University of Colorado (USA), a Master of Philosophy degree in Science and Technology from the University of Waikato, and a Doctor of Philosophy degree in Engineering Science from the University of Auckland.

4. My doctorate research focused on nitrogen fate and transport in small streams.

5. I have nearly 20 years of experience in water resources science and consulting, with a focus on numerical modelling of freshwater systems.

6. I am currently employed by Streamlined Environmental and the USA consulting firm CDM Smith.

7. Prior to working for Streamlined, I was employed by NIWA, where I also performed the bulk of my doctorate research.

8. I have developed and applied catchment, stream, and lake water quality models for systems throughout the world, and I have extensive experience in software development.

9. I have published and presented widely in the areas of water resources engineering, science, and freshwater systems.

10. I have read the Code of Conduct for Expert Witnesses in the Environment Court's 2014 Practice Note and agree to comply with it. I confirm that the opinions I have expressed represent my true and complete professional opinions. The matters addressed by my evidence are within my field of professional expertise. I have not omitted to consider material facts known to me that might alter or detract from the opinions expressed

SCOPE OF EVIDENCE

11. I have been requested by Beef + Lamb New Zealand to provide expert evidence on catchment modelling of landuse and water quality as it relates to the modelling underpinning the proposed Waikato Regional Plan Change 1 (WRPC1). My focus is on nutrients. I investigate the proposed approach to managing agricultural lands in the basin, as well as testing alternative approaches. My evidence is structured under the following headings:

    (a) An overview of the problem, including sources of nutrient in the basin, resulting water quality degradation, nutrient fate and transport, and potential mitigation strategies,

    (b) A description of the catchment nutrient modelling methods employed by the Collaborative Stakeholders Group (CSG) and Technical Leaders Group (TLG) as part of the Healthy Rivers Plan,

    (c) A description of the software that I used for my analysis,

    (d) A description of the baseline basin model construction and verification,

    (e) Presentation and analysis of predictive modelling scenarios focused on potential basin mitigation strategies and quantifying uncertainties in modelling to-date,

    (f) A discussion of model uncertainty,

    (g) Concluding statements and recommendations.

12. The evidence presented here is intended for hearing stream 1. I will be presenting follow-on evidence, focused on alternative management and allocation scenarios, in a separate document for hearing stream 2.

13. My over-arching goal in presenting this evidence is to advance the discussion and science with respect to understanding the source and fate of nutrients in the basin, investigating the potential for mitigation, and setting appropriate policy.

14. Overall, I commend the technical leaders of the Healthy Rivers study on the quality of their work and modelling, particularly given the complexity of the system and the constraints within which they were working. That said, I

have some concerns, and recommendations, related to the work and how it was applied, or not applied, to guide the policy recommendations for Plan Change 1. These are described below.

EXECUTIVE SUMMARY

15. Numerical modelling was used to support policy development and recommendations of the Collaborative Stakeholder Group (CSG) as part of the Healthy Rivers planning process. A catchment model was constructed by the technical team to quantify sources and relative contributions of nutrient load throughout the Waikato and Waipa River basins and to perform predictive simulations. The "baseline" model simulates current nutrient loads and transport in the basins. This catchment model was coupled with a separate economics optimisation model for basin mitigation predictive modelling, in support of the Healthy Rivers process.

16. Although the developed models appear to be useful decision support tools, and were developed with substantial resources and expertise, I have multiple concerns with how the models were parameterised and/or applied (or not applied). These are outlined below.

17. The models, and modelling process, are lacking in transparency. There is insufficient detail in the modelling reports for stakeholders to fully understand critical steps in the modelling process. More importantly, the models themselves, and the supporting datasets, have not been made available to the public. In my opinion, this does not follow best practice for such an important study.

18. Despite noted significant uncertainties in many of the key model parameters, the models are not supported by uncertainty or sensitivity analyses of any sort. Consequently, the robustness of the model calibration and predictive power is unknown. This impacts model credibility and acceptance among stakeholders.

19. With significant resources spent on developing these models, it seems they were underused. The models do not appear to have been directly used to support decision making by the CSG. They do not appear to have been used to inform policy decisions. Rather, the policy appears to have been used to inform the modelling. The models could be used, for example, to identify and develop cost-effective mitigation strategies and identify spatial

priorities for mitigation. They could also be used to clearly demonstrate relative source distributions of nutrient load at key instream locations. Lastly, the models could, and should, be used to set realistic, feasible, and spatially-variable water quality targets throughout the basin and to establish appropriate timeframes for achieving the targets.

20. The models appear to be using outdated landuse and export coefficient (emissions) information. This may be skewing results significantly. In particular, the contribution of dairy farming to current nutrient loads in the basin appears to be underestimated.

21. Much of the model parameterisation is based on a coarse calibration process, which has not been fully detailed. It does not appear that this process effectively isolated key model parameters (e.g. exports vs. attenuation). Nor was there any sort of verification exercise performed. If possible, given available data, the model calibration process should be strengthened to improve confidence in model parameters. This would likely require modelling at a smaller spatial scale, supported by site-specific data. Independent studies of export and attenuation could also be used to refine, and/or verify, model parameterisation.

22. I recommend that these issues be addressed by the Healthy Rivers technical team prior to finalising Plan Change 1 and, going forward, for future management of the basin.

23. To address some of the model application shortcomings described above, and to advance our understanding of the problem and of potential solutions, I developed a new model to simulate water quality in the basin. This model replicates the Healthy Rivers model to the extent possible, based on available information. I used this model to investigate alternative policy scenarios. I also used the model to analyse various baseline model input parameters and assumptions and to assess the impacts of these assumptions on model projections.

24. My modelling demonstrates and quantifies uncertainties associated with key model input parameters.

25. My modelling provides source load partitioning at the targeted river monitoring stations. In my opinion, this is one of the more useful and informative set of outputs that can be generated by a model of this type.

These outputs give an indication of the relative cause and contribution of various land uses to water quality impairment and should be used to inform effective and efficient policy.

26. My modelling results also highlight higher relative cost effectiveness associated with dairy land mitigation, compared to dry stock. In general, more extensive, and intensive, dairy farm mitigation is calculated in the model, compared to dry stock, to optimally achieve the long-term water quality targets. This general pattern of results is not surprising. The input unit mitigation costs in my model, based on published research, are generally lower for dairy compared to dry stock. In other words, a greater reduction in nitrogen loads is simulated in the model, for the same mitigation effort, for the higher leaching dairy farms compared to dry stock farms.

27. Lastly, results highlight the fact that the required level of mitigation effort to achieve the 80-year water quality goals is significant, given the stringent level these targets are set at, and particularly without a commensurate reduction in point source loads. Many parts of the catchment require full re-forestation (or mitigation down to background export levels). More specifically, the modelling identifies that upper basin long-term nitrogen targets may be overly constraining. Without significant point source load reductions in the upper basin, nearly 100% afforestation would be required of all pastoral farm lands to achieve the targets.

NUTRIENT IMPAIRMENT IN THE WAIKATO AND WAIPA RIVER BASINS

28. Excessive nutrient (nitrogen and phosphorus) runoff from catchment lands causes water quality impairment in receiving waters. Potential impairments include excessive plant and algal growth, colour and clarity degradation, and depressed dissolved oxygen levels.

29. It is well-established that nutrient impairment exists in the Waikato and Waipa Rivers and has, in the case of nitrogen, worsened over the past two decades (WRC, 2013). Nitrogen and phosphorus concentrations in the rivers exceed desired target thresholds, in some locations. Floating algae (phytoplankton) levels, and macrophyte growth, are problematic during certain times of the year and at certain locations in the basins.

30. Known sources of nutrient in the river basins, causing the imbalance in the rivers, include: runoff and sub-surface leaching from pastoral agriculture lands, runoff and sub-surface leaching from horticultural lands, point source industrial discharge, point source municipal sewerage (storm and sanitary) discharge, and residential septic tank leaching.

31. With respect to pastoral farming, fertilizer application, particularly when applied at rates in excess of plant requirements, typically represents the largest ultimate source of nutrient loading from farms. Atmospheric nitrogen fixation by grazed grasses and livestock feed inputs also contribute to the imbalance. Livestock activities contribute to the problem by mobilising the nutrients via grazing/feeding on organic-form nutrient and waste discharge of soluble reactive-form nutrient (often near, or directly to, waterways).

32. The intensification of pastoral dairy farming has exacerbated the problem over recent decades. The average national stocking rate for dairy cows increased by 18% from 2.44 cows ha^{-1} to 2.87 cows ha^{-1} over the twenty-year period: 1994–2014. With more cows on a single plot of land, greater fertilizer and feed inputs are required to sustain the herd. Mobilisation of nutrients is also enhanced. The result is higher exports (losses) of nutrient from land to waterway. Dairy nutrient losses, on a per hectare basis, are known to be typically higher than those associated with dry stock farming. This is primarily due to higher stocking, rates requiring greater fertilizer and feed inputs, for dairy compared to dry stock.

33. In addition to farm characteristics, other factors that play a role in determining the per unit-area nutrient loss from pastoral farms include: soil type, slope, climate, and sub-surface hydrology.

34. As rain falls on fertilized paddocks, as well as urine patches and manure, nitrogen and phosphorus mass loads are mobilised and transported downgradient via surface runoff and/or infiltration and sub-surface transport. This type of transport and loading to waterways is termed “diffuse” (as opposed to end-of-pipe “point” discharge of municipal and industrial load). Diffuse pathways from pasture to river can be tortuous, resulting in travel/lag times of varying size and, potentially, attenuation of nutrient load. Sources of diffuse-path attenuation include plant uptake, adsorption to soils and substrate, and denitrification. For my purposes here, I use the terms “export” and “discharge” to differentiate between pre-attenuation losses

from farm to surface or sub-surface pathways vs. post-attenuation loading to receiving waters, respectively.

35. As nutrients are transported downstream in streams and rivers, further attenuation can occur via instream processes such as settling (particulate form), uptake by plant and attached algae, adsorption to bed sediments, and denitrification. This type of attenuation is applicable to both diffuse and point source loads. Attenuation may be increased, in some cases, by water impoundments (lakes and reservoirs) through enhanced settling, biological activity, and residence time.

36. Discussions of catchment nutrient enrichment mitigation options usually start with source control. In general, it is easier to reduce loadings at the source than to remove nutrient mass from primary waterways. Farm-level mitigation options are discussed in the evidence of Dr Chrystal and Mr Parkes.

HEALTHY RIVERS CATCHMENT MODELLING

37. Numerical modelling was used to support policy development and recommendations of the CSG as part of the Healthy Rivers planning process. A catchment model was constructed by the technical team to quantify sources and relative contributions of nutrient load throughout the Waikato and Waipa River basins and to perform predictive simulations. The "baseline" model simulates current nutrient loads and transport in the basins.

38. The model is spreadsheet-based, developed by NIWA scientists for the Healthy Rivers study. It is not publicly available and was not made available for my work. Neither were the specific model inputs directly available. However, a modelling report (Semadeni-Davies et al., 2015) is publicly available, and it describes the basic function, inputs, and outputs of the model.

39. The model simulates the generation and transport of diffuse and point source nutrient loads (total nitrogen and total phosphorus) through the catchment. The model domain includes the entire Waikato River basin: from the outlet of Lake Taupo to the mouth at Port Waikato, and including the full Waipa River basin. Model calculations are performed on an annual average timescale.

40. The model domain is discretised into 74 sub-catchments. Each sub-catchment is further divided, as appropriate, into separate aggregate diffuse source objects based on the following land use categories: dairy farming, dairy support, sheep and beef farming, horticulture, forest, residential, and "miscellaneous" (everything else). Not every sub-catchment included all seven land use categories. Horticulture, for example, is only included in a small subset of the sub-catchments.

41. The model generates diffuse nutrient load exports as a function of user-prescribed land areas (ha) and "export coefficients" (kg ha^{-1} yr^{-1}) for each catchment and land use combination. The export coefficients used in the model were derived from the OVERSEER model (Version 5) and were provided as average annual nutrient loads per unit area, for a given catchment and landuse category. Land areas were based on 2012 data (described further below).

42. Diffuse export loads are attenuated in the model with prescribed attenuation coefficients (unitless). This attenuation represents potential mass losses occurring from the point of export, or leaching, to the point of discharge to the receiving river. Nitrogen attenuation coefficients were set in the model based on a combination of expert panel opinion and model "calibration" adjustments. For the latter, initial attenuation coefficient estimates were adjusted to achieve a better fit of modelled vs. observed downstream nutrient concentrations, on an annual average basis. Phosphorus attenuation coefficients were derived from separate simulations of the NIWA CLUES model.

43. The model authors recognize a limitation in their model calibration process, whereby estimates of "current" export loads are paired with recent observed instream concentration data. The complication here is that a significant portion of the exported nitrogen load travels to the river via subsurface pathways and experiences multi-year (even multi-decade) travel times. In other words, there can be large lags associated with the timing of when nitrogen loads exported at point A are realized at downstream location B. Since exports have been generally increasing with time in the basin, the authors state that the calibrated nitrogen attenuation coefficients (termed "apparent attenuation") likely overestimate catchment attenuation. They, therefore, present a second set of attenuation coefficients ("ultimate

attenuation") that represent their best guess at true attenuation in the basin. To my knowledge, only "apparent" nitrogen attenuation coefficients are used in subsequent model predictive simulations. This limitation of the model does raise concerns about model over-simplification and uncertainties associated with basin attenuation. I explore this further in subsequent sections of my evidence.

44. In addition to diffuse sources of nitrogen and phosphorus, a total of twenty (20) point sources of nutrient load were included in the model. Point source loads are not subject to attenuation in the model.

45. Multiple reservoirs were also included in the model, representing sub-catchment surface storage. These reservoirs provide for additional attenuation of nutrient loads in the model at specified locations. This form of attenuation is the equivalent of instream attenuation and impacts the total instream load (point + diffuse) at the prescribed reservoir location. No other instream attenuation is included in the model.

46. Ultimately, the model was used to calculate current annual average nutrient loads and concentrations at multiple locations throughout the river basins, including a total of nineteen (19) existing water quality monitoring stations.

47. Source load partitioning, either by spatial unit or by source/land use category, at downstream water quality stations is not provided, in any form, in the modelling report. This would seem to be one of the more informative, and useful, outputs that can be generated from this type of modelling, as it would give an indication of the relative cause and contribution of various land uses for to water quality impairment. It is unclear why such information is not provided in the model documentation.

48. It is also unclear how the model was used, if at all, to inform the policy recommendations of Plan Change 1. More specifically, the model does not appear to have been used to set either the long or short-term water quality targets. These targets vary spatially, and there does not appear to be any quantitative, model-based, justification for such spatial variability.

49. The model also does not appear to have been used to develop, or demonstrate, a realistic mitigation pathway to achieving these targets. Indeed, in my opinion, the plan change, in general, lacks any real "teeth" with respect to achieving stated water quality goals. There is nothing in the

plan that ensures that the goals will be achieved within the stated timeframes. The developed catchment model could have been used in this manner to strengthen the plan change.

50. This model represents a coarse, high level, and simplified approach to catchment modelling. I don't question the decision to use a simplified tool for these purposes. However, the limitations of the model should be fully understood when applied for decision making. For example, key to the model's predictive power is the assumed set of attenuation coefficients. Nitrogen attenuation coefficients vary widely in the model across sub-catchments, ranging from 0.05 to 0.5. Nitrogen processes in nature can also vary widely and are difficult to quantify. I discuss these processes briefly in points below. Although site specific data were used, at a coarse level, to parameterise attenuation in the model, flaws in this calibration process, due to time lags, have been noted. Adding to the calibration uncertainty are questions about the assumed land use profile (based on 2012 data) and assumed farm export coefficient values. These are explored in more detail in subsequent sections. It is my opinion that further refinement in this area of the modelling is required if the model is to be used to support mitigation decision making in the future. This refinement should be guided by site-specific measured data and a modelling platform capable of incorporating time-of-travel lags and dynamic basin exports.

51. In addition to the catchment modelling described above, the NIWA model was incorporated into a separate economic optimisation model for a series of basin predictive simulations (Doole et al. 2015[1,2]). The economics model simulations attempt to generally characterize optimal basin mitigation actions to achieve various levels water quality improvement. Details on the manner in which the NIWA model is incorporated into these simulations are not provided. Also unreported are the final water quality conditions in the basin simulated by the economics model for various scenarios, although it is known that long term water quality targets were achieved at specific locations in the simulations. Economics model results focus on overall basin costs. Spatial difference in modelled mitigation requirements are not clearly presented. It is unclear whether spatial differences in soils, runoff potential, or nutrient attenuation have been included in the optimisation algorithm. It is also not clear whether apparent or ultimate nitrogen attenuation coefficients were used in the predictive modelling. I presume

that apparent attenuation was used, although it could be argued that ultimate attenuation would be more appropriate for the long-term simulations. I have concerns about the lack of detailed documentation of the economics modelling tool used for this work and the lack of model transparency and availability.

52. In conclusion, I have no concerns with the overall modelling approach, the software used, the spatial resolution of the model, or even the specific assumptions made. Regarding the latter, I understand the need, as a modeler, to make assumptions, based on the best available information, in developing a useful (if not entirely accurate) model. The concerns that I do have reside in the following areas:

- Demonstration of model robustness and quantification of uncertainty. There does not appear to have been any significant work performed to demonstrate the robustness of the model calibration or of the predictive simulations. For example, significant uncertainty exists in the parameterisation of land use areas, export coefficients, and attenuation coefficients, particularly given noted flaws in the model calibration process associated with nitrogen travel time lags. As noted above, I don't necessarily disagree with the assumed parameter set. However, in my opinion, the modelers did not do an adequate job investigating parameter uncertainty or the impacts of this uncertainty on final simulation results and decision-making. Uncertainty and sensitivity analyses should be used to improve model confidence and demonstrate model robustness to stakeholders.

- Model transparency. Model transparency is lacking. There is insufficient detail in the modelling reports for stakeholders to fully understand such critical steps as the model calibration process or how the catchment water quality model was integrated into the economics model predictive simulations. Further, both models should be made available to the public for review and to gain better acceptance in the wider community. This would seem to be best practice for a study of this importance.

- Further to the two points above, in the recent words of Simon Upton, Parliamentary Commissioner for the Environment (PCE, 2018), "*Understanding uncertainty, and being transparent about incomplete knowledge, is essential if policies or regulations based on models are to be credibly defended*.", and, "*For models used in environmental regulatory decision-making, high standards of transparency are important for a range of reasons. Most fundamentally, those affected by regulations have a right to understand the basis on which the regulations were made.*" I don't believe that the Healthy Rivers modelling team did an adequate job on either of these points.

- Model application. Both the catchment water quality model and the economics optimisation model appear to be solid decision support tools. However, they do not appear to have been used to support any decisions made by the Collaborative Stakeholder Group (CSG). They were not used to inform policy decisions. Rather, the policy appears to have been used to inform the modelling. The models appear to have been utilised to simply demonstrate the potential ramifications of the proposed policy once it was developed, rather than to actually test and refine potential policy options in supporting any decisions made by the Collaborative Stakeholder Group (CSG). With significant resources spent on developing these models, it seems they were underused. The models could be used, for example, to identify and develop cost-effective mitigation strategies and identify spatial priorities for mitigation. They could also be used to clearly demonstrate relative source distributions of nutrient load at key instream locations.

- Lastly, the models could, and should, be used to set realistic and feasible water quality targets throughout the basin and to establish appropriate timeframes for achieving the targets. Note, however, that these recommendations are conditioned on addressing the uncertainty and transparency concerns stated above, at which time the model(s) can be better considered "fit for purpose".

53. The work presented below attempts to address these concerns, in the hope that this new information be used to support final policy or to encourage follow-up work by the NIWA team.

54. This model will hereafter be referred to in this document as the "NIWA model", to differentiate it from my model, described next.

CASM MODELLING SOFTWARE

55. To address some of the model application shortcomings described above, and to advance our understanding of the problem and of potential solutions, I developed a new model to simulate water quality in the basin. I used this model to investigate alternative policy scenarios. I also used the model to analyse various baseline model input parameters and assumptions and to assess the impacts of these assumptions on model projections.

56. For these purposes, I used my own software: the Contaminant Allocation Simulation Model (CASM). CASM is generalised catchment modelling software that was developed prior to this study. I am the principal developer of CASM. It was necessary to build a new tool for these investigations because the Healthy Rivers models were not made available. If the Healthy Rivers models had been made available, I would have gladly used those for this work.

57. CASM calculates the generation of a range of user-defined pollutants at a catchment scale and the fate and transport of the pollutants through the catchment's dendritic stream network. Pollutant sources are represented in the model as individual nodes, discharging to specific streams of any order. Pollutant sources can be either diffuse (e.g. farms) or point (e.g. municipal discharges), although both are represented as single node (point) discharges in the model with differences in implied pathways (attenuation vs. no attenuation). Sources can be aggregated for lower resolution models, or explicitly represented as individual property nodes for higher resolution models.

58. As with the NIWA model, diffuse source pollution calculations in CASM follow the widely used "export coefficient" approach, with prescribed areal average mass loading rates linked to land use categories. Point source loading rates are simply user defined for each constructed point source node. Both diffuse and point source loading parameters can be prescribed as seasonally variable in CASM, but this feature of the software was not used here.

59. Three forms of pollutant attenuation are available in the software: diffuse pathway, instream, and reservoir. The first is applicable for diffuse sources only and represents potential mass losses occurring from the point of export, or leaching, to the point of discharge to the receiving stream. The second captures attenuation that may occur during downstream transport within the stream channel (e.g. due to settling, uptake, or transformation). The third provides for additional enhanced attenuation that may occur in intercepting reservoirs as a function of residence time. Diffuse pathway attenuation in CASM is analogous to, and in the same format as, the attenuation coefficients used in the NIWA model.

60. CASM outputs are generated for any number of user-defined water quality “stations”, at any instream location. Water quality station output include total pollutant loads (kg/month), concentration (mg/L), and source tracking (a breakdown of contributing upstream sources). Instream target concentrations can also be prescribed at these stations for reference, or to trigger mitigation optimization calculations (described below).

61. As a base simulation mode, CASM provides for a deterministic simulation of catchment contaminant fate and transport. Deterministic simulations involve the tracking of contaminant mass from point of export (diffuse) or discharge (point) through a dendritic stream network to a series of downstream monitoring stations. The model calculates source loadings, combines loads at appropriate locations, and attenuates the loads based on user-defined parameters, providing for calculated contaminant loads (and/or concentrations) at any location in the modelled catchment. This mode of simulation provides the same functionality as the NIWA model.

62. CASM can also be operated in an optimisation simulation mode. Optimisation simulations perform the same fate and transport calculations as described above but also calculate an optimal mitigation strategy to achieve prescribed downstream water quality concentration targets. Optimality is determined in the model based on a ranked order list of catchment mitigation actions, specific to associated node locations. The ranked order list is generated internally from user-defined mitigation cost tables associated with each source node. The model optimisation algorithm also incorporates attenuation (and relative upstream position) considerations. Mitigation optimisation is calculated for each water quality

station with a prescribed target. Model calculations proceed from upstream to downstream, resulting in a catchment-wide optimal mitigation strategy that achieves, to the extent possible, water quality goals for all specified locations.

63. Further technical details on the CASM algorithms and calculations are provided in Appendix A of this document.

BASELINE MODEL CONSTRUCTION, VERIFICATION, AND SIMULATION OF CURRENT CONDITIONS

64. A model of the Waikato River catchment was developed using the CASM software, described above. The baseline model aimed to replicate the catchment model developed by NIWA for the Healthy Rivers study (Semadeni-Davies et al., 2015). To the extent possible, the model construct precisely followed that of the NIWA model, including the same spatial resolution (74 sub-catchments), land use classifications, reservoirs, and point sources. Minor adjustments were made to a small number of original nutrient export and attenuation parameters to achieve an acceptable agreement in final model output. This likely reflects the lack of clarity in final NIWA model parameters rather than any significant differences in model construct.

65. Further details on the construction and verification of the CASM baseline model are provided in Appendix B.

66. The constructed model was used to simulate and summarise baseline (roughly current) conditions.

67. Drainage area summaries for select locations, in the form of relative proportional break-down, are provided in Figure 1.

68. Source tracking in the model allows for relative summaries of total mass contributions from various land use categories at specified locations. Such summaries, for the baseline model, are shown in Figure 2 andFigure 3, for select locations.

69. Results show that diffuse losses from dairy land represent the largest contributor to instream TN load at the downstream-most water quality stations in the Waikato and Waipa basins (Port Waikato and Waingaro Road Bridge, respectively). At both locations, combined dairy and dairy support

activities are responsible for the majority of the modelled instream TN load at these stations (55% and 66%, respectively). This is despite that dairy land represents only 29% and 34% of the total basin drainage areas, respectively.

70. Dry stock farms are the second largest individual contributor of nitrogen load in the two river basins but constitute the largest portions of drainage area in the two basins (35 and 37%, respectively).

71. Point sources represent the largest category of contributors to the total nitrogen load at uppermost Waikato basin sites: Ohaaki and Ohakuri,

72. Phosphorus loads are more evenly apportioned between dairy and dry stock, with dry stock identified as the largest contributor to total Waikato (Port Waikato) and Waipa (Waingaro Road) basin loads. Dry stock is also identified as the largest contributor of phosphorus load at the upstream Ohaaki site.

73. Modelled baseline nitrogen concentrations, at each water quality station with a relevant water quality target, are summarised in Table 1: Baseline Model vs. Reference Total Nitrogen Concentrations. For reference, long-term water quality targets and freshwater ecology maximum contaminant levels (MCLs) are also provided, as discussed in the Evidence of Dr Mueller.

74. Modelled average annual baseline nitrogen loads, at each station, are summarised in Table 2: Baseline Model vs. Reference Total Nitrogen Loads. For reference, the average annual loads associated with long-term water quality targets and freshwater ecology maximum contaminant levels (MCLs) are also provided. Model average annual flow rates, at each water quality station, were used to calculate reference loads associated with the water quality targets and MCLs (load = concentration x flow).

Table 1: Baseline Model vs. Reference Total Nitrogen Concentrations

WQ Station Name	**Reach**	**Location (km)**	**Modeled TN (mg/L)**	**80-Year WQ Target (mg/L)**	**MCL TN (mg/L)**
Waikato at Ohaaki	Mainstem	39	0.13	0.134	0.13 – 0.44
Waikato at Ohakuri	Mainstem	78	0.21	0.16	0.13 – 0.44
Waikato at Whakamaru	Mainstem	107	0.27	0.16	0.13 – 0.44
Waikato at Waipapa	Mainstem	130	0.33	0.16	0.13 – 0.44
Waikato at Narrows	Mainstem	208	0.40	0.35	0.44 – 0.7
Waikato at Horotiu Bridge	Mainstem	232	0.43	0.35	0.44 – 0.7
Waikato at Huntly-Tainui Br	Mainstem	255	0.58	0.35	1.6
Waikato at Mercer Bridge	Mainstem	294	0.65	0.35	1.6
Waikato at Tuakau Br	Mainstem	305	0.58	0.35	1.6

Table 2: Baseline Model vs. Reference Total Nitrogen Loads

WQ Station Name	**Reach**	**Location (km)**	**Modeled TN (tpy)**	**80-Year WQ Target (tpy)**	**MCL TN (tpy)**
Waikato at Ohaaki	Mainstem	39	675	689	668 - 2262
Waikato at Ohakuri	Mainstem	78	1365	1055	857 - 2900
Waikato at Whakamaru	Mainstem	107	1792	1080	877 - 2969
Waikato at Waipapa	Mainstem	130	2472	1201	976 - 3302

WQ Station Name	Reach	Location (km)	Modeled TN (tpy)	80-Year WQ Target (tpy)	MCL TN (tpy)
Waikato at Narrows	Mainstem	208	3996	3477	4371 - 6954
Waikato at Horotiu Bridge	Mainstem	232	4504	3642	4579 - 7285
Waikato at Huntly-Tainui Br	Mainstem	255	9792	5960	27247
Waikato at Mercer Bridge	Mainstem	294	11419	6148	28105
Waikato at Tuakau Br	Mainstem	305	11586	6943	31738

Figure 1: Baseline Model Land Use Area Summaries: Relative Proportions

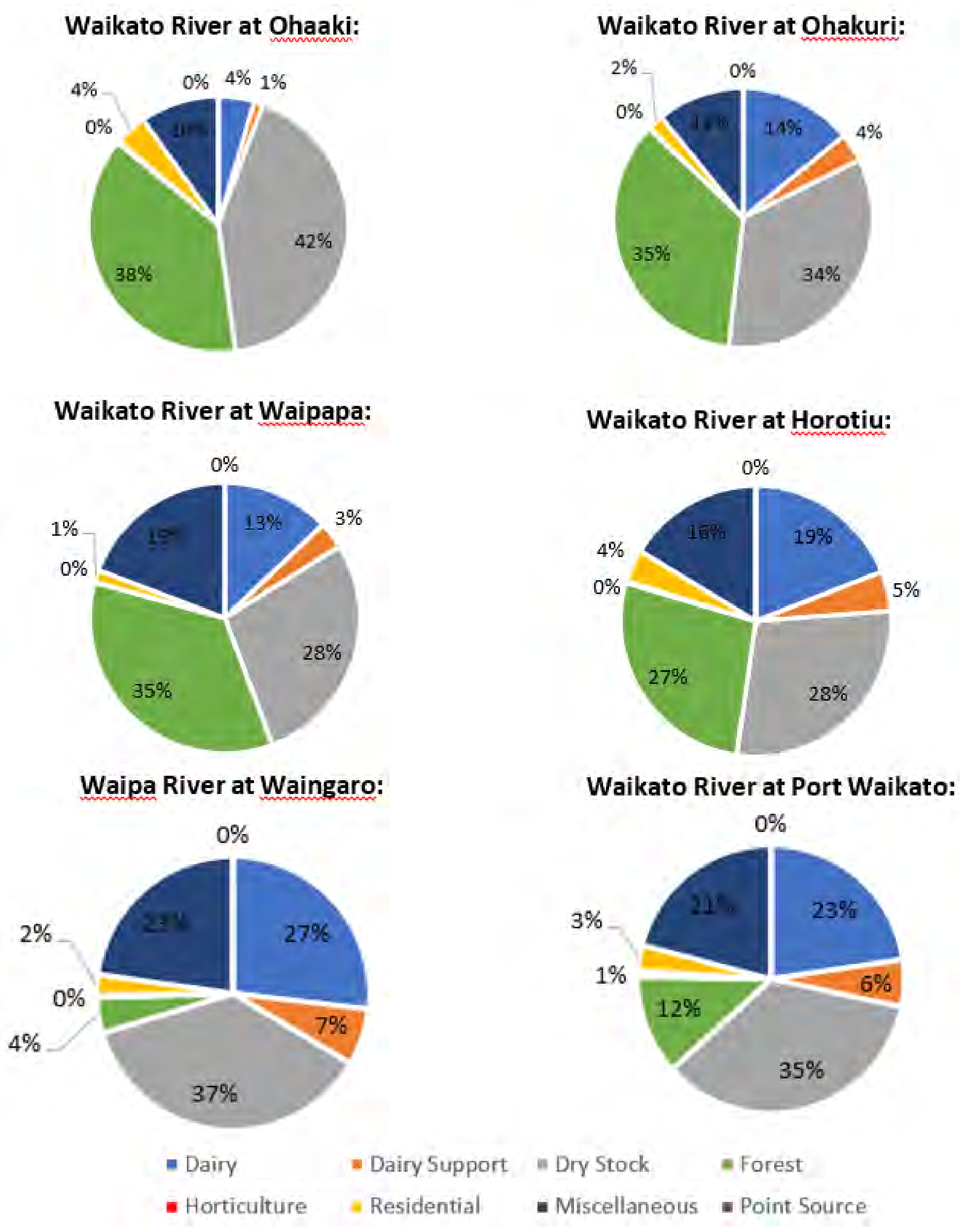
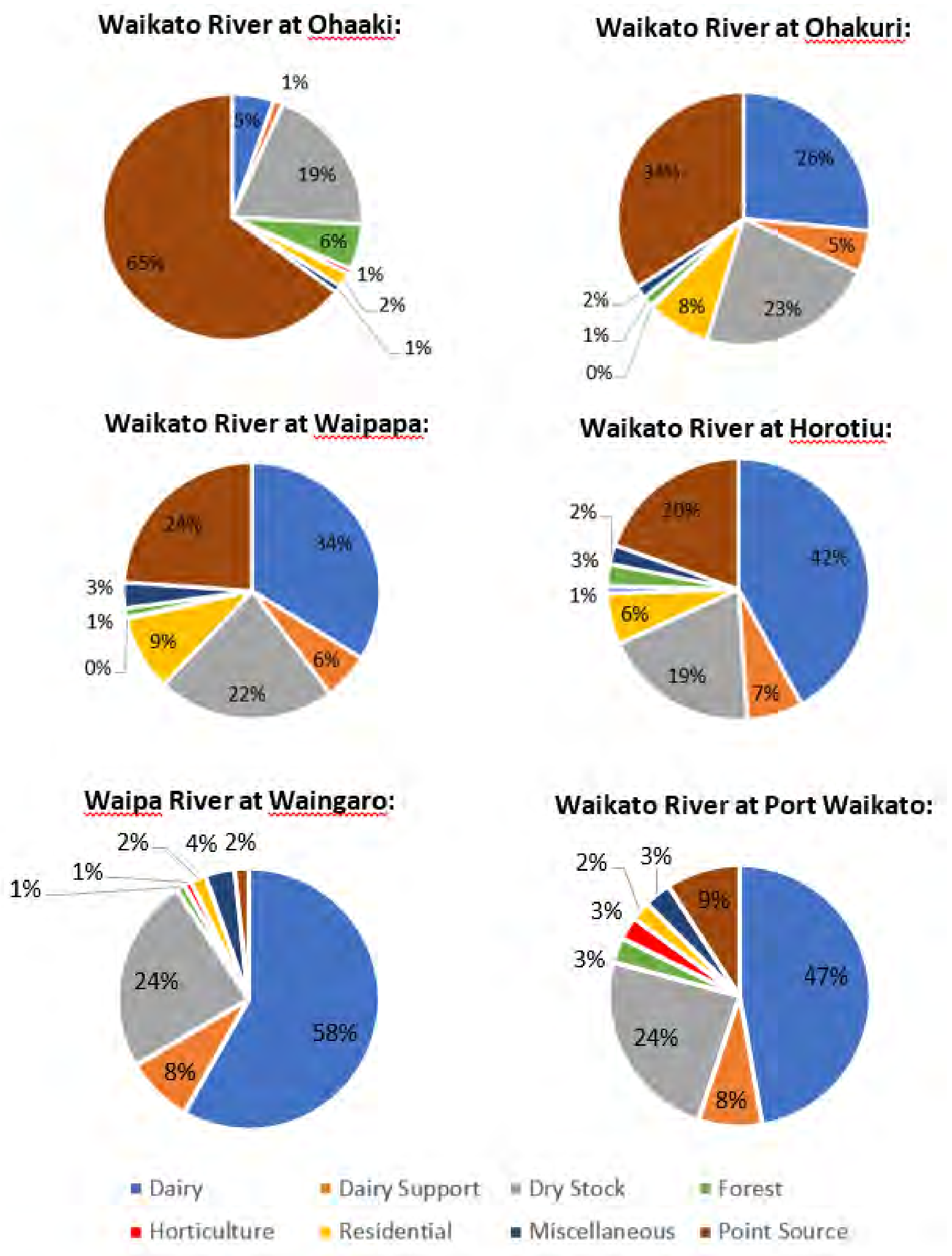


Figure 2: Baseline Model Mass Balance Summaries, TN: Relative Proportions



Waikato River at Ohaaki:

Waikato River at Ohakuri:

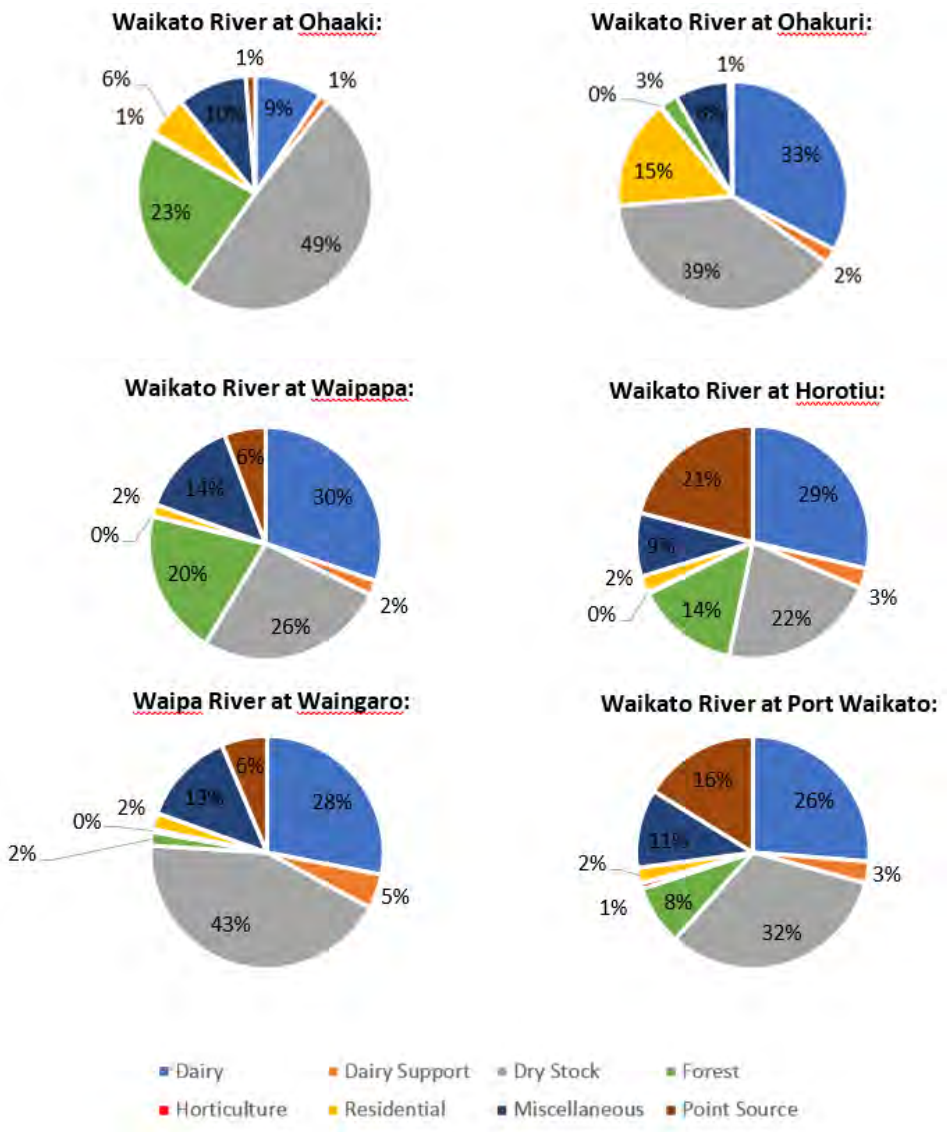
Waikato River at Waipapa:

Waikato River at Horotiu:

Waipa River at Waingaro:

Waikato River at Port Waikato:

Figure 3: Baseline Model Mass Balance Summaries, TP: Relative Proportions



EQUAL ALLOCATION SIMULATION

75. Using the constructed model described above, I performed a series of predictive simulations to investigate the implications for land uses, of meeting the 10 year and 80-year targets in PC1, in accordance with the assumptions of the NIWA model. These simulations are intended to supplement the predictive simulations already performed by the Healthy Rivers technical team and to gain greater insight into the feasibility and effectiveness of various alternative mitigation strategies to better inform final policy setting. These simulations will largely be presented as part of hearing stream 2. However, an “equal allocation” scenario is also presented here

to provide an indication of the magnitude of change in land use that would be required to achieve the currently proposed 80-year water quality targets.

76. In this set of simulations, I investigated the ability of the catchment to achieve downstream nitrogen targets under an assumption of "equal allocation" of diffuse-source nitrogen discharges.

77. For this scenario, I allocated all upstream properties the same nitrogen export allowance (kg ha^{-1} yr^{-1}), regardless of current land use (including forestry). In the first instance, I set downstream nitrogen attribute targets (mg l^{-1}) in the model, for each specified monitoring location, equal to those values published in Plan Change 1 (WRC, 2016) and corresponding to the "long-term" (80-year) planning horizon. All point sources in the model were held steady, at current discharge levels, for these simulations. I used the model to determine the uniform export coefficient value, for all upstream properties, required to achieve downstream attribute targets. As a follow-up (point 6.6), I performed the same type of simulations for water quality targets roughly equal to current median concentrations (maintaining current conditions).

78. Plan Change 1 presents long-term 80-year median nitrogen concentration targets for multiple locations along the Waikato River mainstem. In addition to the long-term targets, short-term (10 year) interim median concentration targets are also presented. These values represent 10% of the total reduction needed to achieve long-term targets. Using these short-term targets, I deduced current median concentrations for each location, which were then truth-checked against published data, using the following equation:

$$X_1 - X_2 = 0.1 * (X_1 - X_3),$$

79. where X_1 = current median concentration, X_2 = short-term median concentration target, and X_3 = long-term median concentration target. In this equation, both X_2 and X_3 are known (published), and X_1 is solved for using simple algebraic manipulations. Additionally, to translate load predictions into concentrations in the model, river flow rates must be assumed. Using the calculated current median concentrations, combined with modelled current total instream nitrogen loads at each location, I calculated representative flow rates (m^3 s^{-1}) with the following equation:

$$Q_1 = \frac{L_1}{X_1}$$

80. where Q_1 = implied current flow rate and L_1 = modelled current total annual instream load at the location of interest. This calculated flow rate simply serves as a consistent reference value to be used for predictive modelling of river concentrations, and (in theory) roughly corresponds to the median flow rate at each location. The flow rates at each targeted location were assumed steady for this exercise (i.e. future reference flow rate = current reference flow rate).

81. With flow rates set as steady values in the model, I followed an iterative approach to determine the equal allocation export requirements. The process was performed for each of the downstream target locations. I set upstream export coefficients to a uniform initial value, across all sub-catchments and land use types. I then adjusted the export coefficients, uniformly, within a series of model runs until the downstream target was achieved.

82. In addition to simulating the achievement of long-term targets, I also used the model to quantify an equal allocation distribution associated with maintaining current conditions. The process followed the same procedure as described above, but current median nitrogen concentrations were substituted for the long-term targets. The results demonstrate how nutrient loads might be equally allocated across the catchment to maintain current water quality conditions. These results also provide a useful baseline reference for assessing the implications of the long-term simulation results, with respect to the required changes in catchment exports.

83. Results of this exercise are summarised in Table 1: Baseline Model vs. Reference Total Nitrogen Concentrations. Results show that equal allocation export requirements, to achieve long-term targets, vary widely across downstream monitoring locations. This variability in outcome is due to the combined variability in the following input parameters: prescribed target concentrations (higher at downstream locations), drainage areas, upstream point sources, assumed flow rates, and sub-catchment attenuation coefficients. For example, the Whakamaru and Waipapa sites are shown to be the most stringent, with respect to required changes in upstream exports. This appears to be due to the lower target concentrations

(0.16 mg/L) combined with significant upstream drainage area and relatively high (per unit drainage area) upstream point source loading.

84. Comparison to the current condition equal allocation scenario indicates that diffuse exports, on average, require net reductions of between 15 to 70%, overall, to achieve 80year long-term targets. This assumes point source discharges remain unchanged in the future. Comparison to land use-specific baseline current exports, indicate that target long-term export coefficients, under an equal allocation scenario, are generally lower than assumed current dry stock values and significantly lower than assumed dairy export values. For one location (Waipapa), the target equal allocation export coefficient is approximately equal to the assumed value for forested lands, implying that full upstream reforestation would be required to achieve the 80-year water quality targets. One of the constraining factors for this site is the presence of relatively high upstream point source loads, including the load from Kinleith Pulp Mill, just upstream of the site.

Table 3: Equal Allocation Scenario Modelling Results

Waikato River Station	**Upstream Drainage Area (ha)**	**Assumed Flow (cms)**	**Current Median Conc. (mg/L)**	**Target Median Conc. (mg/L)**	**Current Instream Load (tpy)**	**Target Instream Load (tpy)**	**Point Source Load (tpy)**	**Target Equal Allocation Export Coeff. (kg-N/ha/yr)**	**Current Condition Equal Allocation Export Coeff. (kg-N/ha/yr)**
Ohakuri	160,477	209	0.21	0.16	1391	1055	481	8	12
Whakamaru	241,422	214	0.27	0.16	1826	1080	481	5.5	12
Waipapa	333,000	238	0.33	0.16	2519	1201	626	3.5	11.5
Narrows	465,871	315	0.4	0.35	4073	3477	729	11.5	13.5
Horotiu	497,368	330	0.43	0.35	4590	3642	929	10.5	14
Huntly	876,303	540	0.58	0.35	9980	5960	1,093	8.5	15
Mercer	1,042,981	557	0.65	0.35	11,638	6148	1,110	7	14
Tuakau	1,067,000	629	0.58	0.35	11,808	6943	1,110	7.5	14

SIMULATION OF PRACTICAL AND OPTIMAL MITIGATION

85. I used the CASM software's optimisation routine to investigate cost-effective mitigation strategies and the practicality of achieving stated Plan Change 1 long-term nitrogen water quality goals.

86. These simulations share similarities with those performed by Doole et al. (2015a and 2015b). However, my focus is on identifying cost-effective mitigation strategies to achieve stated water quality goals, rather than trying to quantify actual basin mitigation costs and profit losses. I base my optimisation on independently constructed mitigation cost tables and baseline model variability in catchment physical characteristics and attenuation rates. I present a simplified, and (arguably) more transparent, alternative to the optimisation work performed in support of the Healthy Rivers study.

87. I used a combination of literature and professional judgement to construct mitigation cost tables for pastoral farming and each of the model sub-catchments based on a small number of selected mitigation option categories. The focus of this exercise was on assigning relative costs to the mitigation categories, also accounting for soil type and land use capability. In other words, actual dollar values associated with mitigation strategies were not important to this analysis. Rather, the relative differences in costs were used to assign mitigation cost rankings used for the identification of optimal strategies. All cost rankings were based on relative unit costs of mitigation ($ kg-N^{-1}): dollar cost per kilogram of nitrogen removed. By this metric, a mitigation action that reduces a greater amount of nitrogen export for one land use category, compared to another, is considered the more cost-effective option.

88. I included two categories of leaching potential based on sub-catchment soils and topography in the mitigation cost tables, generally labelled as "well-drained" or "poorly drained". Poorly drained soils have been presented in the literature as having higher relative unit mitigation costs, compared to well-drained soils, for the mitigation options included here (McKergow et al., 2007). In other words, edge-of-field mitigation is less effective for poorly drained soils. I used land use capability (LUC) designations as a surrogate for detailed soils and topography information. I considered those sub-catchments with a LUC designation of < 4 as "well-drained", while I

considered those $\geq$ 4 as “poorly drained”. Each sub-catchment received a single lumped designation of either “well drained” or “poorly drained” based on the area-weighted average LUC number.

89. I included the following mitigation options in my analysis: stock exclusion from streams (i.e. riparian fencing), riparian planting (or “buffer”), constructed wetlands, Tier 1 stock reductions, Tier 2 stock reductions. Tier 1 stock reductions represent reductions in effective stocking rates required to achieve an approximately 50% reduction in nitrogen exports. For this initial level of reductions, export and stocking rate are assumed to vary approximately linearly, with a 50% export reduction corresponding to an approximately 50% reduction in effective stocking rate, for both dry stock and dairy. Tier 2 stock reductions represent further reductions in stocking rates and corresponding nitrogen exports, down to background (re-forested) levels (non-linear).

90. A summary of the simulated mitigation options, and associated relative cost rankings, is presented in Table 4: Mitigation Relative Costs for Optimisation Simulation. Export reduction percentages were applied to the modelled export coefficient in excess of an assumed background level of 4 kg-N ha^{-1} yr^{-1}, which is the modelled baseline coefficient for forested lands. Treatment sequencing was incorporated into the net export reduction calculation in consideration of the direction of flow (upstream to downstream).

91. Note that I did not include the conversion of land use between farm types (e.g. dairy to dry stock) in the list of mitigation options included here. The list of mitigation options used here is intended to be a useful representative sub-set of options, rather than a comprehensive list. Consideration of mitigation approaches are provided in the evidence of Mr Parkes and Dr Chrystal, and Mr Kessels.

92. I also do not account for farms that already have included mitigation options (e.g. stock exclusion) in place. I assume that the farm lands within each sub-catchment are capable of the full extent of the modelled mitigation range.

93. The scenario modelling presented here is intended to be a contribution to the discussion, provide insight on general mitigation strategy, and serve as

an example of the type of work that, I believe, needs to guide basin mitigation programmes and limit-setting.

94. It may be useful to consider an example farm to clarify the interpretation of these inputs and their development. For example, a dairy farm in a well-drained sub-catchment has a top-ranked mitigation option (least expensive) of stream stock exclusion. This has the potential to reduce the farm export coefficient from approximately 23 kg-N ha^{-1} yr^{-1} (typical baseline) to 22 kg-N ha^{-1} yr^{-1}. The second-ranked mitigation option for that farm is riparian planting. According to the literature, this action has the potential to reduce nitrogen exports by 20%. The export coefficient associated with the combination of these two actions is therefore calculated as: 22 - 0.2 * (23 – 4) = 18 kg-N ha^{-1} yr^{-1}. Note that the 20% reduction is applied to the baseline export coefficient (in excess of background), rather than the post-stock exclusion coefficient, in recognition of the fact that riparian planting is assumed to be upgradient of stream fencing. This may not always be the case, but it is the assumed configuration for this exercise. The third-ranked option for this example farm is a constructed wetland. According to the literature, this action has the potential to reduce nitrogen exports by 60%. The export coefficient associated with the combination of all three mitigation options is therefore calculated as: 18 – 0.6 * (18 – 4) = 9.6 kg-N ha^{-1} yr^{-1}.

95. I simulated three subsets of scenarios with this general construct. The first included only pastoral farming (dairy and dry stock) mitigation, with optimisation calculated based on the costs described above. The second also includes a hypothetical lowest-cost point source mitigation option that results in a 50% decrease in all point source loads. The third simulation involved setting all diffuse source mitigation options to an equal cost, with no point source options, and calculating an optimal strategy based only on positioning in the catchment and effective attenuation coefficients. In other words, this last simulation was used to identify the most effective mitigation targets in terms of spatial locations, irrespective of actual mitigation costs.

96. For all simulations, I used the Plan Change 1 long-term nitrogen concentration targets to constrain the optimisation analysis, with the objective function equating to the minimisation of catchment costs.

97. As done for previous predictive simulations, I set flow rates at water quality stations to the median values implied by the original Healthy Rivers baseline model parameterisation (see Equal Allocation Scenario).

98. Simulation results were mapped by sub-catchment with respect to modelled levels of mitigation required to optimally achieve water quality targets (Figure 4 throughFigure 6). Colour bins used in the maps were set based on associated mitigation levels and actions to provide for an accurate comparison of mitigation requirements by farm type. The size of the coloured areas within each sub-catchment depicts the relative portion of the sub-catchment area that requires the given mitigation. Results provide insight on cost-effective catchment mitigation strategies and the breadth and depth of mitigation required to achieve goals.

99. Cost optimisation simulation results (Figure 10) highlight multiple potential guidelines for achieving prescribed water quality targets, throughout the catchment, in a cost-effective manner. Firstly, modelling shows that the upper catchment will require the most intensive mitigation, spatially, to achieve the nitrogen concentration targets at all stations. This result appears to be primarily driven by the Waikato at Waipapa station, which is a significant constraining point in the model. The combination of a high baseline load and concentration (0.33 mg l^{-1}) with an ambitious target concentration (0.16 mg l^{-1}) results in intensive mitigation requirements. Note that this site is also impacted by the Kinleith Pulp Mill discharge, just upstream of the water quality station.

100. A second important constraining point is the Waikato at Mercer Bridge station. This site is also impacted by a point source discharge immediately upstream: the Meremere sewage works. Again, due to relatively high starting concentrations (0.65 mg l^{-1}) and a low concentration target (0.35 mg l^{-1}), the lower Waikato sub-catchment from Mercer Bridge up to approximately the Horotiu Bridge site requires intensive mitigation, although not as intensive as the catchment above Waipapa. The model identifies the sub-catchment between Horotiu Bridge and Mercer Bridge as an optimal focus area for dairy land mitigation. This is due to lower net attenuation losses in this area immediately upstream of the target site, compared to sub-catchments further upstream. Diffuse source attenuation coefficients in the model are generally higher above Horotiu Bridge compared to

downstream of the bridge. Also playing a role in this spatial distribution is the modelled attenuation in Lake Karapiro, which impacts the effective mitigation cost associated with achieving the Mercer Bridge water quality target with mitigation above Karapiro.

101. In the Waipa basin, the model identifies priority sub-catchments above the Otewa station (dairy only). This, again, is attributable to the lower diffuse-source attenuation rates in these upper sub-catchments compared to downstream sub-catchments in the Waipa basin.

102. Optimisation modelling results also highlight higher relative cost effectiveness associated with dairy land mitigation, compared to dry stock. In general, more extensive, and intensive, dairy farm mitigation is calculated in the model, compared to dry stock, to optimally achieve the prescribed water quality constraints. For example, the model suggests low-level mitigation for dairy farms, but none for dry stock farms, in the lower portion of the Upper Waikato sub-basin (Waikato at Karapiro, Pokaiwhenua, and Karapiro sub-catchments). Similarly, at the bottom of the Lower Waikato, including Waikato at Mercer, Wangape, and Opuatia, a more intensive suite of mitigation actions (including stock reductions) are optimally required for dairy compared to dry stock (wetlands). This general pattern of results is not surprising. The input unit mitigation costs are generally lower for dairy compared to dry stock. In other words, a greater reduction in nitrogen loads are simulated in the model, for the same mitigation effort, for the higher leaching dairy farms compared to dry stock farms.

103. Lastly, results highlight the fact that the required level of mitigation effort to achieve the 80-year water quality goals is significant, given the stringent level these targets are set at, and particularly without a commensurate reduction in point source loads. Many parts of the catchment require full re-forestation (or mitigation down to background export levels). For example, modelling results suggest that, to achieve all stated water quality goals, on a long-term median basis and without any other load reductions, nearly 100% of dairy and dry stock lands upstream of Waipapa will need to be converted to forestry. In other areas of the basin, mitigation requirements are less intensive and, as modelled, can be achieved through various combinations of stock exclusion, riparian planting, and constructed wetlands. With significant point source reductions (Figure 5), mitigation

requirements are much less, including primarily stock exclusion, riparian planting, and constructed wetlands. In such a scenario, full afforestation is required on only relatively small parcels of land.

104. The equal costs scenario identifies priority sub-catchments, prioritized based only on relative differences between current load and target load and modelled flow paths and on attenuation relative to downstream target locations. In other words, it isolates spatial priorities without the confounding relative mitigation cost considerations. Results provide further support of the conclusions drawn above: that upper basin (above Waipapa) and lower basin (below Horotiu Bridge down to the Mercer Bridge) sub-catchments would be prioritized over mid-basin catchments, in order to achieve the 80-year water quality targets. Additionally, the upper Waipa sub-catchments (above Otewa and the Mangapu) are also identified as priority areas. As described above, these spatial differences are primarily attributable to differences in modelled attenuation rates, and stringency of the 80-year water quality targets.

105. It is interesting to note that results indicate that the water quality target at the Waikato at Tuakau Bridge would be achieved without mitigation in the dairy and dry stock-intensive sub-catchments directly above this station (between Mercer Bridge and Tuakau Bridge). This water quality target is non-constraining, given the same target upstream at Mercer Bridge and simulated mitigation above Mercer Bridge. This is due to additional flow dilution between the two stations (e.g. from the Mangatawhiri which has no dairy and very little dry stock land).

Table 4: Mitigation Relative Costs for Optimisation Simulation

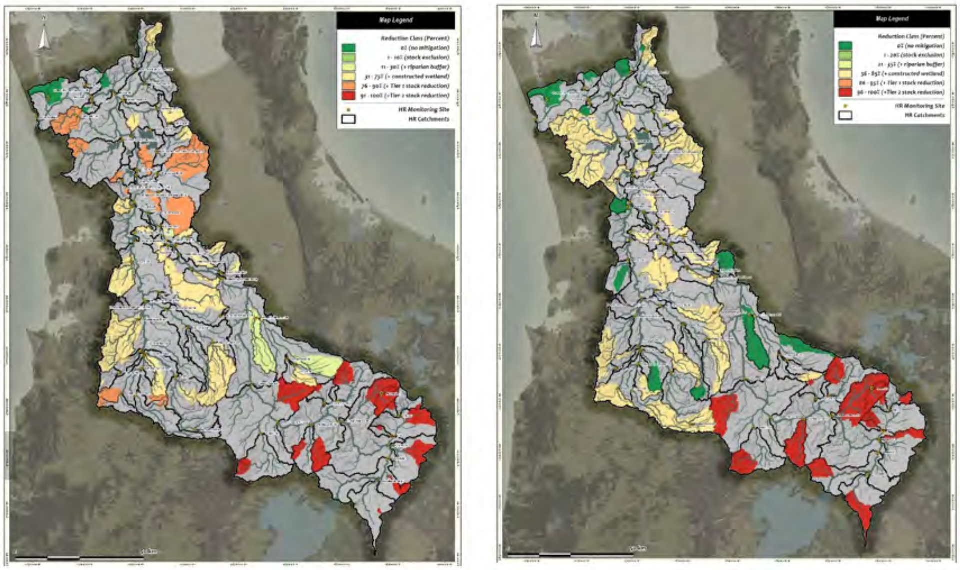
Farm Type	**Soil Type**	**Mitigation Category**	**Assumed N Export Reduction[1]**	**Relative Cost Ranking[2]** **(based on \$/kg-N)**
dairy	well-drained	stock exclusion	1 kg-N ha^{-1} yr^{-1}	1
dairy	poorly drained	stock exclusion	1 kg-N ha^{-1} yr^{-1}	2
dairy	well-drained	riparian buffer	20%	3

Farm Type	**Soil Type**	**Mitigation Category**	**Assumed N Export Reduction[1]**	**Relative Cost Ranking[2]** **(based on $/kg-N)**
dairy	poorly drained	riparian buffer	20%	4
dry stock	well-drained	wetland	60%	5
dairy	well-drained	wetland	60%	6
dry stock	well-drained	stock exclusion	1 kg-N ha^{-1} yr^{-1}	7
dairy	poorly drained	wetland	60%	8
dry stock	well-drained	wetland	25%	9
dry stock	poorly drained	wetland	60%	10
dairy	well-drained	tier 1 stock reduction	50%	11
dairy	poorly drained	tier 1 stock reduction	50%	12
dry stock	well-drained	tier 1 stock reduction	50%	13
dry stock	poorly drained	tier 1 stock reduction	50%	14
dry stock	well-drained	tier 2 stock reduction	to background	15
dry stock	poorly drained	tier 2 stock reduction	to background	16
dairy	well-drained	tier 2 stock reduction	to background	17
dairy	poorly drained	tier 2 stock reduction	to background	18

[1] = Nitrogen removal rates were derived from two primary sources: McKergow et al. (2007) and Horizons Regional Council (2017).

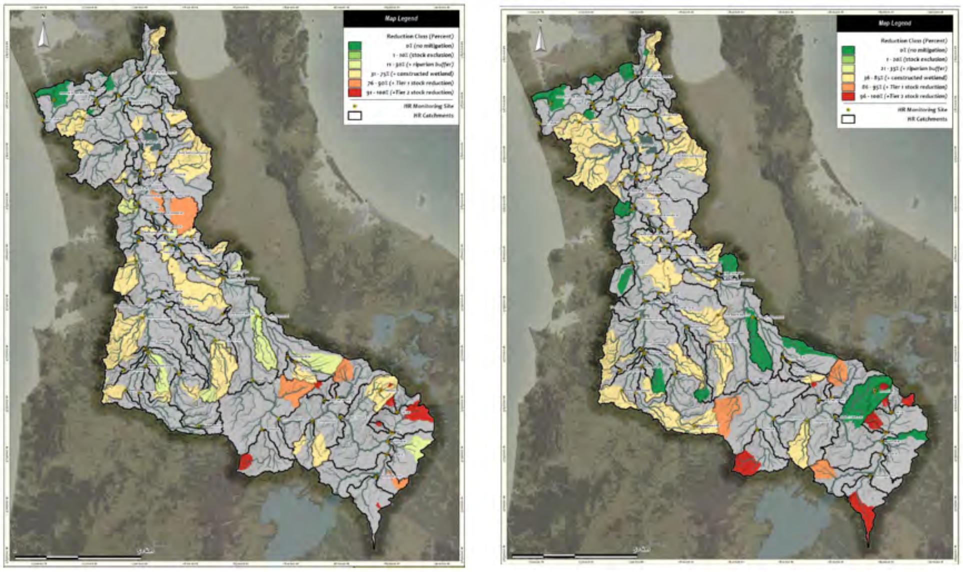
[2] = Relative unit costs of mitigation for all categories except stock reduction were derived from NIWA (2007); stock reduction unit costs were derived from Cox et al. (2013).

Figure 4: Optimisation Simulation Results: Diffuse Source Mitigation Only


a.) Dairy and Dairy Support

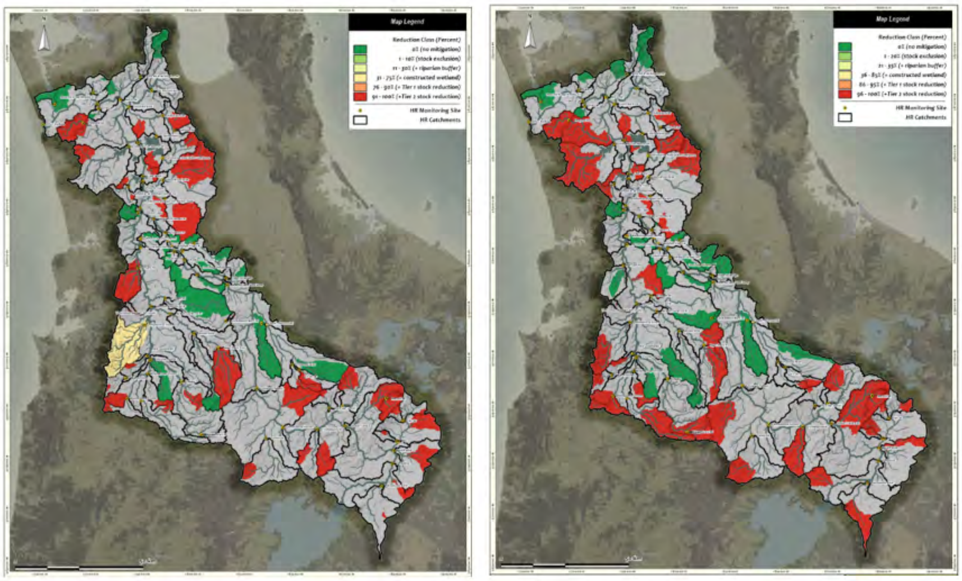
b.) Dry Stock

Figure 5: Optimisation Simulation Results: Diffuse Mitigation + Point Source Reduction


a.) Dairy and Dairy Support

b.) Dry Stock

Figure 6: Optimisation Simulation Results: Equal Cost Mitigation


a.) Dairy and Dairy Support

b.) Dry Stock

LAND USE LAYER UNCERTAINTY

106. The NIWA model was apparently developed based on 2012 land use data, used to apportion sub-catchment areas to the land use categories described above. Details on the land use database used for this analysis are not provided in the available technical reports, nor has the database itself been made available. It is there unclear which land use database was used for the Healthy Rivers modelling. Further, the 2012 database is now outdated and may no longer accurately represents “current” conditions in the basin.

107. To confirm the land use values used in the NIWA modelling, a 2012 Agribase land use layer for the basin was obtained. I compared these data to the 2012 land use data used by NIWA. I also performed a revised baseline model simulation using the AgriBase data to compare model projections of nitrogen load and concentrations at downstream stations.

108. Only land use areas, for each category, were changed for this simulation. Export coefficients, attenuation coefficients, and point source discharges were unchanged from the baseline simulation described above.

109. Because “dairy support” is not explicitly included as a separate category in the Agribase data set, I assumed the same percent of total reported dairy land as applied in the NIWA model for “dairy support” (20%).

110. In the AgriBase data set, the lumped category “Other” appears to include both the “Residential/Urban” and “Miscellaneous” categories of the NIWA model. I therefore disaggregated this lumped category by assuming the same percentage break-down for the two sub-categories as used in the NIWA model.

111. Results of this analysis reveal significant differences between the 2012 AgriBase land use layer and the 2012 layer used in the NIWA modelling. Summaries of land use apportionment above the water quality stations, for the 2012 Agribase dataset, are provided in Figure 7 and can be compared to the NIWA dataset summarised in Figure 1.

112. In general, the Agribase data indicates more dairy land, and less forestry and dry stock land, than included in the NIWA modelling. Differences between the two datasets are largest in the upper basin. For example, the total dairy land percentage above Waipapa in the NIWA dataset is 16%; while in the Agribase dataset the dairy land apportionment is 34%. The larger dairy percentage in the Agribase dataset is offset by a lower forestry percentage of similar magnitude. Similar differences are observed at the Horotiu station. For the basin as a whole, the Agribase dataset indicates a total dairy percentage of 35%, while the NIWA dataset indicates a total dairy percentage of 29%.

113. With respect to nitrogen load apportionment, the two land use datasets project very different stories, with the Agribase dataset indicating a significantly higher total apportionment to dairy (Figure 8) compared to the NIWA dataset. For example, at the Waipapa station, modelling with the Agribase dataset shows a total nitrogen load contribution from dairy of 61%, compared to NIWA modelling results of 40%. For the basin as a whole (results at Port Waikato), the differences in dairy nitrogen load contributions are 62% vs. 55%. For phosphorus, the Agribase dataset suggests that dairy, not dry stock, is the single largest contributor in the basin (41% of the total load at Port Waikato).

Modelled baseline nutrient concentrations at targeted instream stations also differ significantly as a consequence of the differences in assumed land use layers. Modelled median nutrient concentrations at those instream stations with water quality targets, for both datasets, are summarised in

114. Table 5: Agribase (2012) vs. Baseline (2012) Land Use: Modelled Concentrations. Modelled mainstem nitrogen concentrations are approximately 40 to 50% higher for the Agribase land use, compared to the NIWA land use layer, for the sites between (and including) Whakamaru and the Horotiu Bridge site. Between Huntly and Port Waikato, the modelled difference in nitrogen concentration is between approximately 15 and 20%. Significant differences are also noted for results in the Waipa basin (not shown).

115. Modelled mainstem phosphorus concentrations are approximately 25 to 40% higher for the Agribase land use, compared to the NIWA land use layer, for the sites between (and including) Whakamaru and the Horotiu Bridge site. Between Huntly and Port Waikato, the modelled difference in phosphorus concentration is between approximately 15 and 20%. Again, significant differences are also noted for the Waipa basin (not shown).

116. The source of differences between the two datasets is not known. Nor is it known which data set is more accurate. However, I have more confidence in the Agribase numbers because I know their source and have processed the numbers myself. I have less confidence in the NIWA numbers because the only source reference provided in published reports is the short statement, "regional land use data were supplied for this project by WRC…" (Semadeni-Davies et al., 2015). The data directly provided by WRC have not been made available to the public.

117. In addition to potential errors in data sets and/or processing, differences between the two data sets might also be attributable to the dynamic nature of land use in the basin. It is known that land clearing and dairy intensification have occurred at a rapid pace over the past decade in the basin, particularly in the upper basin. Indeed, Agribase land use data for 2018 show sharp differences when compared to Agribase 2012 data (more dairy, less dry stock). Therefore, a portion of the differences observed in this analysis may be attributable to differences in timing of the land use "snap shots". The NIWA data set may actually be an older snap shot of the basin, with the Agribase data set a more accurate depiction of current basin conditions.

118. I see two significant implications of this analysis. The first is that the NIWA modelling may grossly underestimate the contribution of dairy to observed

and projected nutrient loads in the basin. As described above, calculations using the Agribase data set show dairy contributions to total nutrient loads to be up to 50% higher than the loads generated using the NIWA land use data set, at certain locations in the basin. The second implication is that basin attenuation coefficients may be significantly underestimated in the NIWA model. If nutrient exports were underestimated in the NIWA model, due to land use inaccuracy, then the model calibration exercise would have resulted in an underestimate of nutrient attenuation (to achieve the same calculated downstream concentrations). In other words, high attenuation may be compensating for low load exports in the baseline NIWA model.

119. These results also carry implications for predictive scenario simulations. The extent of mitigation required to achieve water quality goals, in terms of % export load reduction, is likely underestimated in the predictive modelling to-date. By source sector, dairy mitigation requirements, especially, may be more extensive, and intensive, than modelled to-date.

120. While it is unclear to what extent, if any, NIWA modelling results featured in Healthy Rivers CSG decision-making, it is apparent that those modelling results may be inaccurate due simply to inaccuracies in assumed current land use in the basin.

Figure 7: Agribase (2012) Baseline Model Land Use Area Summaries: Relative Proportions

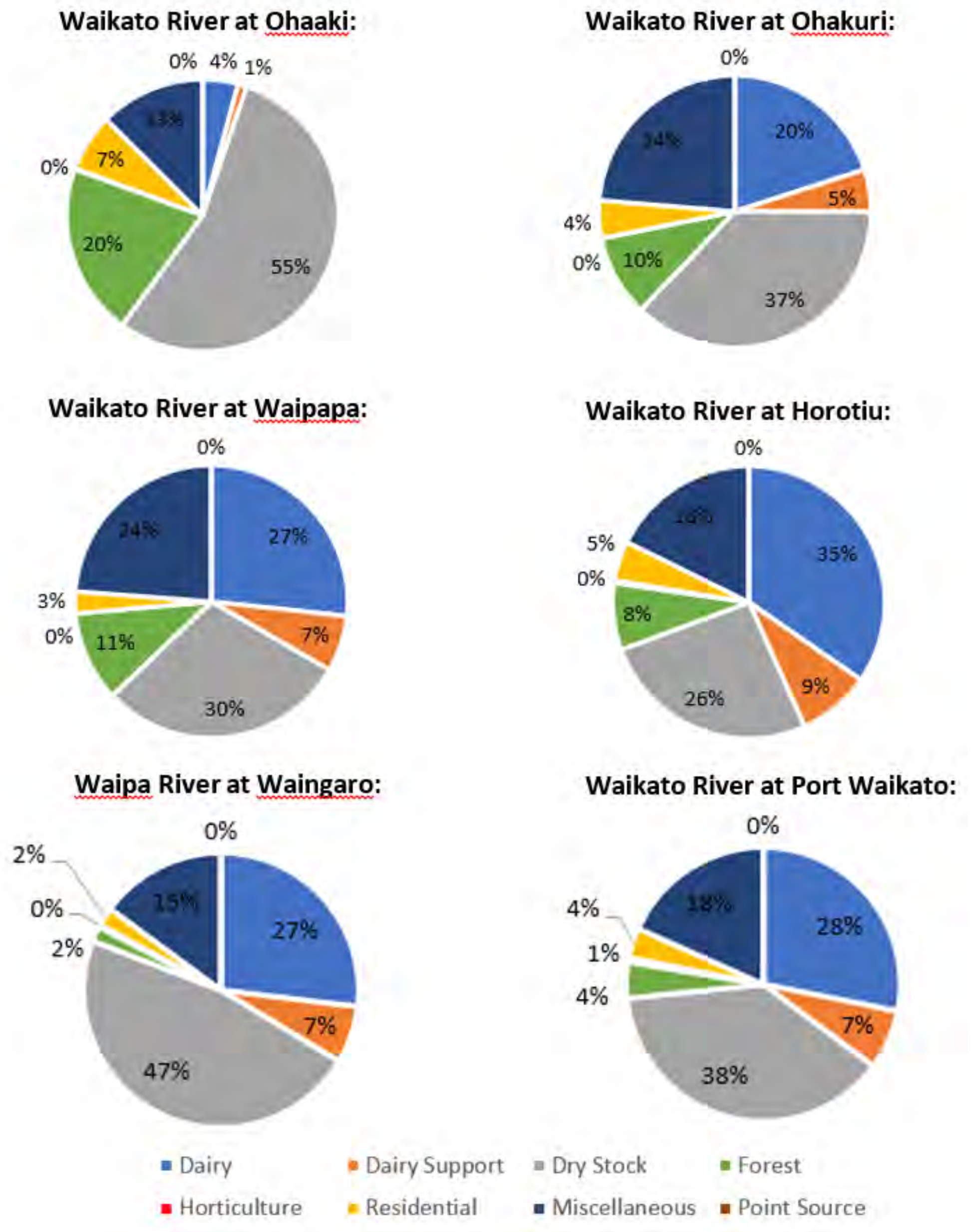


Figure 8: Agribase (2012) Baseline Model Mass Balance Summaries, TN: Relative Proportions

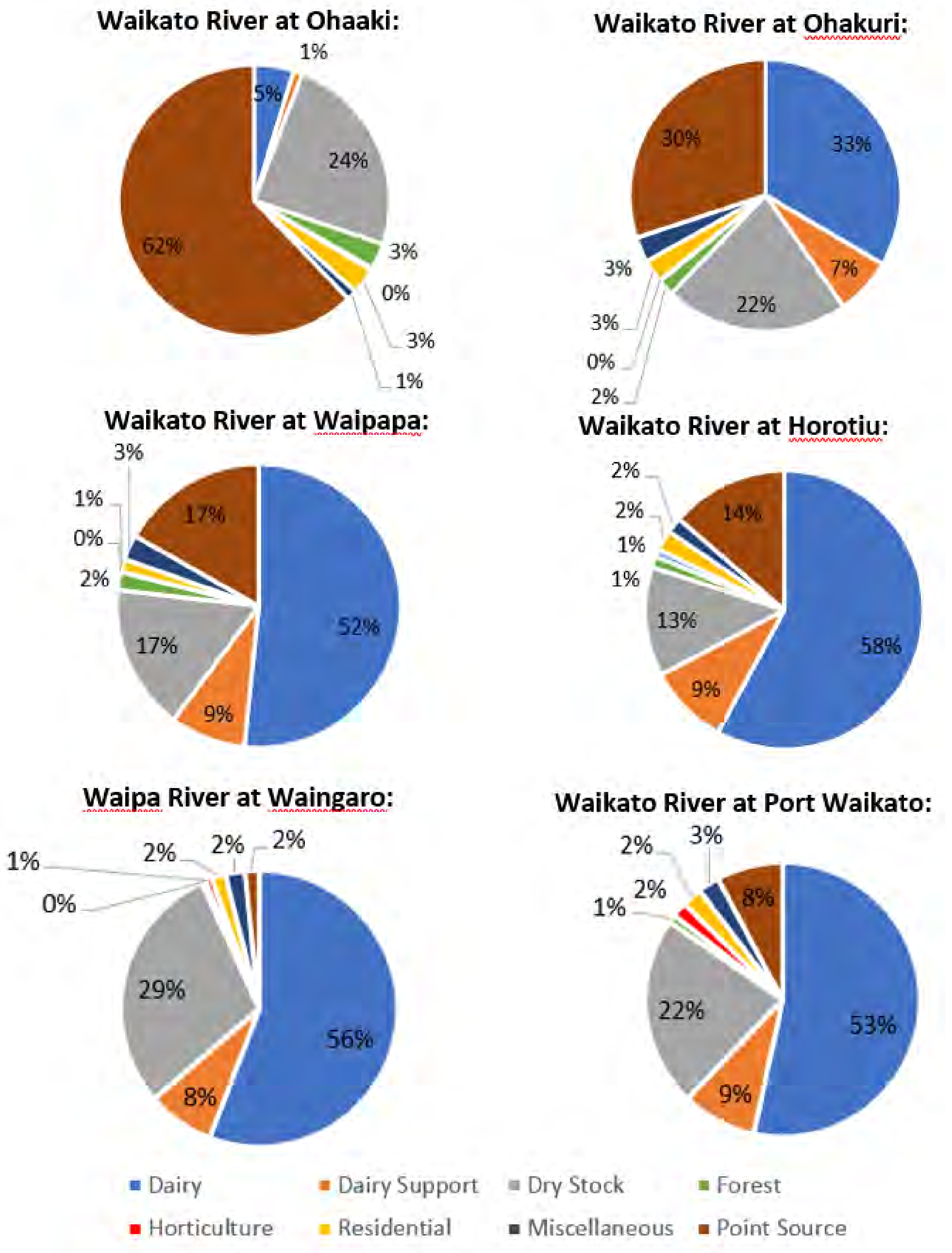


Figure 9: Agribase (2012) Baseline Model Mass Balance Summaries, TP: Relative Proportions

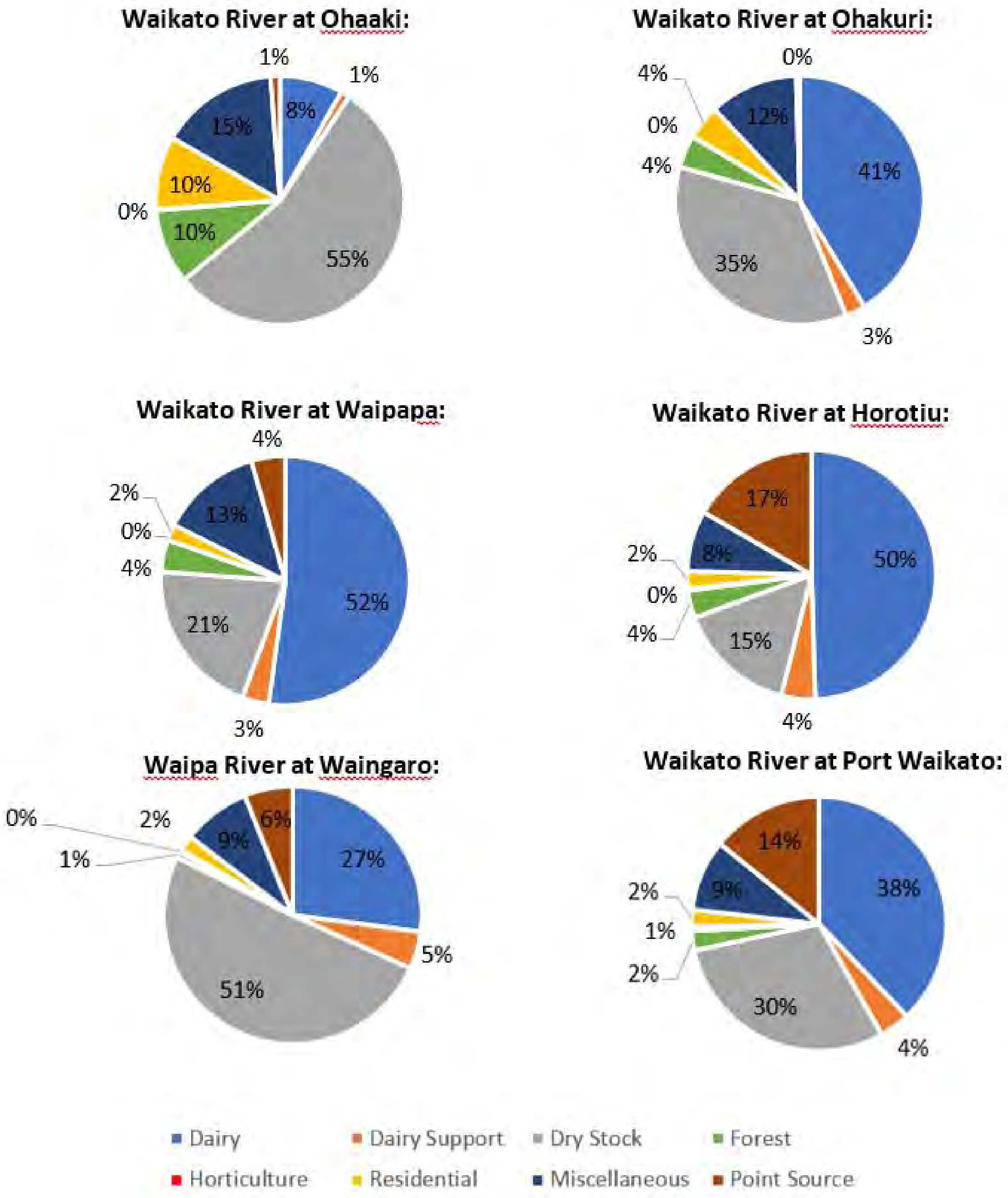


Table 5: Agribase (2012) vs. Baseline (2012) Land Use: Modelled Concentrations

WQ Station Name	Reach	Location (km)	Agribase TN (mg/L)	NIWA TN (mg/L)	Agribase TP (mg/)	NIWA TP (mg/L)
Waikato at Ohaaki	Mainstem	39	0.14	0.13	0.011	0.010
Waikato at Ohakuri	Mainstem	78	0.23	0.21	0.023	0.020
Waikato at Whakamaru	Mainstem	107	0.37	0.27	0.038	0.027
Waikato at Waipapa	Mainstem	130	0.47	0.33	0.046	0.035
Waikato at Narrows	Mainstem	208	0.60	0.40	0.053	0.040
Waikato at Horotiu Bridge	Mainstem	232	0.62	0.43	0.060	0.048
Waikato at Huntly-Tainui Br	Mainstem	255	0.70	0.58	0.054	0.045
Waikato at Mercer Bridge	Mainstem	294	0.77	0.65	0.062	0.054
Waikato at Tuakau Br	Mainstem	305	0.69	0.58	0.055	0.048

EXPORT COEFFICIENT UNCERTAINTY

121. To the best of my knowledge, the export coefficients used in the NIWA baseline model were derived from the OVERSEER software, Version 5. This version of OVERSEER is no longer up-to-date. Dairy and dry stock export coefficients, in particular, have changed significantly in the model (Version 6) since that older version.

122. Beef and Lamb NZ (B+LNZ) have recently undertaken an analysis of OVERSEER export coefficients and the export values used in the NIWA baseline model. That work is described in the evidence submitted by Dr. Jane Chrystal. In that analysis, Dr. Chrystal used published studies to

estimate relative differences (%) in nitrogen losses (exports) between dry stock and dairy farms. She applied these differences to modelled nitrogen exports from reference dry stock farm, using the current version of OVERSEER (6.3), to estimate current dairy farm exports. Estimated current farm export coefficients from that analysis, both dry stock and dairy, are approximately 40 – 60% higher than those assumed in the NIWA baseline model.

123. These results are supported by other independent studies that have noted a significant increase in OVERSEER export coefficients in Version 6, compared to Version 5 (PCE, 2018). The differences in export coefficient values are likely attributable to a combination of changes in farming intensity, particularly dairy farms, over the past 5 – 10 years and, presumably, improvements in the OVERSEER algorithms and internal parameter assumptions. At the very least, the differences identify a range of uncertainty relevant to the assumed pastoral farm export coefficients in my (and NIWA's) catchment modelling.

124. To assess model sensitivity to this uncertainty in nitrogen export coefficient parameterization, I re-ran my baseline model with updated dairy and dry stock export coefficients. Based on the findings above, I increased both sets of export coefficients by 50%. This 50% increase was applied to all sub-catchments for dairy, dairy support, and dry stock diffuse source objects in the model.

125. I made no other changes to the baseline model for this exercise. I focused only on nitrogen.

126. Not surprisingly, modelling results exhibit significant changes to key model output due to the simulated changes in farm export coefficients. Simulated downstream nitrogen concentrations at water quality stations are approximately 30 – 45% higher than baseline (Table 6: Updated vs. Original Baseline Export Coefficients: Modelled Concentrations). At the uppermost site, Ohaaki, the nitrogen concentration is approximately 15% higher than baseline. With the revised export coefficients, the relative contributions of both dairy and dry stock to downstream nitrogen loads is also increased (Figure 10), compared to baseline (Figure 1).

127. It is not possible to confirm which export coefficient dataset is more accurate, and I have no opinion either way. However, this exercise does highlight the significant uncertainty in this key model parameter, particularly given the recent changes in OVERSEER. As above (see Section 8.12), the implications of this are that: a.) the relative contributions of pastoral farming to basin nitrogen loads may be significantly underestimated in the NIWA modelling, and b.) nitrogen attenuation rates may be underestimated in the NIWA model (if the model calibration exercise used inaccurate pastoral farm export coefficients).

128. Due to the baseline model parameter uncertainty described above, the uncertainty associated with the Healthy Rivers predictive modelling, using the combination of catchment water quality and economics models, is also magnified, reducing my confidence in those simulations.

Figure 10: Updated Export Coefficient Mass Balance Summaries, TN: Relative Proportions

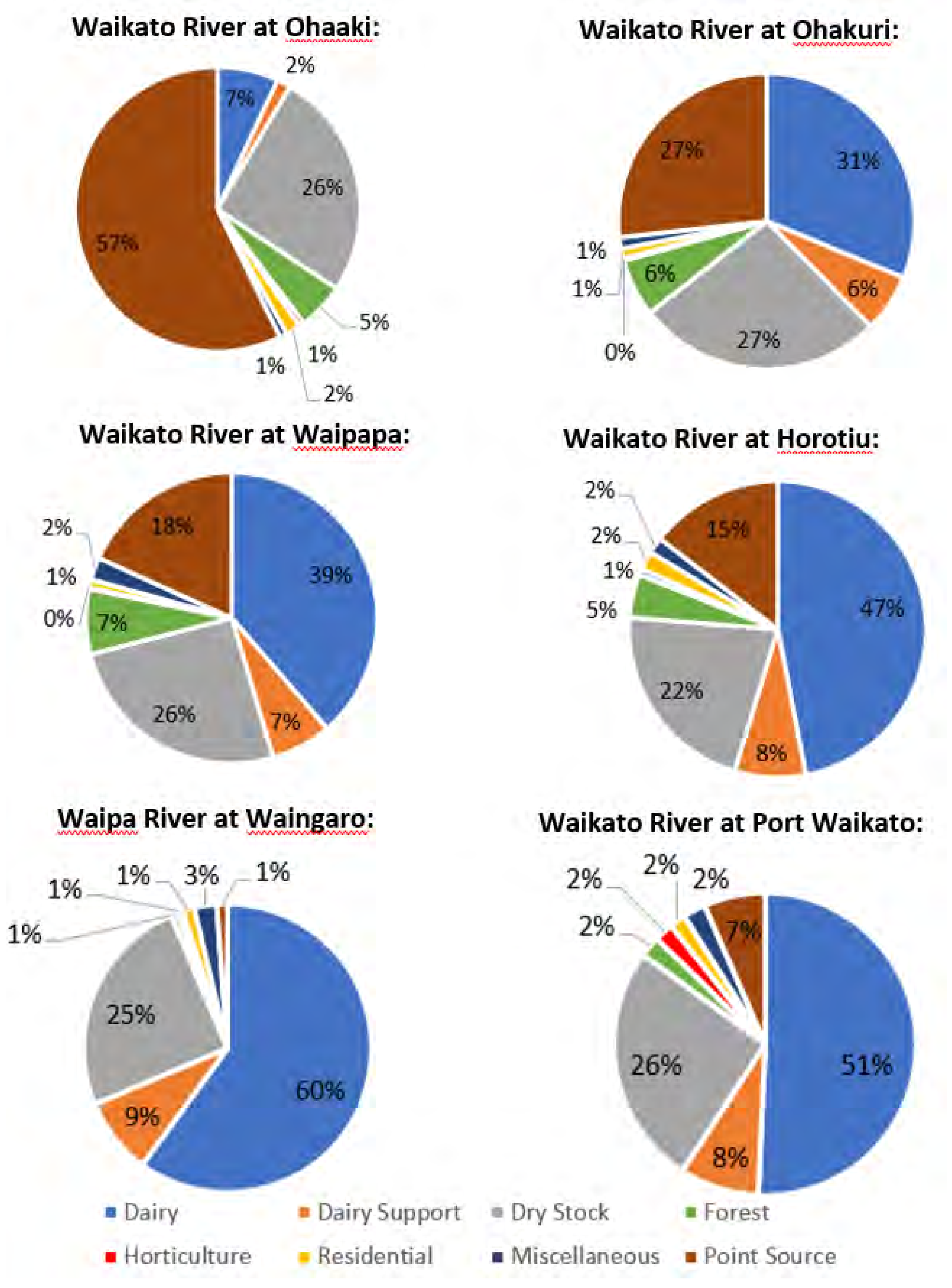


Table 6: Updated vs. Original Baseline Export Coefficients: Modelled Concentrations

WQ Station Name	Reach	Location (km)	Updated TN (mg/L)	Original TN (mg/L)
Waikato at Ohaaki	Mainstem	39	0.15	0.13
Waikato at Ohakuri	Mainstem	78	0.26	0.21
Waikato at Whakamaru	Mainstem	107	0.35	0.27
Waikato at Waipapa	Mainstem	130	0.43	0.33
Waikato at Narrows	Mainstem	208	0.55	0.40
Waikato at Horotiu Bridge	Mainstem	232	0.58	0.43
Waikato at Huntly-Tainui Br	Mainstem	255	0.81	0.58
Waikato at Mercer Bridge	Mainstem	294	0.91	0.65
Waikato at Tuakau Br	Mainstem	305	0.82	0.58

ADDITIONAL MODEL UNCERTAINTY

129. Significant uncertainty exists in the results of both the Healthy Rivers modelling and the new modelling presented here.

130. I agree with the sources of model uncertainty described by Semadeni-Davies et al. (2015). These include: land use-based export coefficient estimates, calibration data, point source load estimates, the potential for recent land use changes, the coarse spatial and temporal resolution of the model, and estimated attenuation rates.

131. Model uncertainty is reduced through calibration and verification exercises using measured data. Neither the NIWA model, nor the new model presented here, were rigorously calibrated. Neither were the models applied to an independent data set as part of a verification exercise. Model parameters, in general, appear to be based more on expert opinion than observed data.

132. As a consequence, the uncertainty associated with the modelling performed in support of the Healthy Rivers study should be viewed as relatively high

compared to most published catchment water quality modelling studies. Results, including those presented here, should be considered screening level, from which we can only draw useful general insight and guidelines.

133. I recommend additional and ongoing work to reduce the uncertainty, and improve the accuracy, of the catchment model. Presumably, the model will continue to be used to guide basin regulation and mitigation. This work should ideally involve more rigorous catchment monitoring, modelling, and parameterisation, likely at a sub-catchment scale.

134. As noted above, I also recommend that a set of sensitivity analyses be performed with the current model to better understand, and quantify, model uncertainty and the implications for model predictive simulations and final conclusions drawn to-date.

135. Attenuation rates, particularly, are highly uncertain. They also play a critical role in the modelling. Modelled mitigation requirements, and optimality, are both heavily dependent on assumed attenuation rates.

136. Assumed sub-catchment nitrogen attenuation rates vary widely in the NIWA model, and in my own model, ranging from 0.05 to 0.9. These were set primarily based on expert opinion. They were also supported by a coarse calibration process whereby some modelled rates were adjusted to better align modelled total instream loads with independently estimated loads based on measured data. A recent study by Singh et al. (2017), using a combination of field measurements, OVERSEER export simulations, and mass balance calculations, quantified nitrogen attenuation rates in the Rangitikei River basin at the high end of the range used in our models (average of 0.84).

137. The multiplicative combination of export coefficients and attenuation rates determine modelled instream loads from each sub-catchment in the NIWA model and my own model. Even if these modelled loads exactly replicated observed loads (i.e. within a calibration exercise), the relative apportionment of the two parameters is uncertain. The type of calibration exercise used to support the NIWA model does not isolate these two important parameters. So, while we may have confidence that the model does a reasonable job of simulating the combination of the two, we have less confidence that the individual parameter values are accurate. This is

compounded by the uncertainty associated with underlying land use apportionment in the model, as discussed above.

138. This has ramifications for using the model for predictive simulations or for allocation. For example, different model apportionments of attenuation vs. export, for the same model calibration result, can result in different predictions of mitigation impacts (depending on the mathematical form of the mitigation model) and different per hectare nitrogen allocations to achieve a desired water quality outcome. The latter is particularly important if the model is to be used to support nutrient allocation in the future. As described in Sections 4 and 9, attenuation rates are also a consideration for prioritising sub-catchments for mitigation. Mitigation, at least in theory, is less cost-effective (less load reduction for the same action) in sub-catchments with higher relative attenuation rates compared to lower attenuation sub-catchments. Again, it is therefore important to have an accurate parameterisation of both export coefficients and attenuation rates individually, rather than simply in concert.

139. A more rigorous calibration exercise would likely require modelling at a smaller spatial scale, supported by site-specific data. For example, applying the model to selected sub-catchments with abundant observed data (ideally at multiple spatial locations and an extended period of record), and well-defined land use, could allow for the effective isolation of export vs. attenuation parameters and greatly improve model confidence. Independent studies of export and attenuation could also be used to refine, and/or verify, model parameterisation.

140. Further, I find the discussion of apparent vs. ultimate attenuation rates unsettling. The importance of this distinction appears to have been somewhat glossed over in the published reports. The calibration performed to parameterise the NIWA model was complicated by the fact that they used a synoptic set of observed instream concentration data to parameterise exports and attenuation associated with the same time period. In reality, a significant portion of the observed nutrient mass in the c. 2012 data set originated in exports that occurred years, even decades, earlier. Since land use in the basin has changed dramatically over the past decade, this assumption introduces significant error. The modelers attempt to rectify this error by introducing the concept of “ultimate” attenuation coefficients, which

are intended to be a more accurate representation of actual attenuation in the basin. They were set based on expert opinion only, rather than a quantitative calibration process. It also does not appear that the ultimate attenuation coefficients were used in any of the predictive modelling simulations. This is likely due to the fact that the steady-state models do not readily accommodate such representation of attenuation. However, it does cloud the predictive simulation results and adds uncertainty to all results presented.

141. I recommend that work be done to better quantify attenuation rates and export coefficients throughout the basin. More accurate, and defensible, attenuation and export rates will be critical to future basin decision-making, including Farm Environment Plans and the prioritisation of sub-catchments. As noted above, site-specific rates could be better quantified with sub-catchment modelling and/or mass balance calculations supported by measured data and empirical studies. Direct incorporation of lag time estimates associated with the nutrient loads could also improve the quantification of both export and attenuation rates in the basin. Simple time lag representation of load transport, within a dynamic version of the catchment model and coupled with time-variable synoptic observed data sets, might provide for a more useful and accurate predictive tool.

CONCLUSIONS

142. Based on my own numerical modelling and analysis, I have presented evidence that supports the following arguments:

(a) Diffuse loads from dairy lands represent the single largest source category of nitrogen in both the Waipa and larger Waikato River basins, comprising over half of the total load in both basins. This should be made fully transparent in all work going forward.

(b) Diffuse phosphorus loads are more evenly distributed across source categories. Depending on the land use layer used, the largest contributor of phosphorus in the Waikato basin is either dry stock (NIWA land use) or dairy (Agribase land use). Diffuse loads from dry stock lands represent the single largest source category of phosphorus in the Waipa basin.

(c) Point source discharges represent the largest contributor of nitrogen load in the upper Waikato basin (above Ohakuri).

(d) Long-term (80-year) nitrogen targets could be achieved in the basin with an equal allocation of nitrogen export “allowances” across all land use types, even without reductions in point sources, but would require significant land use change. Under such a scheme, the extent of export reduction required by upstream diffuse sources varies widely by location in the basin. For example, to achieve the target at the Waikato River at Waipapa station, without point source reductions, would require complete afforestation upstream of the station. Contrastingly, achieving the less stringent published target at the Narrows or Horotiu sites could be achieved with an equal allocation allowance approximately equivalent to the current average dry stock export coefficient (11 kg ha^{-1} yr^{-1}).

(e) The upper basin long-term nitrogen targets (specifically the target at the Waipapa station) appear to be overly constraining. Without significant point source load reductions above this station, nearly 100% afforestation would be required of all pastoral farm lands in this part of the basin to achieve the targets.

(f) An example optimal pathway to achieving long-term water quality goals has been identified in the work presented here. The pathway includes a series of extensive diffuse source mitigation actions: including stock exclusion, riparian planting, constructed wetlands, stock reductions, and, in some sub-catchments, conversion of agriculture to forestry. The pathway identified here should not be considered truly optimal, as not all mitigation options were considered, and relative costing and efficacy was based on limited published literature. More importantly, this work highlights the type of analysis that should be more rigorously performed in the future to support and guide on-going mitigation efforts in the basin.

(g) With significant point source load reductions (-50%), long-term nitrogen goals can be achieved without extensive land use conversion. Accompanied by point source reductions, diffuse source mitigation requirements would be more practically achievable and require less-intensive actions for the majority of the basin. Required mitigation actions under this modelled scenario include stock exclusion, riparian planting, and constructed wetlands.

(h) Based on published studies, results demonstrate a cost-effective strategy generally prioritising dairy mitigation over dry stock mitigation, as the former achieves greater reductions in nitrogen export for the same mitigation action and cost. Note that I make no suggestion here of how mitigation costs should be allocated.

(i) The Upper Waikato (above Waipapa), Upper Waipa (above Otewa and the Mangapu), and part of the Lower Waikato (between Horotiu Bridge and Mercer Bridge) basins should be prioritised for diffuse source mitigation if all stated nitrogen goals are to be achieved. These sub-catchments require the greatest reduction in nitrogen load to achieve associated water quality goals. They are also characterized by generally lower relative attenuation rates, as parameterised in the original baseline model and supported by calibration exercises and expert opinion. Lower attenuation equates to lower effective unit mitigation costs (more “bang for buck”) and higher prioritisation.

(j) Further downstream, the Waikato at Tuakau Bridge target has been identified as non-constraining, benefiting from high quality dilution water from the Mangatawhiri Stream.

(k) Importantly, the land use layer used in the NIWA catchment model to inform CSG decision-making appears to be uncertain and, possibly, inaccurate. An independently obtained land use layer, for the same time period (2012), exhibits significant differences when compared to the land use layer used in the NIWA model. These differences lower my confidence in the NIWA modelling results and suggest that both the contribution of dairy to current river nutrient loads, and catchment attenuation rates, may both be significantly underestimated in the NIWA model.

(l) Pastoral farm nitrogen export coefficients assumed in the NIWA catchment are based on an outdated version of OVERSEER and are likely underestimated. My modelling demonstrates significant sensitivity of key model outputs to the range of uncertainty associated with farm export coefficients, reducing my confidence in the NIWA modelling results.

(m) As a consequence of the above, model calculations used to support decision-making may be inaccurate to the point of being misleading for decision-makers.

143. More generally, future work should focus on quantifying, and potentially reducing, model uncertainty, particularly in the areas of export coefficients and nutrient attenuation. I recommend that additional calibration/verification exercises be performed, potentially at a sub-catchment scale, to isolate export and attenuation rates and reduce model uncertainty. Additionally, in line with the recommendations of the Parliamentary Commissioner for the Environment (PCE, 2018) for regulatory models, I recommend that formal uncertainty and/or sensitivity analyses be conducted with the NIWA model. This will greatly improve model credibility, defensibility, and acceptance, and may identify important areas for model improvement.

144. In line with PCE recommendations on transparency, I recommend that both the NIWA catchment model and the supporting economics optimisation model, and all supporting data and parameterisation work, be made publicly available. Transparency is decidedly lacking in the Healthy Rivers modelling performed to-date.

145. Additionally, the incorporation of simple lag time estimates in future catchment modelling may improve the predictive power and accuracy of the models and provide better regulatory decision support. I agree with NIWA (Semadeni-Davies et al., 2015) that an annual timestep dynamic model could help better understand year-to-year variability in basin loads and water quality and may help better parameterise the model (e.g. attenuation and export coefficients). Taking this idea further, I recommend the incorporation of *seasonality* in future modelling efforts, if able to be adequately supported by available data. Export coefficients, attenuation rates and river flow rates (dilution) are all known to vary seasonally in nature.

146. Lastly, it is my opinion that the models developed by the NIWA team to support the Healthy Rivers study were not used enough to either a.) investigate a range of cost-effective and practical strategies to achieve water quality goals in the basin, or b.) establish achievable, and

appropriately spatially variable, water quality targets for both the short and long-term. I recommend that, subject to the improvements in baseline modelling recommended above, the models be further applied to firm up policy and planning going forward in these two areas.

Dated this day 15 February 2019

Dr Tim Cox

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APPENDIX A: CASM TECHNICAL NOTES

147. Export loads associated with each diffuse source node are calculated, at each model timestep, as the product of the prescribed export coefficient and the source node land area:

$$\mathrm{exportLoad} = \mathrm{EC} * \mathrm{A}$$

where EC = export coefficient (kg ha^{-1} yr^{-1}) and A = land area associated with the source (ha) and exportLoad is in units of kg yr^{-1}.

148. Resulting loads, discharged to the receiving stream, are calculated as the export load, minus diffuse pathway attenuation:

$$\mathrm{dischargeLoad} = \mathrm{exportLoad} * (1 - \mathrm{Atten}),$$

where Atten = diffuse pathway attenuation coefficient (unitless), and dischargeLoad is in units of kg yr^{-1}.

149. Reservoir attenuation is calculated as the product of the prescribed residence time and the prescribed first order attenuation rate constant:

$$\mathrm{Atten}_{\mathrm{res}} = \mathrm{t}_{\mathrm{r}} * \beta,$$

where $Atten_{res}$ = reservoir attenuation coefficient (unitless), t_r = reservoir residence time (months), and β = first order attenuation rate constant (mo^{-1}).

150. An “effective” instream attenuation coefficient is calculated for each travel path between discharge point, A and downstream water quality station location, B. This calculation is performed for each source node and water quality station combination and incorporates instream attenuation in all reaches between A and B. It also incorporates reservoir attenuation, included in the same manner as reach attenuation. The calculation of an effective instream attenuation coefficient, for the travel path between points A and B, can be written as:

$$\mathrm{atten}_{\mathrm{eff}} = \sum_{i=1}^{n} a_i \prod_{j=1}^{i} (1 - a_j),$$

where $atten_{eff}$ = effective attenuation coefficient between points A and B, n = the total number of sub-reaches (and reservoirs) between points A and B, and a_i = instream attenuation coefficient associated with reach (or reservoir) i. As an example, for a pathway consisting of three sub-reaches (n = 3), this equation could be expanded to:

$$\mathrm{atten_{eff}} = \mathrm{a_1} + \mathrm{a_2}(1 - \mathrm{a_1}) + \mathrm{a_3}(1 - \mathrm{a_2})(1 - \mathrm{a_3}).$$

151. Total mass loads are calculated, at each model timestep, for each water quality station. These loads are calculated as the sum of each upstream node discharge load minus the instream attenuation associated with the travel path (“effective” attenuation). This calculation can be written as:

$$\mathrm{L_j} = \sum_{\mathrm{i=1}}^{\mathrm{n}} \mathrm{dischargeLoad_i}(1 - \mathrm{atten_{eff}^{i}}),$$

where L_j = the total mass load realized at water quality station j, n = total number of source nodes upstream of given water quality station (j), and the $\mathrm{atten_{eff}}^{i}$ = the calculated effective attenuation coefficient associated with the mass parcel pathway between source node i and the given water quality station.

152. For mitigation optimisation simulations, an optimisation routine is called, at each timestep, whereby an optimal mitigation strategy is determined based on achieving prescribed water quality station target concentrations (objective), while minimizing mitigation costs (constraints).

153. The first step in the model’s optimisation routine is the ranking of all mitigation options associated with all source nodes in the catchment. A unique set of source node mitigation rankings are assigned for each water quality station. Rankings are based on prescribed unit mitigation costs (most expensive to least expensive), but also account for the relative positioning of the source node (relative to the water quality station) and the pathway effective attenuation. In other words, a unique set of rankings is compiled for each station to capture differences in mitigation effectiveness due to relative upstream positioning and total pathway attenuation. Each of the five (5) mitigation levels prescribed for a given source node are included as elements in the compilation of ranked mitigation options. For example, if there are ten (10) source nodes in a modelled catchment, each with five (5) levels of prescribed mitigation, then a total of fifty (50) mitigation options/actions are included in the final ranked list.

154. For each mitigation action, an incremental export/discharge load is assigned. This load is derived from the prescribed mitigation cost tables and represents the incremental export (for diffuse sources) or discharge (point sources) load between levels of mitigation. In other words, it is the load reduction associated with a given mitigation level. Or, put another way, it is the load that would be discharged if the specific mitigation action is not taken.

155. Effective unit mitigation costs, reflecting both diffuse pathway and instream attenuation, are calculated (for each upstream source node and mitigation level) as:

$$\mathrm{cost}_{\mathrm{eff\ i,j}} = \frac{\mathrm{cost}_{\mathrm{i,j}}}{(1-\mathrm{Atten}_{\mathrm{i}})(1-\mathrm{atten}^{\mathrm{i}}_{\mathrm{eff}})},$$

where $\mathrm{cost}_{\mathrm{eff\ i,j}}$ = the effective unit cost of mitigation associated with node i and mitigation level j (\$ kg^{-1}), $\mathrm{cost}_{\mathrm{i,j}}$ = original prescribed unit cost of mitigation associated with node i and mitigation level j (\$ kg^{-1}), $\mathrm{Atten}_{\mathrm{i}}$ = diffuse pathway attenuation coefficient for node i, and $\mathrm{atten}^{\mathrm{i}}_{\mathrm{eff}}$ = effective instream attenuation coefficient for node i and given water quality station. Note that for point source nodes, diffuse pathway attenuation coefficients are always equal to 0.

156. Once rankings are calculated, the model then proceeds, in ranked order (most expensive to least expensive), to assign (i.e. "allocate") incremental export/discharge loads (described above) to source nodes, starting from zero total load at each node. At each allocation step, the model checks resulting downstream water quality station concentrations and compares to the prescribed target. If the calculated concentration is less than the target, then another load allocation is performed for the next ranked mitigation action. If the calculated concentration is greater than, or equal to, the target then the allocation ceases. Note that, for all source nodes downstream of a given water quality station, a full allocation of load is provided (i.e. no mitigation is required). The logic here is that downstream loads have no impact on upstream water quality.

157. In this way, the model ensures that the objective function (target concentration) is achieved and total mitigation costs are minimised. Note that the model performs the calculations described above for each water quality station with a prescribed target concentration. The calculations

proceed from upstream to downstream based on station location and ultimately ensure that all target concentrations are achieved. The logic behind this upstream to downstream sequential approach is that the only way upstream station targets can be achieved is through upstream node mitigation. This mitigation must happen, regardless of downstream activities. Thus, this required upstream mitigation is included first. Then, whatever remaining mitigation is required to achieve downstream targets is calculated and incorporated into the overall mitigation scheme.

APPENDIX B: CASM BASELINE MODEL CONSTRUCTION AND VERIFICATION

158. The same sub-catchment delineations used in the NIWA model were used in my model: 74 in total. These sub-catchments are well-described in the Semadeni-Davies (2015) report. As in the NIWA model, each sub-catchment was further divided, as appropriate, into separate aggregate diffuse source objects based on the following land use categories: dairy farming, dairy support, sheep and beef farming, horticulture, forest, residential, and "miscellaneous" (everything else).

159. Each diffuse source object includes a total land area associated with the given land use and sub-catchment combination, and a unique set of export coefficients (kg ha^{-1} yr^{-1}) and diffuse pathway attenuation coefficients (unitless) for total nitrogen (TN) and total phosphorus (TP), respectively. Each diffuse source object is also parameterized with a discharge location (km) which establishes relative upstream/downstream positioning and connectivity in the model. The kilometre markers in the model correspond to the bottom of each sub-catchment drainage area. Model sub-catchments are summarized in Table 7: Model Sub-Catchment Characteristics.

160. Summaries of the model diffuse source objects, and associated nitrogen and phosphorus exports, are provided in Table 8: Model Diffuse Source Objects: Nitrogen Exports.andTable 9: Model Diffuse Source Objects: Phosphorus Exports., respectively. Assumed diffuse source export coefficients, averaged by land use type, are summarized in Table 10: Model Catchment Average Export Coefficients (kg ha-1 yr-1). Diffuse source export coefficients were set in the model based on data provided by NIWA.

161. In addition to diffuse sources of nitrogen and phosphorus, a total of twenty (20) point sources of nutrient load were included in the model (Table 11: Model Point Sources). Point source loads were prescribed to exactly replicate those reported in the NIWA modelling and are not subject to attenuation in the model.

162. As noted above, some of the sub-catchments in the NIWA model discharge a portion of their nutrient load to the sub-surface. As described in Semadeni-Davies et al. (2015), the model assumes that the sub-surface loads are realized in the model at the next downstream sub-catchment, and

subject to diffuse pathway attenuation only within that downstream sub-catchment. For our modelling, we incorporated these sub-surface pathways by calculating "effective" attenuation coefficients, for the applicable sub-catchments, as weighted average values of the published upper and lower linked sub-catchment coefficients, weighted according to the assigned sub-surface flow factor. As an example, the Pokaiwhenua sub-catchment (# 19) has been assigned a sub-surface flow factor of 0.63 and an attenuation coefficient of 0.5. Conceptually, this means that 63% of the drainage from this sub-catchment enters the sub-surface, prior to attenuation, and emerges in the downstream sub-catchment (Waikato at Karapiro), where it is then subject to attenuation. The attenuation coefficient assigned to the Waikato at Karapiro sub-catchment is 0.4. In our model, then, the net effective attenuation coefficient for the Pokaiwhenua subcatchment is set equal to: 0.63*0.4 + 0.37*0.5 = 0.437.

163. Precisely following the NIWA model construct, multiple reservoir objects were also included in the model, representing sub-catchment surface storage. As described above, model reservoir objects provide for additional attenuation of nutrient loads in the model at specified locations. This form of attenuation is the equivalent of instream attenuation and impacts the total instream load (point + diffuse) at the prescribed reservoir location. Model reservoir objects are summarised in Table 12: Model Reservoir Objects..

164. Other than reservoir attenuation, no other instream attenuation is included in the model. Again, this follows the construct of the NIWA model.

165. Despite best efforts to replicate the NIWA model precisely, an exact replication was not possible due primarily to the fact that the NIWA model was not publicly available. Without the actual model, it was impossible to verify all final inputs and outputs of that model. Instead, I relied on separate reports and datasets to splice together inputs and compare outputs. Consequently, there is uncertainty in our model inputs, with respect to replicating NIWA model inputs exactly. Not surprisingly, small discrepancies in output, compared to the reported NIWA model output, were found with the original model parameterization. Model parameter adjustments were therefore appropriate to achieve an acceptable agreement in key output values (instream nutrient loads) throughout the catchment. This process was guided by a comparison of modelled instream

loads, my model vs. NIWA model, at the downstream end of each of the 74 model sub-catchments.

166. For nitrogen, a total of six (6) sub-catchment attenuation coefficients were reduced from original values to achieve acceptable agreement (± 10%) of modelled loads at each of the 74 monitoring locations (Table 13: Nitrogen Attenuation Coefficient Adjustments.).

167. For phosphorus, the model calibration process involved, firstly, increasing TP export coefficients for select sub-catchments (Table 14: Phosphorus Export Coefficient Adjustments.). The additional loads are intended to represent the "erosion sediment phosphorus" loads included in the NIWA model (Semadeni-Davies et al., 2015). While these loads are described in the referenced report, final load values are not provided. Therefore, the calibration exercise described here was intended to back-calculate those loads for inclusion in our model, represented with export coefficient adjustments. Export coefficients were adjusted uniformly across land use categories within a sub-catchment. In other words, the same incremental increase was added to all diffuse source model objects within a sub-catchment. In addition to increasing export coefficients, a single sub-basin attenuation coefficient (Waiotapu at Homestead) was increased as part of the calibration process. This attenuation coefficient was increased from 0.07 to 0.6. This combination of model parameter adjustments for phosphorus, like nitrogen, resulted in acceptable agreement (± 10%) of modelled loads, compared to published loads, for each of the 74 monitoring locations.

168. The final model output for the baseline model agrees very well with the output published in the NIWA study (Table 15: Model Verification Results: Modelled Instream TN Load and Table 16: Model Verification Results: Modelled Instream TP Load). Note that the loads shown in these tables equate to total load, in the streams, at the bottom of each of the 74 model sub-catchments. In other words, the values include loads from upstream linked sub-catchments, and from point sources, and include appropriate attenuation losses. Simulated instream loads match published NIWA loads within 10%, and in most cases within 5%. The total catchment instream annual load (Waikato River at Port Waikato) predicted by my model

matches the NIWA published load for the same location within 4% for total nitrogen and within 1% for total phosphorus.

Table 7: Model Sub-Catchment Characteristics

Sub-Catchment	**Healthy Rivers Map ID**	**Total Land Area (ha)**	**Model Receiving Stream**	**TN Diffuse Pathway Attenuation Coefficient (unitless)**	**TP Diffuse Pathway Attenuation Coefficient (unitless)**
Pueto	1	20,029	Pueto Stream	0.4	0.09
Waikato at Ohaaki	2	29,009	Mainstem	0.5	0.07
Waikato at Ohakuri	3	53,139	Mainstem	0.65	0.07
Torepatutahi	4	21,721	Mainstem	0.7	0.09
Mangakara	5	2,235	Waiotapu Stream	0.2	0.1
Waiotapu at Homestead	6	20,478	Waiotapu Stream	0.2	0.07
Kawaunui	7	2,134	Waiotapu Stream	0.2	0.076
Waiotapu at Campbell	8	6,079	Waiotapu Stream	0.2	0.08
Otamakokore	9	4,573	Mainstem	0.37	0.08
Whirinaki	10	1,080	Mainstem	0.37	0.05
Waikato at Whakamaru	11	44,665	Mainstem	0.55	0.07
Waipapa	12	10,049	Mainstem	0.55	0.07
Tahunaatara	13	20,816	Mainstem	0.48	0.06
Mangaharakeke	14	5,415	Mainstem	0.4	0.07
Waikato at Waipapa	15	69,392	Mainstem	0.5	0.06
Mangakino	16	22,186	Mainstem	0.05	0.05
Mangamingi	17	5,175	Pokaiwhenua Stream	0.1	0.7
Whakauru	18	5,302	Pokaiwhenua Stream	0.13	0.517
Pokaiwhenua	19	32,701	Pokaiwhenua Stream	0.437	0.4039

Sub-Catchment	Healthy Rivers Map ID	Total Land Area (ha)	Model Receiving Stream	TN Diffuse Pathway Attenuation Coefficient (unitless)	TP Diffuse Pathway Attenuation Coefficient (unitless)
Little Waipa	20	10,649	Mainstem	0.49	0.1
Waikato at Karapiro	21	53,969	Mainstem	0.4	0.6
Karapiro	22	6,741	Mainstem	0.4	0.0833
Waikato at Narrows	23	12,987	Mainstem	0.4	0.08
Mangawhero	24	5,347	Mainstem	0.4	0.0914
Waikato at BridgeSt Br (Ham Traffic Br)	25	5,072	Mainstem	0.4	0.04
Mangaonua	26	8,096	Mainstem	0.4	0.1
Mangakotukutuku	27	2,708	Mainstem	0.4	0.09
Mangaone	28	6,760	Mainstem	0.4	0.12
Waikato at Horotiu Br	29	5,405	Mainstem	0.5	0.04
Waitawhiriwhiri	30	2,223	Mainstem	0.3	0.11
Kirikiriroa	31	1,233	Mainstem	0.3	0.06
Waikato at Huntly-Tainui Br	32	17,322	Mainstem	0.05	0.9
Komakorau	33	16,399	Mainstem	0.05	0.1
Mangawara	34	35,884	Mangawara Stream	0.05	0.09
Waikato at Rangiriri	35	6,853	Mainstem	0.05	0.06
Awaroa at Harris/Te Ohaki Br	36	4,730	Mainstem	0.05	0.04
Awaroa at Sansons Br	37	4,561	Mainstem	0.05	0.08
Waikato at Mercer Br	38	45,168	Mainstem	0.05	0.06
Whangape	39	31,767	Mainstem	0.05	0.07

Sub-Catchment	Healthy Rivers Map ID	Total Land Area (ha)	Model Receiving Stream	TN Diffuse Pathway Attenuation Coefficient (unitless)	TP Diffuse Pathway Attenuation Coefficient (unitless)
Whangamarino at Island Block Rd	40	14,365	Whangamarino River	0.05	0.05
Whangamarino at Jefferies Rd Br	41	9,701	Whangamarino River	0.05	0.5
Waerenga	42	1,959	Whangamarino River	0.05	0.3713
Matahuru	43	10,637	Whangamarino River	0.05	0.08
Waikare	44	10,418	Whangamarino River	0.05	0.05
Opuatia	45	7,067	Mainstem	0.05	0.1
Mangatangi	46	19,452	Mainstem	0.35	0.08
Waikato at Tuakau Br	47	15,178	Mainstem	0.05	0.07
Ohaeroa	48	2,033	Mainstem	0.05	0.07
Mangatawhiri	49	6,808	Mainstem	0.15	0.06
Waikato at Port Waikato	50	28,148	Mainstem	0.05	0.07
Whakapipi	51	4,648	Mainstem	0.05	0.13
Awaroa (Waiuku)	52	2,506	Mainstem	0.05	0.09
Waipa at Mangaokewa Rd	100	3,221	Waipa River	0.05	0.05
Waipa at Otewa	101	28,665	Waipa River	0.05	0.04
Mangaokewa	102	17,419	Mangapu River	0.05	0.07
Mangarapa	103	5,443	Mangapu River	0.05	0.05
Mangapu	104	16,170	Mangapu River	0.05	0.04
Mangarama	105	5,528	Mangapu River	0.05	0.07
Waipa at Otorohanga	106	13,889	Waipa River	0.4	0.04

Sub-Catchment	Healthy Rivers Map ID	Total Land Area (ha)	Model Receiving Stream	TN Diffuse Pathway Attenuation Coefficient (unitless)	TP Diffuse Pathway Attenuation Coefficient (unitless)
Waipa at Pirongia-Ngutunui Rd Br	107	43,607	Waipa River	0.25	0.04
Waitomo at Tumutumu Rd	108	4,318	Waitomo Stream	0.05	0.08
Waitomo at SH31 Otorohanga	109	4,393	Waitomo Stream	0.05	0.02
Moakurarua	110	20,630	Waipa River	0.05	0.04
Punui at Bartons Corner Rd Br	111	22,785	Punui River	0.25	0.04
Punui at Wharepapa	112	16,853	Punui River	0.15	0.09
Mangatutu	113	12,269	Punui River	0.39	0.04
Mangapiko	114	28,069	Waipa River	0.35	0.06
Mangaohoi	115	431	Waipa River	0.2	0.04
Waipa at SH23 Br Whatawhata	116	31,506	Waipa River	0.2	0.07
Mangauika	117	978	Waipa River	0.11	0.06
Kaniwhaniwha	118	10,259	Waipa River	0.4	0.05
Waipa at Waingaro Rd Br	119	15,484	Waipa River	0.4	0.06
Ohote	120	4,041	Waipa River	0.45	0.09
Firewood	121	3,372	Waipa River	0.1	0.09

Table 8: Model Diffuse Source Objects: Nitrogen Exports.

	Dairy		*Dairy Support*		*Dry Stock*		*Forest*		*Horticulture*		*Residential*		*Miscellaneous*	
Name	**Area (ha)**	**N Export Coeff (kg/ha/yr)**	**Area (ha)**	**N Export Coeff (kg/ha/yr)**	**Area (ha)**	**N Export Coeff (kg/ha/yr)**	**Area (ha)**	**N Export Coeff (kg/ha/yr)**	**Area**	**N Export Coeff (kg/ha/yr)**	**Area (ha)**	**N Export Coeff (kg/ha/yr)**	**Area (ha)**	**N Export Coeff (kg/ha/yr)**
Pueto	162	29.6	41	27.0	8,147	11.8	10,173	4.0	11	66.3	140	12.0	1,353	2.5
Waikato at Ohaaki	2,184	29.6	546	27.0	12,646	11.8	8,006	4.0	130	66.1	1,938	12.0	3,557	2.5
Waikato at Ohakuri	9,240	44.3	2,310	27.0	24,290	11.8	10,385	4.0	0	0.0	550	12.0	6,365	2.5
Torepatutahi	4,174	28.3	1,043	27.0	4,279	11.8	11,270	4.0	0	0.0	189	12.0	760	2.5
Mangakara	242	28.3	61	27.0	1,109	11.8	310	4.0	0	0.0	21	12.0	493	2.5
Waiotapu at Homestead	4,579	28.3	1,145	27.0	2,224	11.8	10,356	4.0	0	0.0	203	12.0	1,970	2.5
Kawaunui	626	28.3	157	27.0	704	11.8	199	4.0	0	0.0	6	12.0	443	2.5
Waiotapu at Campbell	314	28.3	79	27.0	1,919	11.8	2,838	4.0	0	0.0	49	12.0	806	2.5
Otamakokore	1,453	28.3	363	27.0	1,805	11.8	176	4.0	0	0.0	57	12.0	791	2.5
Whirinaki	135	28.3	34	27.0	614	11.8	45	4.0	0	0.0	4	12.0	248	2.5
Waikato at Whakamaru	5,137	44.3	1,284	27.0	9,586	11.8	24,690	4.0	0	0.0	356	12.0	3,612	2.5
Waipapa	1,645	44.3	411	27.0	4,783	11.8	2,580	4.0	25	66.5	83	12.0	523	2.5
Tahunaatara	3,743	44.3	936	27.0	5,599	11.8	5,938	4.0	0	0.0	133	12.0	4,467	2.5
Mangaharakeke	456	44.3	114	27.0	371	11.7	4,324	4.0	0	0.0	58	12.0	92	2.5
Waikato at Waipapa	8,122	44.3	2,030	27.0	11,340	11.8	26,890	4.0	0	0.0	1,128	12.0	19,861	2.5
Mangakino	2,020	44.3	505	27.0	7,137	11.8	1,593	4.0	0	0.0	116	12.0	10,812	2.5
Mangamingi	1,803	44.3	451	27.0	827	11.8	1,106	4.0	0	0.0	738	12.0	250	2.5
Whakauru	1,436	44.3	359	27.0	1,315	11.8	1,757	4.0	0	0.0	349	12.0	87	2.5
Pokaiwhenua	8,475	44.3	2,119	27.0	6,623	11.8	12,313	4.0	0	0.0	360	12.0	2,811	2.5
Little Waipa	5,114	44.3	1,279	27.0	2,616	11.8	1,283	4.0	0	0.0	117	12.0	240	2.5
Waikato at Karapiro	15,771	39.6	3,943	27.0	17,163	11.8	6,550	4.0	323	65.8	770	12.0	9,450	2.5
Karapiro	1,294	27.5	323	15.6	4,179	11.4	277	4.0	36	65.5	68	12.0	564	2.5
Waikato at Narrows	3,975	27.5	994	15.6	4,268	11.4	173	4.0	124	65.8	1,603	12.0	1,850	2.5
Mangawhero	2,247	27.5	562	15.6	2,004	11.4	10	4.0	46	65.7	143	12.0	335	2.5
Waikato at BridgeSt Br (Ham T	1,221	32.5	305	19.0	1,725	11.5	10	4.0	200	65.7	999	12.0	613	2.5
Mangaonua	2,579	27.5	645	15.6	3,333	11.4	55	4.0	90	66.0	162	12.0	1,232	2.5
Mangakotukutuku	1,164	29.2	291	27.2	571	11.5	6	4.0	1	64.5	502	12.0	172	2.5
Mangaone	1,811	27.5	453	15.6	2,199	11.4	39	4.0	113	66.1	1,214	12.0	931	2.5
Waikato at Horotiu Br	740	32.5	185	19.0	422	11.4	9	4.0	2	66.5	3,784	12.0	263	2.5
Waitawhiriwhiri	460	32.5	115	19.0	334	11.5	16	4.0	0	0.0	1,197	12.0	101	2.5
Kirikiriroa	207	32.5	52	19.0	80	11.5	0	0.0	0	0.0	800	12.0	94	2.5
Waikato at Huntly-Tainui Br	6,999	29.2	1,750	27.2	3,115	10.3	136	4.0	77	65.9	1,398	12.0	3,847	2.5
Komakorau	10,547	32.5	2,637	19.0	2,488	10.4	27	4.0	23	65.5	235	12.0	443	2.5
Mangawara	15,054	32.5	3,764	19.0	11,079	10.4	459	4.0	0	0.0	400	12.0	5,128	2.5
Waikato at Rangiriri	1,500	22.8	375	22.7	2,096	10.4	120	4.0	0	0.0	597	12.0	2,165	2.5
Awaroa at Harris/Te Ohaki Br	800	22.8	200	22.7	2,264	10.4	36	4.0	0	0.0	112	12.0	1,319	2.5
Awaroa at Sansons Br	206	22.8	51	22.7	2,100	10.4	770	4.0	0	0.0	70	12.0	1,364	2.5
Waikato at Mercer Br	6,718	20.9	1,679	22.7	23,091	10.4	2,431	4.0	977	65.8	1,152	12.0	8,869	2.5
Whangape	3,250	22.8	813	22.7	21,722	10.4	1,083	4.0	0	0.0	383	12.0	4,516	2.5
Whangamarino at Island Block	1,907	18.0	477	22.7	5,140	10.4	918	4.0	204	65.7	449	12.0	5,270	2.5
Whangamarino at Jefferies Rd	2,912	18.0	728	22.7	3,517	10.4	1,581	4.0	30	66.0	150	12.0	784	2.5
Waerenga	95	18.0	24	17.4	1,267	10.4	367	4.0	0	0.0	16	12.0	190	2.5
Matahuru	1,722	18.0	430	19.0	6,474	10.4	316	4.0	0	0.0	163	12.0	1,533	2.5
Waikare	1,817	18.0	454	22.7	2,774	10.4	110	4.0	72		317	12.0	4,875	2.5
Opuatia	206	29.2	51	27.2	4,750	10.4	1,450	4.0	94	66.8	84	12.0	685	2.5
Mangatangi	3,524	18.0	881	17.4	6,750	10.4	1,100	4.0	6	66.4	168	12.0	7,023	2.5
Waikato at Tuakau Br	1,138	22.8	284	22.7	5,163	10.4	350	4.0	684	65.8	687	12.0	6,828	2.5
Ohaeroa	286	22.8	72	22.7	1,142	10.4	60	4.0	123	65.8	47	12.0	302	2.5
Mangatawhiri	2	18.0	0	17.4	376	10.4	420	4.0	0	0.0	7	12.0	5,990	2.5
Waikato at Port Waikato	6,322	22.8	1,581	22.7	7,575	10.4	2,065	4.0	950	65.8	878	12.0	8,813	2.5
Whakapipi	131	22.8	33	22.7	1,783	10.4	40	4.0	1,000	65.8	1,000	12.0	677	2.5
Awaroa (Waiuku)	442	22.8	110	22.7	1,500	10.3	26	4.0	27	65.9	248	12.0	154	2.5
Waipa at Mangaokewa Rd	0	0.0	0	0.0	950	10.2	1,208	4.0	0	0.0	20	12.0	1,039	2.5
Waipa at Otewa	2,150	35.0	538	17.4	8,973	10.2	1,524	4.0	0	0.0	292	12.0	15,189	2.5
Mangaokewa	928	35.0	232	17.4	10,722	10.2	1,484	4.0	0	0.0	346	12.0	3,705	2.5
Mangarapa	925	35.0	231	17.4	3,523	10.2	123	4.0	0	0.0	61	12.0	579	2.5
Mangapu	3,253	35.0	813	17.4	9,247	10.2	420	4.0	0	0.0	656	12.0	1,714	2.5
Mangarama	850	35.0	212	17.4	3,932	10.2	91	4.0	0	0.0	49	12.0	393	2.5
Waipa at Otorohanga	6,260	35.0	1,565	17.4	4,521	10.2	173	4.0	0	0.0	446	12.0	988	2.5
Waipa at Pirongia-Ngutunui Rd	21,296	35.0	5,324	17.4	9,933	10.2	547	4.0	156	65.8	940	12.0	5,411	2.5
Waitomo at Tumutumu Rd	224	35.0	56	17.4	1,673	10.2	545	4.0	0	0.0	84	12.0	1,736	2.5
Waitomo at SH31 Otorohanga	447	35.0	112	17.4	2,142	10.2	313	4.0	0	0.0	77	12.0	1,302	2.5
Moakurarua	2,396	35.0	599	17.4	8,454	10.2	1,441	4.0	0	0.0	394	12.0	7,347	2.5
Punui at Bartons Corner Rd Br	11,301	35.0	2,825	17.4	6,863	10.2	526	4.0	304	65.7	507	12.0	459	2.5
Punui at Wharepapa	3,075	35.0	769	17.4	8,242	10.2	327	4.0	0	0.0	206	12.0	4,233	2.5
Mangatutu	2,691	35.0	673	17.4	2,765	10.2	243	4.0	0	0.0	197	12.0	5,700	2.5
Mangapiko	12,823	35.0	3,206	17.4	8,021	10.3	651	4.0	34	65.8	1,154	12.0	2,181	2.5
Mangaohoi	8	35.0	2	17.4	44	11.0	0	4.0	0	0.0	2	12.0	374	2.5
Waipa at SH23 Br Whatawhata	13,752	29.2	3,438	27.2	7,842	10.2	745	4.0	122	65.8	1,202	12.0	4,405	2.5
Mangauika	46	35.0	12	17.4	28	10.2	29	4.0	0	0.0	7	12.0	857	2.5
Kaniwhaniwha	1,841	35.0	460	17.4	2,924	10.2	70	4.0	0	0.0	127	12.0	4,837	2.5
Waipa at Waingaro Rd Br	2,823	29.2	706	27.2	5,521	10.3	1,360	4.0	106	65.9	809	12.0	4,160	2.5
Ohote	1,067	22.8	267	22.7	1,987	10.4	18	4.0	12	64.5	390	12.0	300	2.5
Firewood	144	29.2	36	27.2	1,672	10.3	400	4.0	0	0.0	52	12.0	1,068	2.5

Table 9: Model Diffuse Source Objects: Phosphorus Exports.

	Dairy		*Dairy Support*		*Dry Stock*		*Forest*		*Horticulture*		*Residential*		*Miscellaneous*	
Name	**Area (ha)**	**P Export Coeff (kg/ha/yr)**	**Area (ha)**	**P Export Coeff (kg/ha/yr)**	**Area (ha)**	**P Export Coeff (kg/ha/yr)**	**Area (ha)**	**P Export Coeff (kg/ha/yr)**	**Area**	**P Export Coeff (kg/ha/yr)**	**Area (ha)**	**P Export Coeff (kg/ha/yr)**	**Area (ha)**	**P Export Coeff (kg/ha/yr)**
Pueto	162	1.4	41	0.4	8,147	0.8	10,173	0.3	11	1.2	140	0.6	1,353	0.4
Waikato at Ohaaki	2,184	2.4	546	1.4	12,646	1.8	8,006	1.3	130	2.2	1,938	1.6	3,557	1.4
Waikato at Ohakuri	9,240	2.7	2,310	0.4	24,290	0.8	10,385	0.3	0	0.0	550	0.6	6,365	0.4
Torepatutahi	4,174	1.8	1,043	0.4	4,279	0.8	11,270	0.3	0	0.0	189	0.6	760	0.4
Mangakara	242	1.8	61	0.4	1,109	0.8	310	0.3	0	0.0	21	0.6	493	0.4
Waiotapu at Homestead	4,579	1.8	1,145	0.4	2,224	0.8	10,356	0.3	0	0.0	203	0.6	1,970	0.4
Kawaunui	626	5.5	157	4.1	704	4.5	199	4.0	0	3.7	6	4.3	443	4.1
Waiotapu at Campbell	314	1.8	79	0.4	1,919	0.8	2,838	0.3	0	0.0	49	0.6	806	0.4
Otamakokore	1,453	1.8	363	0.4	1,805	0.8	176	0.3	0	0.0	57	0.6	791	0.4
Whirinaki	135	1.8	34	0.4	614	0.8	45	0.3	0	0.0	4	0.6	248	0.4
Waikato at Whakamaru	5,137	2.7	1,284	0.4	9,586	0.8	24,690	0.3	0	0.0	356	0.6	3,612	0.4
Waipapa	1,645	3.0	411	0.7	4,783	1.0	2,580	0.6	25	1.5	83	0.9	523	0.7
Tahunaatara	3,743	2.7	936	0.4	5,599	0.8	5,938	0.3	0	0.0	133	0.6	4,467	0.4
Mangaharakeke	456	2.7	114	0.4	371	0.8	4,324	0.3	0	0.0	58	0.6	92	0.4
Waikato at Waipapa	8,122	3.9	2,030	1.6	11,340	2.0	26,890	1.5	0	1.2	1,128	1.8	19,861	1.6
Mangakino	2,020	2.7	505	0.4	7,137	0.8	1,593	0.3	0	0.0	116	0.6	10,812	0.4
Mangamingi	1,803	2.7	451	0.4	827	0.8	1,106	0.3	0	0.0	738	0.6	250	0.4
Whakauru	1,436	5.2	359	2.9	1,315	3.3	1,757	2.8	0	2.5	349	3.1	87	2.9
Pokaiwhenua	8,475	4.7	2,119	2.4	6,623	2.8	12,313	2.3	0	2.0	360	2.6	2,811	2.4
Little Waipa	5,114	2.7	1,279	0.4	2,616	0.8	1,283	0.3	0	0.0	117	0.6	240	0.4
Waikato at Karapiro	15,771	1.7	3,943	0.4	17,163	0.8	6,550	0.3	323	1.2	770	0.6	9,450	0.4
Karapiro	1,294	2.6	323	2.8	4,179	2.5	277	2.0	36	2.9	68	2.3	564	2.1
Waikato at Narrows	3,975	0.9	994	1.1	4,268	0.8	173	0.3	124	1.2	1,603	0.6	1,850	0.4
Mangawhero	2,247	1.4	562	1.6	2,004	1.3	10	0.8	46	1.7	143	1.1	335	0.9
Waikato at BridgeSt Br (Ham T	1,221	0.9	305	0.3	1,725	0.8	10	0.3	200	1.2	999	0.6	613	0.4
Mangaonua	2,579	0.9	645	1.1	3,333	0.8	55	0.3	90	1.2	162	0.6	1,232	0.4
Mangakotukutuku	1,164	0.6	291	0.3	571	0.9	6	0.3	1	1.2	502	0.6	172	0.4
Mangaone	1,811	0.9	453	1.1	2,199	0.8	39	0.3	113	1.2	1,214	0.6	931	0.4
Waikato at Horotiu Br	740	0.9	185	0.3	422	0.8	9	0.3	2	1.3	3,784	0.6	263	0.4
Waitawhiriwhiri	460	0.9	115	0.3	334	0.9	16	0.3	0	0.0	1,197	0.6	101	0.4
Kirikiriroa	207	0.9	52	0.3	80	0.8	0	0.0	0	0.0	800	0.6	94	0.4
Waikato at Huntly-Tainui Br	6,999	0.6	1,750	0.3	3,115	0.8	136	0.3	77	1.2	1,398	0.6	3,847	0.4
Komakorau	10,547	0.9	2,637	0.3	2,488	0.8	27	0.3	23	1.2	235	0.6	443	0.4
Mangawara	15,054	0.9	3,764	0.3	11,079	0.8	459	0.3	0	0.0	400	0.6	5,128	0.4
Waikato at Rangiriri	1,500	1.1	375	0.2	2,096	0.8	120	0.3	0	0.0	597	0.6	2,165	0.4
Awaroa at Harris/Te Ohaki Br	800	1.1	200	0.2	2,264	0.9	36	0.4	0	0.1	112	0.7	1,319	0.5
Awaroa at Sansons Br	206	1.3	51	0.4	2,100	1.0	770	0.5	0	0.2	70	0.8	1,364	0.6
Waikato at Mercer Br	6,718	2.0	1,679	1.2	23,091	1.8	2,431	1.3	977	2.2	1,152	1.6	8,869	1.4
Whangape	3,250	1.3	813	0.4	21,722	1.1	1,083	0.5	0	0.2	383	0.8	4,516	0.6
Whangamarino at Island Block	1,907	0.9	477	0.2	5,140	0.8	918	0.3	204	1.2	449	0.6	5,270	0.4
Whangamarino at Jefferies Rd	2,912	0.9	728	0.2	3,517	0.8	1,581	0.3	30	1.2	150	0.6	784	0.4
Waerenga	95	3.9	24	3.5	1,267	3.8	367	3.3	0	3.0	16	3.6	190	3.4
Matahuru	1,722	1.0	430	0.5	6,474	1.0	316	0.4	0	0.1	163	0.7	1,533	0.5
Waikare	1,817	0.9	454	0.2	2,774	0.8	110	0.3	72	1.2	317	0.6	4,875	0.4
Opuatia	206	0.9	51	0.6	4,750	1.1	1,450	0.6	94	1.6	84	0.9	685	0.7
Mangatangi	3,524	0.9	881	0.5	6,750	0.8	1,100	0.3	6	1.2	168	0.6	7,023	0.4
Waikato at Tuakau Br	1,138	1.1	284	0.2	5,163	0.8	350	0.3	684	1.2	687	0.6	6,828	0.4
Ohaeroa	286	1.3	72	0.4	1,142	1.1	60	0.5	123	1.5	47	0.8	302	0.6
Mangatawhiri	2	1.0	0	0.6	376	0.9	420	0.4	0	0.1	7	0.7	5,990	0.5
Waikato at Port Waikato	6,322	1.1	1,581	0.2	7,575	0.8	2,065	0.3	950	1.2	878	0.6	8,813	0.4
Whakapipi	131	1.1	33	0.2	1,783	0.8	40	0.3	1,000	1.2	1,000	0.6	677	0.4
Awaroa (Waiuku)	442	1.1	110	0.2	1,500	0.8	26	0.3	27	1.2	248	0.6	154	0.4
Waipa at Mangaokewa Rd	0	0.0	0	0.0	950	0.8	1,208	0.3	0	0.0	20	0.6	1,039	0.4
Waipa at Otewa	2,150	0.8	538	0.5	8,973	0.8	1,524	0.3	0	0.0	292	0.6	15,189	0.4
Mangaokewa	928	0.8	232	0.6	10,722	0.9	1,484	0.4	0	0.1	346	0.7	3,705	0.5
Mangarapa	925	1.1	231	0.9	3,523	1.2	123	0.7	0	0.4	61	1.0	579	0.8
Mangapu	3,253	1.3	813	1.0	9,247	1.3	420	0.8	0	0.5	656	1.1	1,714	0.9
Mangarama	850	1.1	212	0.9	3,932	1.2	91	0.7	0	0.4	49	1.0	393	0.8
Waipa at Otorohanga	6,260	0.8	1,565	0.5	4,521	0.8	173	0.3	0	0.0	446	0.6	988	0.4
Waipa at Pirongia-Ngutunui Rd	21,296	0.8	5,324	0.5	9,933	0.8	547	0.3	156	1.2	940	0.6	5,411	0.4
Waitomo at Tumutumu Rd	224	0.9	56	0.7	1,673	1.0	545	0.4	0	0.1	84	0.7	1,736	0.5
Waitomo at SH31 Otorohanga	447	0.8	112	0.5	2,142	0.8	313	0.3	0	0.0	77	0.6	1,302	0.4
Moakurarua	2,396	0.9	599	0.7	8,454	1.0	1,441	0.5	0	0.2	394	0.8	7,347	0.6
Punui at Bartons Corner Rd Br	11,301	0.8	2,825	0.5	6,863	0.8	526	0.3	304	1.2	507	0.6	459	0.4
Punui at Wharepapa	3,075	0.8	769	0.5	8,242	0.8	327	0.3	0	0.0	206	0.6	4,233	0.4
Mangatutu	2,691	0.8	673	0.5	2,765	0.8	243	0.3	0	0.0	197	0.6	5,700	0.4
Mangapiko	12,823	0.8	3,206	0.5	8,021	0.8	651	0.3	34	1.2	1,154	0.6	2,181	0.4
Mangaohoi	8	0.8	2	0.5	44	0.8	0	0.0	0	0.0	2	0.6	374	0.4
Waipa at SH23 Br Whatawhata	13,752	0.6	3,438	0.3	7,842	0.8	745	0.3	122	1.2	1,202	0.6	4,405	0.4
Mangauika	46	0.8	12	0.5	28	0.8	29	0.3	0	0.0	7	0.6	857	0.4
Kaniwhaniwha	1,841	0.9	460	0.7	2,924	1.0	70	0.5	0	0.2	127	0.8	4,837	0.6
Waipa at Waingaro Rd Br	2,823	0.6	706	0.3	5,521	0.8	1,360	0.3	106	1.2	809	0.6	4,160	0.4
Ohote	1,067	1.1	267	0.2	1,987	0.8	18	0.3	12	1.2	390	0.6	300	0.4
Firewood	144	0.7	36	0.5	1,672	1.0	400	0.5	0	0.2	52	0.8	1,068	0.6

Table 10: Model Catchment Average Export Coefficients (kg ha-1 yr-1)

Land use Category	TN Export Coefficient	TP Export Coefficient
dairy	31	1.1
dry stock	11	0.8
forest	4	0.3
horticulture	65	1.2
residential	12	0.6
miscellaneous	2.5	0.4

Table 11: Model Point Sources

Point Source	Sub-Catchment	TN Load (tpy)	TP Load (tpy)
Pueto Geothermal	Pueto	1	0
Wairakei Power Station	Waikato at Ohaaki	396	0
Otumuheki Geothermal	Waikato at Ohaaki	4	0
Pararikiki Geothermal	Waikato at Ohaaki	36	0
Ohaaki Power Station	Waikato at Ohakuri	1	0.7
Torepatutahi Geothermal	Torepatutahi	7	0
Waiotapu Geothermal	Waiotapu at Homestead	31	0
Waiotapu Geothermal 2	Waiotapu at Campbell	5	0
Kinleith pulp mill	Waikato at Waipapa	145	19
Tokoroa sewage	Mangamingi	32	6.5
Hautapu dairy and Cambridge sewage	Waikato at Narrows	71	9
Te Rapa dairy and Hamilton sewage	Waikato at Horotiu Br.	200	74
Te Kuiti sewage	Mangapu	26	4

Point Source	Sub-Catchment	TN Load (tpy)	TP Load (tpy)
Otorohanga sewage	Waipa at Pirongia-Ngutunui Br	14	2
Te Awamutu dairy and sewage	Mangapiko	26	12
Horotiu meatworks and Ngaruawahia sewage	Waikato at Huntly-Tainui Br.	98	16
Huntly sewage	Waikato at Rangiriri	14	4
Te Kauwhata sewage	Whangamarino at Island Block Rd	2	0.9
Meremere sewage	Waikato at Mercer Br.	1	0.2
Tuakau rendering and Tuakau/Pukekohe sewage	Waikato at Port Waikato	51	22

Table 12: Model Reservoir Objects.

Object Name	Sub-catchment	Effective TN Attenuation Coeff. (unitless)	Effective TP Attenuation Coeff. (unitless)
Ohaaki Storage	Waikato at Ohaaki	0.002	0.003
Ohakuri Storage	Waikato at Ohakuri	0.03	0.049
Whakamaru Storage	Waikato at Whakamaru	0.023	0.037
Waipapa Storage	Waikato at Waipapa	0.014	0.23
Karapiro Storage	Waikato at Karapiro	0.024	0.04

Table 13: Nitrogen Attenuation Coefficient Adjustments.

Sub-catchment	**Original Attenuation Coeff. (unitless)**	**Adjusted Attenuation Coefficient (unitless)**
Pueto	0.6	0.4
Torepatutahi	0.88	0.7
Mangaharakeke	0.57	0.4
Waitawhiriwhiri	0.5	0.3
Kirikiriroa	0.5	0.3
Mangaohoi	0.35	0.2

Table 14: Phosphorus Export Coefficient Adjustments.

Sub-catchment	**Export Coefficient Adjustment Term[1]** **(kg ha^{-1} yr^{-1})**
Waikato at Ohaaki	+1
Kawaunui	+3.7
Waipapa	+0.28
Waikato at Waipapa	+1.2
Whakauru	+2.5
Pokaiwhenua	+2
Karapiro	+1.7
Mangawhero	+0.5
Awaroa at Harris/Te Ohaki Br	+0.05
Awaroa at Sansons Br	+0.20
Waikato at Mercer Br	+1
Whangape	+0.24
Waerenga	+3

Sub-catchment	Export Coefficient Adjustment Term[1] (kg ha^{-1} yr^{-1})
Matahuru	+0.13
Opuatia	+0.30
Ohaeroa	+0.23
Mangatawhiri	+0.1
Mangaokewa	+0.09
Mangarapa	+0.40
Mangapu	+0.50
Mangarama	+0.36
Waitomo at Tumutumu Rd	+0.14
Moakurarua	+0.20
Kaniwhaniwha	+0.16
Firewood	+0.16

[1] = added to each land use category within each sub-catchment, representing additional loads from soil erosion.

Table 15: Model Verification Results: Modelled Instream TN Load

Sub-Catchment	Healthy Rivers Map ID	Healthy Rivers Modelled (tpy)	My Modelled (tpy)	% Diff
Pueto	1	97	90	-7%
Waikato at Ohaaki	2	710	675	-5%
Waikato at Ohakuri	3	1,453	1,365	-6%
Torepatutahi	4	80	81	1%
Mangakara	5	20	19	-3%
Waiotapu at Homestead	6	302	308	2%

Sub-Catchment	Healthy Rivers Map ID	Healthy Rivers Modelled (tpy)	My Modelled (tpy)	% Diff
Kawaunui	7	5	5	-1%
Waiotapu at Campbell	8	46	43	-6%
Otamakokore	9	49	48	-3%
Whirinaki	10	8	8	-4%
Waikato at Whakamaru	11	1,966	1,792	-9%
Waipapa	12	54	49	-9%
Tahunaatara	13	170	153	-10%
Mangaharakeke	14	30	28	-9%
Waikato at Waipapa	15	2,729	2,472	-9%
Mangakino	16	213	211	-1%
Mangamingi	17	220	223	2%
Whakauru	18	25	24	-3%
Pokaiwhenua	19	336	329	-2%
Little Waipa	20	155	152	-1%
Waikato at Karapiro	21	3,951	3,686	-7%
Karapiro	22	19	19	-2%
Waikato at Narrows	23	4,274	3,996	-6%
Mangawhero	24	34	34	-2%
Waikato at Bridge St Br (Ham Traffic Br)	25	4,521	4,226	-7%
Mangaonua	26	80	78	-3%
Mangakotukutuku	27	36	33	-7%
Mangaone	28	71	64	-10%
Waikato at Horotiu Br	29	4,823	4,504	-7%

Sub-Catchment	**Healthy Rivers Map ID**	**Healthy Rivers Modelled (tpy)**	**My Modelled (tpy)**	**% Diff**
Waitawhiriwhiri	30	25	25	-1%
Kirikiriroa	31	14	13	-9%
Waikato at Huntly-Tainui Br	32	10,174	9,792	-4%
Komakorau	33	403	403	0%
Mangawara	34	661	660	0%
Waikato at Rangiriri	35	10,345	9,961	-4%
Awaroa at Harris/Te Ohaki Br	36	82	82	-1%
Awaroa at Sansons Br	37	34	33	-1%
Waikato at Mercer Br	38	11,817	11,419	-3%
Whangape	39	322	321	0%
Whangamarino at Island Block Rd	40	456	453	-1%
Whangamarino at Jefferies Rd Br	41	129	128	0%
Waerenga	42	6	5	-1%
Matahuru	43	108	108	0%
Waikare	44	197	196	-1%
Opuatia	45	68	68	-1%
Mangatangi	46	121	113	-7%
Waikato at Tuakau Br	47	12,016	11,586	-4%
Ohaeroa	48	20	20	0%
Mangatawhiri	49	20	18	-13%
Waikato at Port Waikato	50	12,543	12,138	-3%
Whakapipi	51	97	97	-1%

Sub-Catchment	Healthy Rivers Map ID	Healthy Rivers Modelled (tpy)	My Modelled (tpy)	% Diff
Awaroa (Waiuku)	52	32	32	0%
Waipa at Mangaokewa Rd	100	17	17	-2%
Waipa at Otewa	101	232	229	-1%
Mangaokewa	102	158	157	-1%
Mangarapa	103	72	71	0%
Mangapu	104	553	551	0%
Mangarama	105	72	72	0%
Waipa at Otorohanga	106	416	424	2%
Waipa at Pirongia-Ngutunui Rd Br	107	2,696	2,668	-1%
Waitomo at Tumutumu Rd	108	32	31.8	-1%
Waitomo at SH31 Otorohanga	109	75	74	-1%
Moakurarua	110	201	199	-1%
Punui at Bartons Corner Rd Br	111	699	687	-2%
Punui at Wharepapa	112	189	187	-1%
Mangatutu	113	99	93	-7%
Mangapiko	114	432	425	-2%
Mangaohoi	115	2	1	-5%
Waipa at SH23 Br Whatawhata	116	3,703	3,656	-1%
Mangauika	117	4	4	-6%
Kaniwhaniwha	118	75	70	-7%
Waipa at Waingaro Rd Br	119	3,887	3,827	-2%

Sub-Catchment	Healthy Rivers Map ID	Healthy Rivers Modelled (tpy)	My Modelled (tpy)	% Diff
Ohote	120	34	32	-7%
Firewood	121	25	25	-2%

Table 16: Model Verification Results: Modelled Instream TP Load

Sub-Catchment	Healthy Rivers Map ID	Healthy Rivers Modelled (tpy)	My Modelled (tpy)	% Diff
Pueto	1	10.1	9.2	-9%
Waikato at Ohaaki	2	56.2	53.4	-5%
Waikato at Ohakuri	3	138.7	131.5	-5%
Torepatutahi	4	14.1	13.7	-3%
Mangakara	5	1.6	1.4	-10%
Waiotapu at Homestead	6	18.7	19.3	3%
Kawaunui	7	1.8	1.8	-1%
Waiotapu at Campbell	8	3.1	3.0	-3%
Otamakokore	9	4.3	4.2	-3%
Whirinaki	10	0.8	0.8	0%
Waikato at Whakamaru	11	190.7	184.4	-3%
Waipapa	12	8.8	7.9	-10%
Tahunaatara	13	17.9	17.3	-3%
Mangaharakeke	14	2.8	2.7	-3%
Waikato at Waipapa	15	265.9	264.7	0%
Mangakino	16	15.9	15.2	-5%
Mangamingi	17	17.9	17.7	-1%

Sub-Catchment	Healthy Rivers Map ID	Healthy Rivers Modelled (tpy)	My Modelled (tpy)	% Diff
Whakauru	18	5.4	5.2	-4%
Pokaiwhenua	19	49.9	51.8	4%
Little Waipa	20	15.3	15.2	0%
Waikato at Karapiro	21	361.7	361.1	0%
Karapiro	22	5.4	5.1	-6%
Waikato at Narrows	23	389.6	401.3	3%
Mangawhero	24	4.1	3.7	-9%
Waikato at BridgeSt Br (Ham Traffic Br)	25	405.7	416.7	3%
Mangaonua	26	6.2	5.8	-7%
Mangakotukutuku	27	1.6	1.5	-5%
Mangaone	28	4.7	4.5	-4%
Waikato at Horotiu Br	29	485.2	496.0	2%
Waitawhiriwhiri	30	1.4	1.4	-3%
Kirikiriroa	31	0.8	0.7	-8%
Waikato at Huntly-Tainui Br	32	778.4	774.7	0%
Komakorau	33	11.5	11.5	0%
Mangawara	34	24.7	24.1	-3%
Waikato at Rangiriri	35	794.2	790.2	-1%
Awaroa at Harris/Te Ohaki Br	36	6.8	6.9	2%
Awaroa at Sansons Br	37	3.5	3.5	-1%
Waikato at Mercer Br	38	912.4	942.3	3%
Whangape	39	30.0	29.6	-1%
Whangamarino at Island Block Rd	40	31.9	31.7	-1%

Sub-Catchment	Healthy Rivers Map ID	Healthy Rivers Modelled (tpy)	My Modelled (tpy)	% Diff
Whangamarino at Jefferies Rd Br	41	7.7	7.8	1%
Waerenga	42	1.5	1.5	0%
Matahuru	43	8.7	8.6	-2%
Waikare	44	14.7	14.5	-1%
Opuatia	45	6.5	6.5	0%
Mangatangi	46	12.6	11.4	-9%
Waikato at Tuakau Br	47	926.7	954.6	3%
Ohaeroa	48	1.5	1.3	-10%
Mangatawhiri	49	3.1	3.3	7%
Waikato at Port Waikato	50	972.4	1001.5	3%
Whakapipi	51	3.2	3.3	2%
Awaroa (Waiuku)	52	1.8	1.8	1%
Waipa at Mangaokewa Rd	100	1.6	1.5	-6%
Waipa at Otewa	101	18.1	17.0	-6%
Mangaokewa	102	12.8	12.6	-2%
Mangarapa	103	6.0	5.9	-1%
Mangapu	104	42.0	43.8	4%
Mangarama	105	5.9	5.8	-1%
Waipa at Otorohanga	106	27.9	28.7	3%
Waipa at Pirongia-Ngutunui Rd Br	107	158.2	156.5	-1%
Waitomo at Tumutumu Rd	108	2.9	2.9	-2%
Waitomo at SH31 Otorohanga	109	6.1	5.6	-8%

Sub-Catchment	Healthy Rivers Map ID	Healthy Rivers Modelled (tpy)	My Modelled (tpy)	% Diff
Moakurarua	110	16.4	16.2	-1%
Punui at Bartons Corner Rd Br	111	34.2	33.4	-2%
Punui at Wharepapa	112	10.9	10.5	-4%
Mangatutu	113	7.1	6.9	-3%
Mangapiko	114	31.4	30.6	-3%
Mangaohoi	115	0.2	0.2	-7%
Waipa at SH23 Br Whatawhata	116	215.5	212.0	-2%
Mangauika	117	0.4	0.4	-1%
Kaniwhaniwha	118	7.5	7.4	-1%
Waipa at Waingaro Rd Br	119	230.9	225.9	-2%
Ohote	120	2.9	2.9	0%
Firewood	121	2.4	2.4	-2%