Minimum drain setback distances to protect New Zealand wetlands: tool development

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Image – Moawhitu Wetland on Rangitoto ki te Tonga/D'Urville Island (J Blyth).

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Contributors

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Limitation Statement

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Executive Summary

The purpose of this report is to document the development of a new drainage model that could be applied to New Zealand freshwater wetlands, to identify potential effects of historical and new drains, and provide guidance on appropriate setback distances to ensure the values of wetland ecosystems are not adversely affected by lowered water levels.

The development of this wetland drain setback tool (WDST) will directly support the implementation of the National Environmental Standards for Freshwater (NES-F) that were gazetted in 2020. The NES-F has established rules to protect and restore wetlands. It is now prohibited to undertake earthworks or modify the water cycle within a natural wetland or non-complying within 100m of a wetland if it is likely to lead to partial or complete drainage, unless exempted for specific reasons such as wetland restoration.

As there is a lack of national guidance on what an acceptable level is (if any) of water level decline for different wetland types (i.e., marsh, swamp, fen, pakihi or bog), the WDST aims to increase confidence in understanding the effects of drainage on wetland ecosystem health. The tool would support users to make more informed decisions on drainage setbacks, given the challenges with collating data on wetland hydrology and understanding local site settings that are highly variable (for example, changes in soil layers and hydraulic conductivity).

The specific goals of the project were to develop and evaluate the viability of the WDST for New Zealand conditions and recommend subsequent steps for tool development prior to application by practitioners. The project involved five key steps:

1. development of a conceptual model to evaluate how drain systems affect the hydrology (water levels) of natural freshwater wetlands in New Zealand,
2. representation of the drain-wetland model in numerical software,
3. collection of site-specific data to refine and validate the numerical modelling approach to predict wetland water levels that are impacted by drainage,
4. application of conceptual and numerical models to a hypothetical drain development scenario, and,
5. development of two national-scale datasets (maps) on hydraulic conductivity (Ksat) and Land Surface Recharge (LSR) to provide input data in the absence of site-measurements.

The conceptual model provided a simplified representation of a wetland hydrological system that summarises the core hydrological principles in wetlands when they are affected by drainage. This aims to reduce the need for complicated modelling or technical drainage assessments at each wetland being considered for drainage related effects. Representation of the conceptual drainage model was undertaken numerically in the software COMSOL Multiphysics, which allowed the integration of complex governing equations such as the groundwater flow equation.

Site specific data was collected and used during modelling, including climate and soil depth and conductivity information, with the models calibrated against water levels measured in wetland monitoring bores in close proximity to existing drains. An acceptable calibration helps prove the suitability of the modelling approach to predict drain effects on water levels (shallow groundwater drawdown). The sites were Queen Elizabeth Park (QEP) in Greater Wellington Region, Otakairangi Wetland in Northland Region, and Moawhitu Wetland in Marlborough Region. Site visits were conducted at two of these wetlands to collect additional verification data on saturated hydraulic conductivity (Ksat), drain dimensions, and depth to a low permeability layer.

The transient numerical models for each were simulated for 280 – 900 days, dependent on available water level monitoring records. Satisfactory to strong model calibrations were achieved based on the Nash-Sutcliffe Efficiency (NSE) (ranging from 0.58 – 0.92), with PBIAS ± 1-2%. This indicates the conceptual drainage model was suitable to predict water level responses at various lateral distances from a drain, and the parameters and theory behind the drainage model has merit for further development.

A hypothetical land development scenario was then tested to consider how the tool may be applied. This considered a single lot subdivision near a wetland on the Kāpiti Coast, where a boundary drain was proposed to lower the water table. Four scenarios were modelled to indicate the sensitivity of certain parameters on the lateral setback distance. These were the drain depth (at 1.5 m and 2 m) and Ksat (moderate permeability of 72 mm/hr and rapid permeability of 288 mm/hr). Input data was sourced from national maps and local site settings. The lateral setback distance was predicted where there would be minimal drawdown (~<10 mm) and drawdown of 50 mm and 150 mm.

The results of this simulation are presented in the table below and indicate setback distances ranging from 51m to 173m to ensure there is minimal change (<10mm) in wetland water levels.

Predicted lateral setback distance (m) for a hypothetical drainage scenario on the Kāpiti Coast

Long term average water level drawdown	**Drain depth = 1.5 m**		**Drain depth = 2 m**	
	Ksat – moderate	Ksat – rapid	Ksat – moderate	Ksat – rapid
Minimal/no change (<10 mm)	51 m	132.5 m	82.1 m	173.1 m
50 mm	48.6 m	123.7 m	78.7 m	164.2 m
150 mm	42.5 m	103.9 m	70.1 m	144.4 m

Overall, the conceptual drainage model and numerical modelling results provide confidence that a national tool to estimate drainage effects near wetlands is feasible. In all situations where the WDST was applied it performed suitably.

Further refinement of the WDST is recommended to provide greater confidence in its application for different wetland settings. It is recommended that verification of the drainage model is undertaken at a further 10 wetlands (where monitoring data exists), and additional data collection is undertaken for input parameters such as Ksat.

Our view is the tool could also be developed into a web-based application where users may enter local site data to predict drainage setback distances for protecting wetland ecosystems. The model and web-based interface could be supported by technical guidance material to ensure the applications and limitations are clear and that its use is appropriate for the scenario.

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1 Introduction

Globally and nationally wetlands have been intensively drained. Drainage and clearance are still occurring in New Zealand, and existing drains within wetlands and on adjacent land uses continue to have a detrimental effect on wetland eco-hydrology.

National Environmental Standards for Freshwater (NES-F) were gazetted in 2020 and have assigned a range of rules relating to wetlands, which includes earthworks and drainage. It is now prohibited to undertake earthworks or modify the water cycle within a natural wetland if it is likely to lead to partial or complete drainage, unless exempted for specific reasons. In addition, the NES-F also assigns a non-complying activity status for any earthworks or modification of the water cycle within 100m of a natural wetland, if it is likely to lead to partial or complete drainage (unless exempted for specific reasons such as wetland restoration).

Restoration of wetlands subject to historical drainage is also a commonly encountered situation, and understanding the effects of the existing drains on the wetland sites hydrology would aid in prioritising restoration efforts across different sites.

An assessment (see Section 2.1) of the hydrological impacts on wetlands from surface drainage (through excavations) demonstrated the effects can vary widely and are dependent on a number of different parameters.

Subsequently, it was considered useful to develop and validate a methodology that can be used as a first step in assessing appropriate drainage setback distances needed to protect natural wetlands from drainage excavations and for guiding restoration. This method would need to be practical, with the potential for it to be nationally applicable for a range of organisations. In the future, a tool could be developed from the method that may allow a range of users to input local site data or common parameters to then undertake an assessment of potential drainage risks to a wetland, which may help with consent applications and assessing against regional and national rules.

Two phases have been completed. Phase 1 was an initial desktop investigation of approaches for evaluating minimum drain setbacks, while phase 2 (this report) involved further development of a method, numerical modelling and field verification.

The overall goals of this phase of the project were to:

- Develop a wetland drain setback tool suitable for New Zealand,
- Evaluate the viability of the tool, taking into account data requirements and availability,
- Recommend next steps to develop a tool suitable for application by practitioners.

2 Background

2.1 Phase 1 Investigations

Phase 1[1] was initiated by the Department of Conservation and completed in 2021. This phase sought to identify two methods (simple or detailed) to assess the lateral effects of drains on wetland water levels. The memorandum provided recommendations about how these methods could be further developed to suit a local (New Zealand) setting. Phase 1 considered national and international literature on the water level response in different wetlands subject to some form of drainage (i.e., open ditches or tile drains), and showed the zone of influence could vary from 5 m to potentially over 200 m.

This amount of water level drawdown was dependent on a range of parameters, such as soil hydraulic conductivity (and soil type), excavation size and extent, topography and climate.

A number of empirical equations exist to determine optimal drainage spacing in agricultural and horticultural settings under steady state conditions. Such equations (i.e., Hooghoudt and Ernst) have been extensively applied internationally to guide land development (many at sites that were formerly wetlands). The review considered whether these agricultural drainage equations could be re-arranged to instead solve for an acceptable setback distance of a drain from a wetland boundary, by ensuring minimal effects on the wetlands water table. Through this review, it was identified that a similar process of thinking had been undertaken in the United States[2]. This led to the development of an equation that could estimate the lateral setback distance required from a road drain, in order to 'marginally satisfy the wetland hydrological criteria'. That equation has since been assessed in DRAINMOD and validated for five soil types in North Carolina where drainage ditches of varying sizes were present.

The phase 1 memorandum provided recommendations about a simplified or detailed method that could be applied in New Zealand to develop an equation or tool which could be used to assess lateral setback distances. The detailed method was subsequently selected for Phase 2 (this report), and involves assessing the suitability of the Skaggs *et al*. 2003[2] equation, re-development of the equation (if it was not suitable in its existing form), numerical modelling and field verification at wetland sites with water level monitoring data near and in drains.

2.2 Workshop Summary

Following establishment of a project team for Phase 2, a full day workshop was held in Wellington with representatives from;

- Department of Conservation,
- Greater Wellington Regional Council,

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[1] Blyth, J. 2021. Development of a methodology to assess drain setback distances near wetlands ('Phase 1'). Prepared for Department of Conservation by Collaborations.

[2] Skaggs, R.W., Chescheir, G. M., & Phillips, B.D. (2003). Methods to determine lateral effects of a drainage ditch on wetland hydrology. Transactions of American Society of Agricultural Engineers. Vol. 48(2): 577−584.

- The University of Waikato,
- Ministry for the Environment,
- Aqualinc and;
- Collaborations

The purpose of the workshop was to consider the Skaggs *et al.* 2003 equation in greater detail (including worked examples), looking at the limitations of its input parameters and applicability to national legislation (i.e., NES-F rules for wetlands). Outcomes of the workshop sought to re-define the objective and methodology of phase 2 of the project. A summary of the workshop is described in points below.

1. The Skaggs method[2] applied a parameter (referred to as t25) that considered the time taken for different soils to have 25 cm of drawdown from a drain. This was considered to be an acceptable amount to marginally satisfy wetland hydrological criteria in the United States. This parameter did not align with New Zealand's national legislation or objectives to reduce wetland degradation. That is, because a 25cm drawdown would contribute to a decline in wetland condition. Subsequently, it was identified that the equation would need to be adapted.

2. Drainage effects on wetlands are highly variable, due to the range of governing controls on water levels (from soil conductivity through to climate). The national dataset (particularly relating to wetlands) was determined to be sparse, especially for wetland specific information on soil hydraulic conductivity, water level and flow monitoring.
    a. Subsequently, development of a method would need to account for this limited dataset and also limited wetlands with appropriate data for verification.

3. There is no existing clear guidance on what an acceptable level (if any) of water level decline is for different wetland types (i.e., marsh, swamp, fen, pakihi or bog). Each wetland has variations in its hydrological regime depending on inputs from surface water, groundwater or rainwater. Some wetlands (for example, bogs), have small water level ranges and species adapted to these conditions, where a small change in water levels due to drainage could lead to significant ecosystem responses. Other wetlands (for example, swamps) may be more resilient to some drainage effects due to the highly variable water level regime.
    a. Given drains lower water tables, if 'no effect' was considered as the primary objective of the method, it could result in large setback distances (i.e., greater than 100 m). Consideration of an appropriate level of drainage effect is ongoing and not something that can be determined in this project.

4. In order to assess the effect of new drains or excavations on a wetland, it would firstly require delineation of the wetland boundary (and type). This is required under the National Policy Statement for Freshwater Management[3], however many regions are yet to delineate all natural inland wetlands.

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[3] Ministry for the Environment. 2020. National Policy Statement for Freshwater Management 2020. August.

2.2.1 Outcomes from Workshop

Based on the technical workshop discussions it was concluded that a new conceptualisation would be necessary for the New Zealand wetland setting. The new conceptual model does not rely directly on initial concepts from Hooghoudt, Ernst[4] and Skaggs or other analytical drainage equations. However, it still solves the same partial differential equation (PDE) that Hooghoudt and Skaggs intended to solve.

The key difference lies in the approach taken. While Hooghoudt and Skaggs used analytical equations and made simplifying assumptions, the revised model we have developed incorporates fewer simplifications and allows for more flexibility in terms of input parameters and boundary conditions. Instead of relying on analytical equations, the new model utilises numerical modelling methods and algorithms to directly approximate solutions to the PDE. Ali Shokri (Waikato University) was actioned to lead the re-development of the drainage conceptualisation and modelling with support from John Bright (Aqualinc), James Blyth (Collaborations) and funding partners. The new tool would be validated based on the transient numerical simulations conducted in the COMSOL Multiphysics software (see Section 4).

3 Conceptual understanding of drain effects on wetlands

3.1 Conceptual model – Drain effects and wetland water levels

We developed a conceptual model for New Zealand to evaluate how drain systems affect the hydrology (water levels) of natural freshwater wetlands.

The conceptual model provides a simplified representation of the wetlands hydrological system. While there are many variations across different wetlands, for example, soil hydraulic conductivity, drain depth or annual rainfall recharge, there are some core governing principles that have strong influences on most wetlands hydrological cycles when they are affected by drainage. These have been generalised in the conceptual model to help lead the development of a tool that can be applied quickly and relatively easily for guidance, as long as the limitations are known. This aims to reduce the need for complicated modelling or technical drainage assessments at each wetland being assessed.

The purpose of this section is to provide an overview of the key elements of the conceptual model and describe the assumptions made during its development. Figure 1 presents a diagram illustrating the conceptualisation of the drainage model, including the numerical domain, boundary conditions, and other input parameters. Several of these parameters are important in their influences on modelling results. A description of the parameters is detailed in the points below.

- land surface recharge (LSR) represents the precipitation received by the wetland in excess of the soil water deficit. National maps have been developed to support this work (see Section 4.4).

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[4] Van Beers, W.F.J. (1979). Some Nomographs for the Calculations of Drain Spacing. International Institute for Land Reclamation and Improvement (ILRI). The Netherlands

- depth to the sealing/low permeability layer (hs) indicates the distance from the ground surface to the impermeable layer that restricts water movement. This assumes that there is some level of low permeability beneath the wetland that restricts vertical water losses out of the system.
- drain depth (hD) represents the distance from the ground surface to the drainage system. The depth of the drain has a strong influence on the long-term water table drawdown.
- drain catchment distance (LC) is also featured, signifying the distance from the drain to the outer limit of its influence area. For example, in a parallel drainage system, the drain catchment distance (LC) is half of the distance between the drains. This parameter helps confine the model domain to a localised area that may be affected by drainage, without needing to model an entire site or wetland complex.
- drain setback distance (LD) is depicted, showing the distance between the drain and the nearest setback boundary. This is the primary parameter to be solved in the model for guidance, and can be manipulated by modifying other parameters (such as drain depth) to identify an appropriate LD for a water level decline considered acceptable (i.e., 2-5 cm)
- additionally, there are three different boundary conditions implemented in the model. The No Flow Boundary (NFB) restricts water flow across its boundary (with its location governed by LC or hS), while the Constant Head Boundary (CHB) maintains a constant hydraulic head at its boundary. Lastly, the Constant Flow Boundary (CFB) ensures a consistent flow rate across its boundary, in this case from LSR.

Further technical detail on the modelling conceptualisation can be found in Appendix Section A.1.

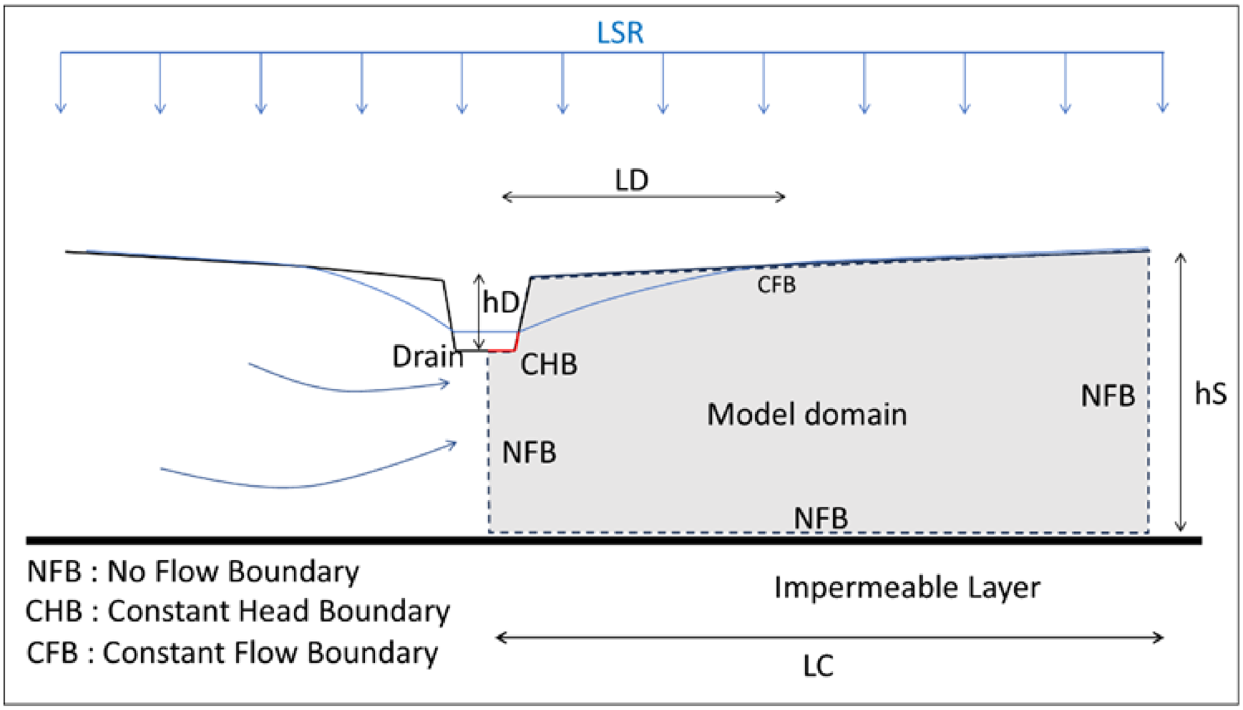

Figure 1. Schematic representation of the model conceptualisation, highlighting important parameters, including the depth to the sealing/low permeability layer (hs), drain depth (hD), drain catchment distance (LC), drain setback distance (LD), and implemented boundary conditions NFB (No Flow Boundary), CHB (Constant Head Boundary), and CFB (Constant Flow Boundary).

4 Development of a simple modelling tool to assess drain effects on wetlands

4.1 Overview

Representation of the conceptual drainage model was undertaken numerically in the software COMSOL Multiphysics, which allowed the integration of complex governing equations such as the groundwater flow equation. A model was built for three selected wetland verification sites, ones that had known drainage impacts and monitoring data to support model calibrations.

Site specific data was collected and used during modelling, including climate and soil depth and conductivity information, with the models calibrated against shallow groundwater levels from wetland monitoring bores in close proximity to existing drains. An acceptable calibration helps prove the suitability of the conceptual drainage model to predict the lateral effects of drains on shallow groundwater drawdown.

4.2 Selected verification sites

Three wetlands were selected for modelling (Table 1). These sites were primarily chosen based on known water level data and locations around the country (different climate and soil types). Water level loggers installed in wetland drains and perpendicular to drains at varying distances allowed transient data collection; significant for validating numerical models. See Figure 2 for an overview of where the verification sites are located.

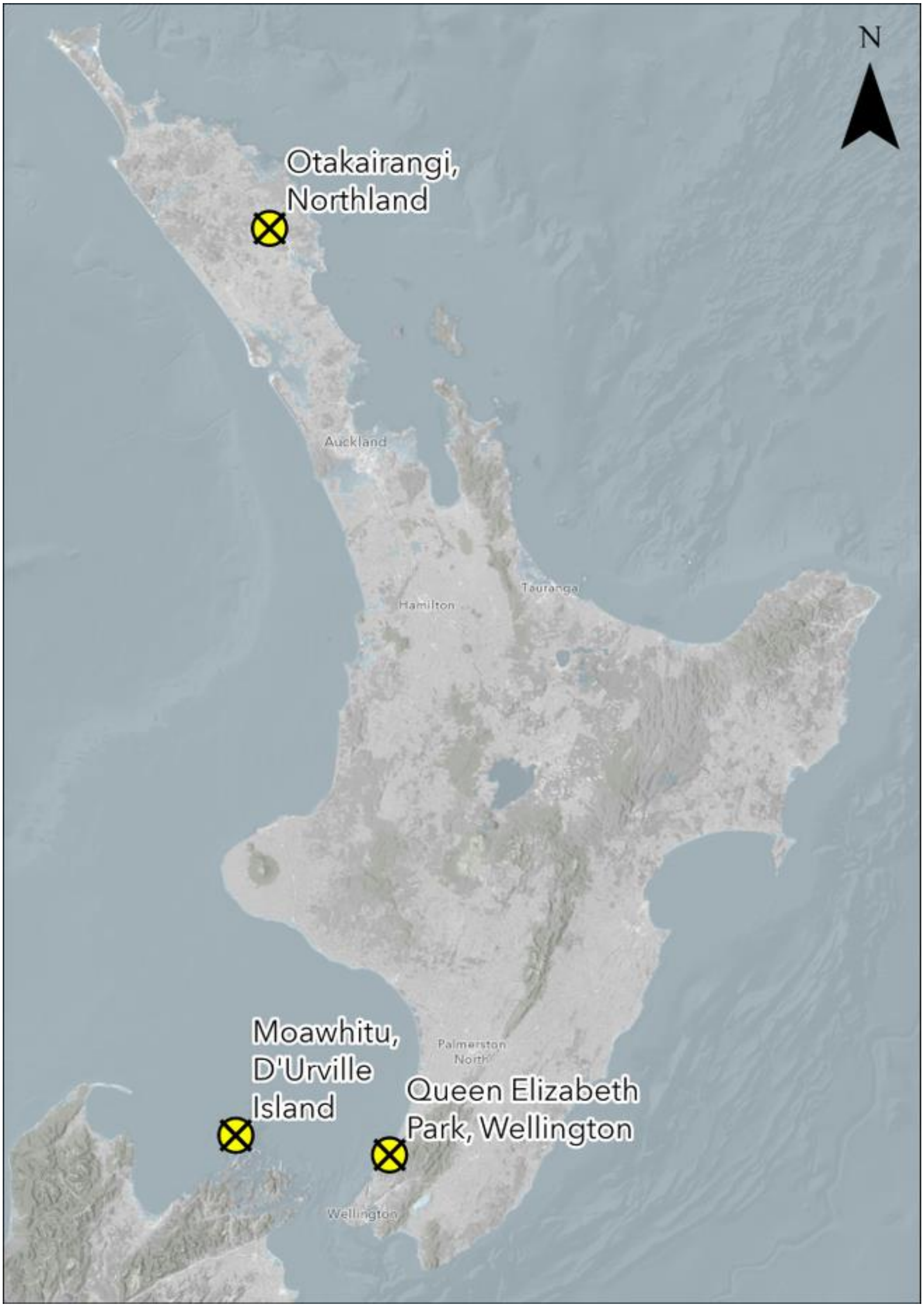

Figure 2. Overview of the three selected wetland verification sites

Figure C1 – Figure C3 in Appendix C present each of the wetland verification sites in greater detail.

Table 1. Wetlands used for method verification

Wetland	Location	Catchment and Drainage Description	Wetland Type
Queen Elizabeth Park	Wellington Region – Kāpiti Coast near Raumati	A historic 80+ha peatland, surrounded by sand dune ridges and some hill country. Extensively drained for agricultural and in the process of being restored. The surface water catchment applied in modelling of a single drain to the north is small (63.9 ha), with surface water inputs from urban and mixed wetland landuses, direct rainfall and surface water from a small but steep hill country catchment to the east.	Historically a peatland, however following drainage and farming, there is now a mosaic of wetland types depending on hydrological drivers and level of farming modification. Degraded peat is common throughout the site.
Moawhitu Wetland	Marlborough Region – D'Urville Island, Greville Harbour	An extensively drained coastal wetland of ~70 ha that was historically used for agriculture, but is now public land and in the process of being restored. Bounded by sand dune ridges to the south and steep forested (native) catchments, a network of drains dissects the wetland before draining to a single outlet location to the sea. A single drain with a surface catchment of 92.7 ha was modelled.	Historically this wetland is likely to have had a mosaic of fen and swamp wetland types, with inputs from surface water along defined stream paths, shallow groundwater and rainfall. Decayed organic matter is present, having accumulated within the wetland at depths of up to 3 m, with silty clay identified beneath this. The site is now a degraded swamp.
Otakairangi Wetland	Northland Region – Whangarei near the Wairua River	A ~260 ha remnant wetland that has been subject to drainage around the fringes and has a large central drain cut through the middle of the wetland for flow conveyance from the upper catchment (~2140 ha).	Historically it was likely the wetland exhibited fen and bog conditions, although its position in the lower catchment would indicate parts may have been swampland with increased surface water and nutrients. Following drainage and development, there is now a mosaic of wetland types, with swamp margins (along the primary drain) transitioning to fen and bog further away from any surface water inputs.

4.3 Model input data requirements

The three verification sites incorporated a range of input data to both build and calibrate the numerical models to represent the current effects of existing drains within the wetlands. This included identification of parameters in Figure 1 and;

- Rainfall and evapotranspiration timeseries data aligning with water level monitoring periods,
- Shallow groundwater level monitoring data on a 30-minute timestep at bores perpendicular to existing drains,
- Depth to a potential impermeable layer, gathered from hand augering up to 5 mbgl,
- Soil hydraulic conductivity data, collected from a combination of literature data and field investigations checks (through slug tests conducted within the wetlands),
- Drain dimensions (depth and width).

Further detail is provided in Appendix A Section A.4.

4.4 National input data for modelling tool

As part of this study, we developed two national datasets that could be used to support a tool, following Phase 1 of this project and the workshop (see Section 2) identifying the national data gaps that make drainage assessments challenging.

These have been presented as maps in Appendix B showing the estimated annual land surface recharge (LSR) and soil drainage rates (the latter was assumed to be a suitable proxy for hydraulic conductivity, or Ksat). The maps are intended to provide information where there may be an absence of local site data, or for rapid preliminary assessments that may screen risks of drainage to a wetland.

The verification models did not utilise these national maps, as the more comprehensive input data collected for each site allowed LSR and soil hydraulic conductivity to be predicted through the numerical modelling process.

A technical description on the development of these maps is provided in Appendix A Section A.6 and A.7.

5 Model results (water levels)

Overall, the verification of models at Queen Elizabeth Park, Moawhitu Wetland, and Otakairangi Wetland show the drainage models are suitable in simulating the water levels in observations bores that were perpendicular to a drain. This indicates that the conceptual model has merit as a high-level tool that can simplify the complex drainage problem and provide guidance around potential lateral effects, and setback distances of drains near wetlands.

Further detailed technical information about the modelling results has been described in Appendix A Section A.8, while calibration results for each of the wetlands has been presented in the sub-sections below.

5.1.1 Queen Elizabeth Park – Kāpiti Coast

Queen Elizabeth Park, located in the Wellington Region – Kāpiti Coast near Raumati, was selected as the first site for model verification. The objective was to calibrate the numerical drainage model to align closely with field observations at a monitoring bore located ~65 m away from an existing drain, and accurately represent the hydrogeological characteristics of the area. Figure 3 presents the accompanying conceptual model diagram, illustrating the hydrogeological features of the Queen Elizabeth Park.

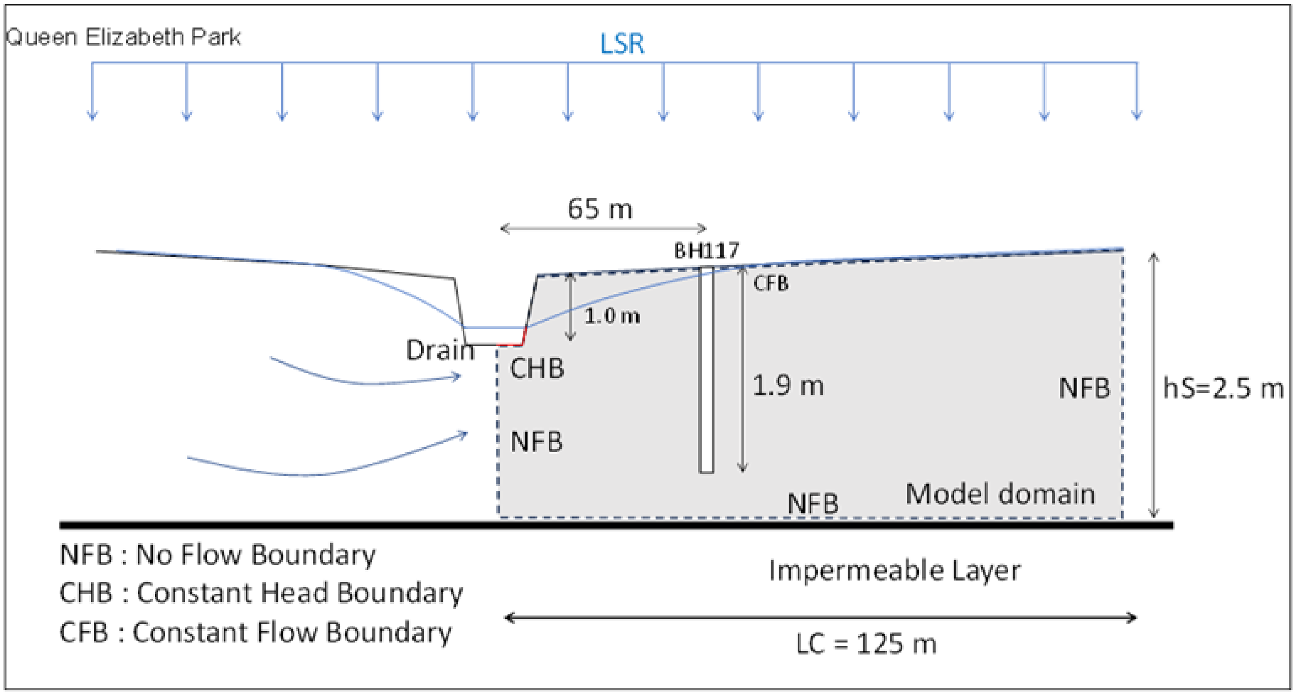

Figure 3. Conceptual model for shallow groundwater dynamics at Queen Elizabeth Park

The calibration process involved an iterative assessment of physical parameter values to accurately represent the monitored water levels at bore BH117, within Queen Elizabeth Park. These calibrated parameter values include the maximum infiltration capacity (i-cap) set at 20 mm/day, hydraulic conductivity of $8x10^{-5}$ m/s, and specific yield (Sy) of 0.035. Selection of the parameters was chosen based on a combination of established knowledge, theoretical considerations[5,6], and available field data (see Section A.8 in Appendix A). This comprehensive approach ensured that the calibrated model parameters reflected the hydrogeological characteristics of Queen Elizabeth Park as best as possible and were within known literature bounds.

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[5] Williams, A., Gilman, K., & Barker, J. 1995. Methods for the prediction of the impact of groundwater abstraction on East Anglian wetlands. British Geological Survey Report WD/95/SR.

[6] Lv, M., Xu, Z., Yang, Z.-L., Lu, H., & Lv, M. (2021). A comprehensive review of specific yield in land surface and groundwater studies. Journal of Advances in Modeling Earth Systems, 13, e2020MS002270. https://doi.org/10.1029/2020MS002270

A comparison was made between the model's predictions and observed water levels at BH117 to evaluate its performance. Figure 4, shown below, illustrates the comparison of observed and modelled water levels at BH117 in Queen Elizabeth Park.

The calibrated model exhibited a Nash-Sutcliffe Efficiency (NSE) value of 0.58, indicating reasonable agreement between observed and modelled values. The coefficient of determination (R2) was also determined to be 0.62, suggesting a strong correlation. The percent bias (Pbias) was calculated at 0.46%, indicating a slight positive bias or overestimation of the modelled results compared to the observed values.

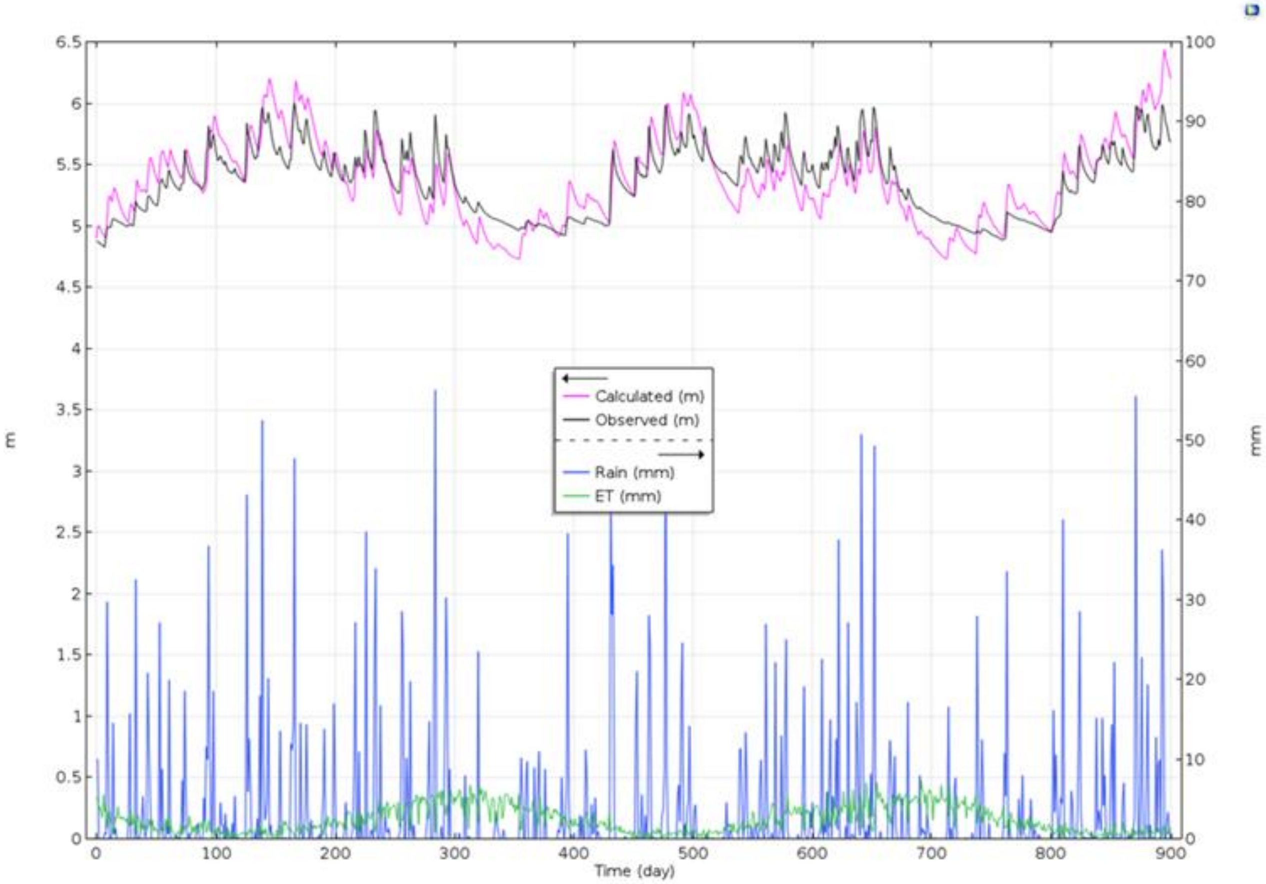

Figure 4. Comparison of observed and modelled water levels at BH117, Queen Elizabeth Park

The models calibrated Ksat value of $8x10^{-5}$ m/s was significantly higher in permeability than the slug tests conducted near the monitoring site (4.45×10^{-7} m/s). Possible reasons for this include:

- Water level monitoring data in BH117 may not truly reflect groundwater within the unconfined aquifer. The ‘flashy’ nature of the hydrographs in Figure 4 and ground surface level data indicate some of these events would result in above ground water levels. Consequences of this would be an increase in the calibrated Ksat to reflect higher drainage rates.
- The limited impermeable layer beneath the wetland may be resulting in vertical movement of groundwater out of the wetland (in addition to lateral movement towards the drain), while also being influenced by coastal (tidal) effects on the regional groundwater table.

These findings highlight that the conceptual drainage model is useful in simulating shallow drainage and its effects on water levels at Queen Elizabeth Park, however, is also identifies the complexities of drainage at certain wetland sites and the importance of having a good understanding of the sites hydrological setting and quality of the input data.

5.1.2 Moawhitu Wetland – D'Urville Island

The verification process extended to Moawhitu Wetland, located in the Marlborough Region on D'Urville Island, Greville Harbour. The primary objective was to calibrate the groundwater model to accurately represent the hydrogeological conditions specific to this wetland, taking into account the presence of a drain within the wetland. The conceptual model diagram for Moawhitu Wetland, presented in Figure 5, provides an overview of the groundwater dynamics within the wetland area.

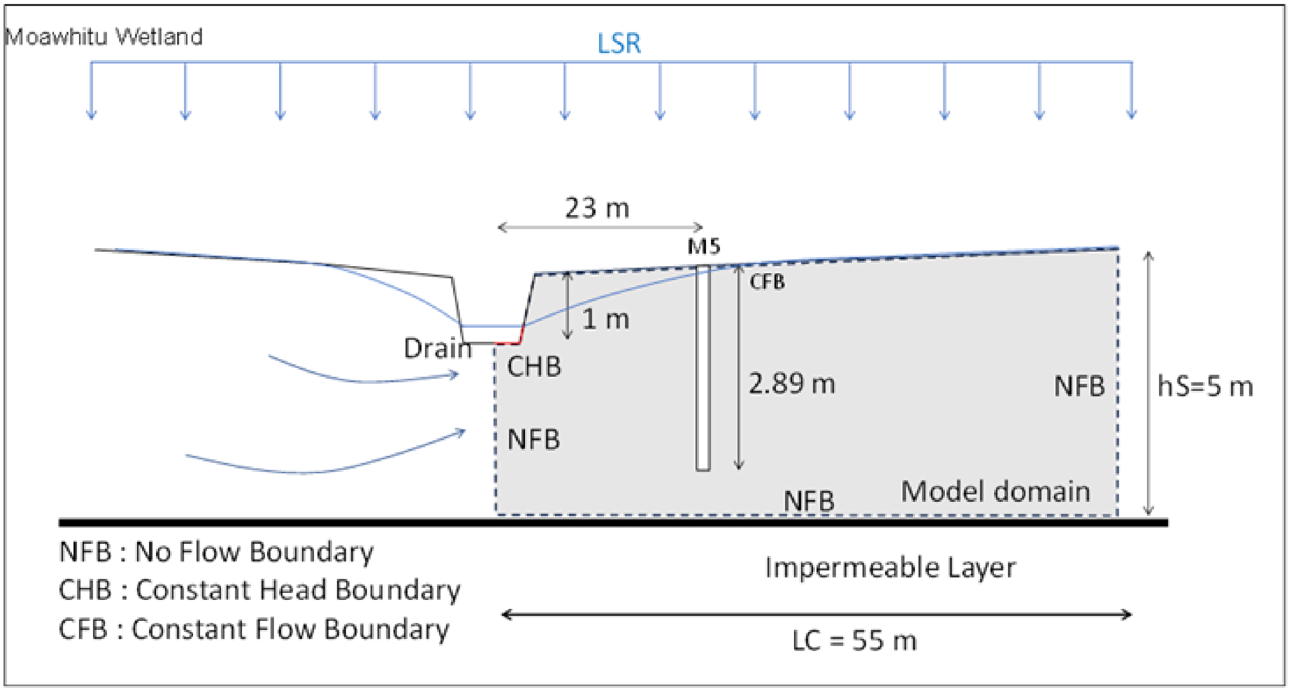

Figure 5. Conceptual model for shallow groundwater dynamics at Moawhitu Wetland

After thorough calibration, the model parameters adopted were a hydraulic conductivity of 2.3x10^{-8} m/s, the maximum infiltration capacity (i-cap) of 30 mm/day, and the specific yield (Sy) of 0.085. Notably, the average slug test yielded a Ksat value of 2.96x10^{-8} m/s, which perfectly aligns with the calibrated Ksat value (2.3x10^{-8} m/s) for this site. This provides good confidence in the conceptual drainage model at this site.

A comparison was conducted between observed and calculated water levels at observation point M5 in Moawhitu Wetland to evaluate the model's performance. Figure 6 presents this comparison.

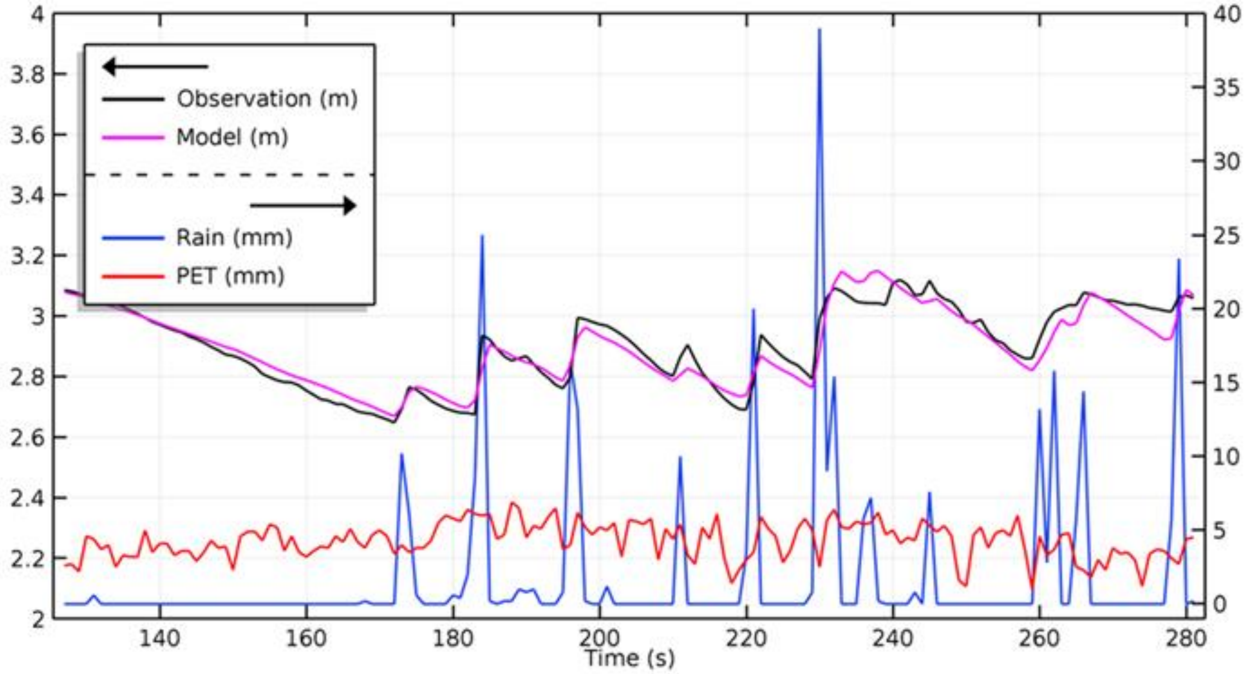

Figure 6. Comparison of observed and modelled water levels at bore M5, Moawhitu Wetland.

The calibrated model exhibited an impressive Nash-Sutcliffe Efficiency (NSE) value of 0.92 and R^2 of 0.93, indicating a strong accuracy and correlation between observed and modelled values. The percent bias was calculated at 0.1%, indicating minimal deviation between the modelled and observed results. These findings further validate the effectiveness of the conceptual model in simulating drainage dynamics at Moawhitu Wetland and contribute valuable insights into the hydrological processes within the study area.

5.1.3 Otakairangi Wetland – Whangarei

The final site selected for verification was Otakairangi Wetland, located near the Wairua River in Whangarei, Northland Region. Field data (specifically Ksat and depth to impermeable layer) was unavailable due to poor weather restricting four separate collection attempts. The calibration process ensured that the parameter values were modified within literature bounds and suitably represented the expected hydrogeological conditions for Otakairangi Wetland. The conceptual model diagram for this site, depicted in Figure 7, provides an overview of the groundwater dynamics.

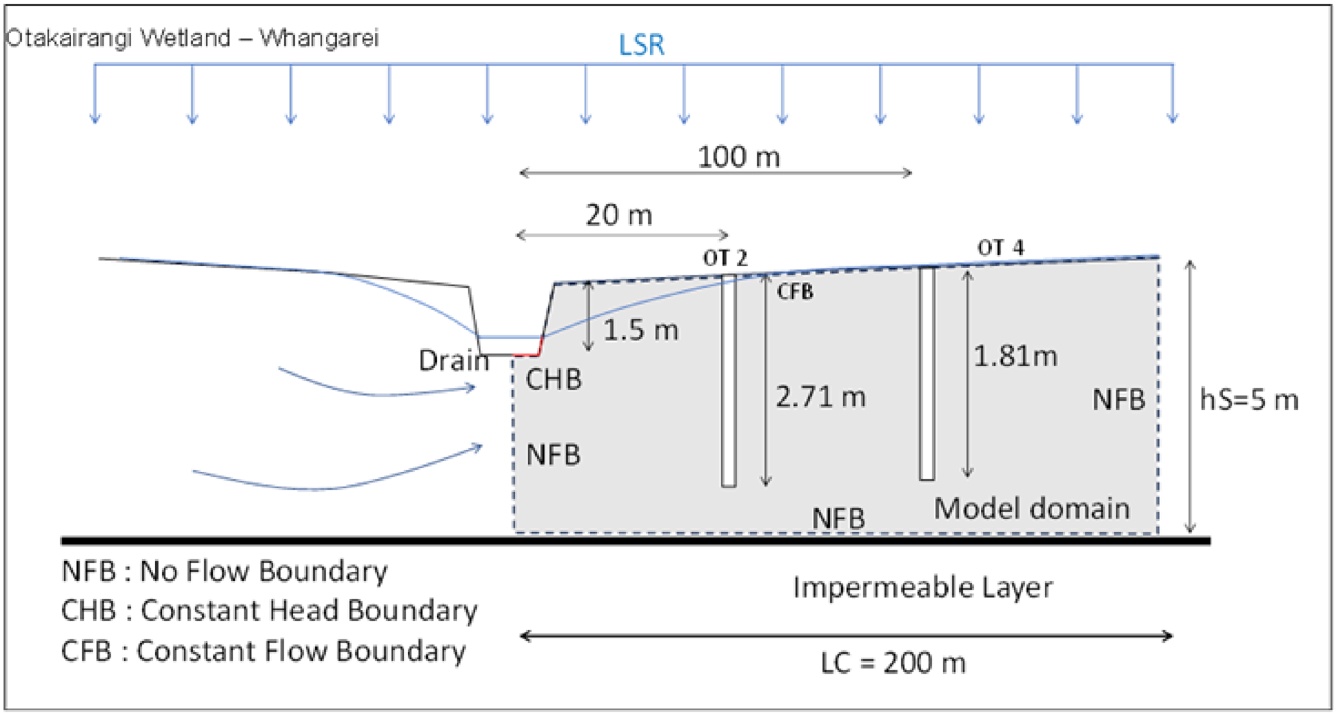

Figure 7. Conceptual model for shallow groundwater dynamics at Otakairangi Wetland – Whangarei

The hydraulic conductivity for Otakairangi Wetland was calibrated as 1.6x10^{-8} m/s, the maximum infiltration capacity (i-cap) was set at 8.5 mm/day, and the specific yield (Sy) was estimated to be 0.11 through calibration. Whilst no field data was available to validate the calibrated Ksat value at this site, the value is similar to Ksat values collected from slug tests in Moawhitu wetland (see Table A 1 in Appendix A).

The calibrated model exhibited a Nash-Sutcliffe Efficiency value of 0.59, indicating a reasonable agreement between the observed and modelled values. The percent bias was calculated at -0.6%, indicating a minimal deviation between the modelled and expected results. Furthermore, the coefficient of determination (R^2) was determined to be 0.75, demonstrating a strong correlation between the observed and modelled water levels. Figure 8 presents a comparison between the calculated data and the observed records at bore OB4 in Otakairangi Wetland – Whangarei, providing additional insights into the model's performance.

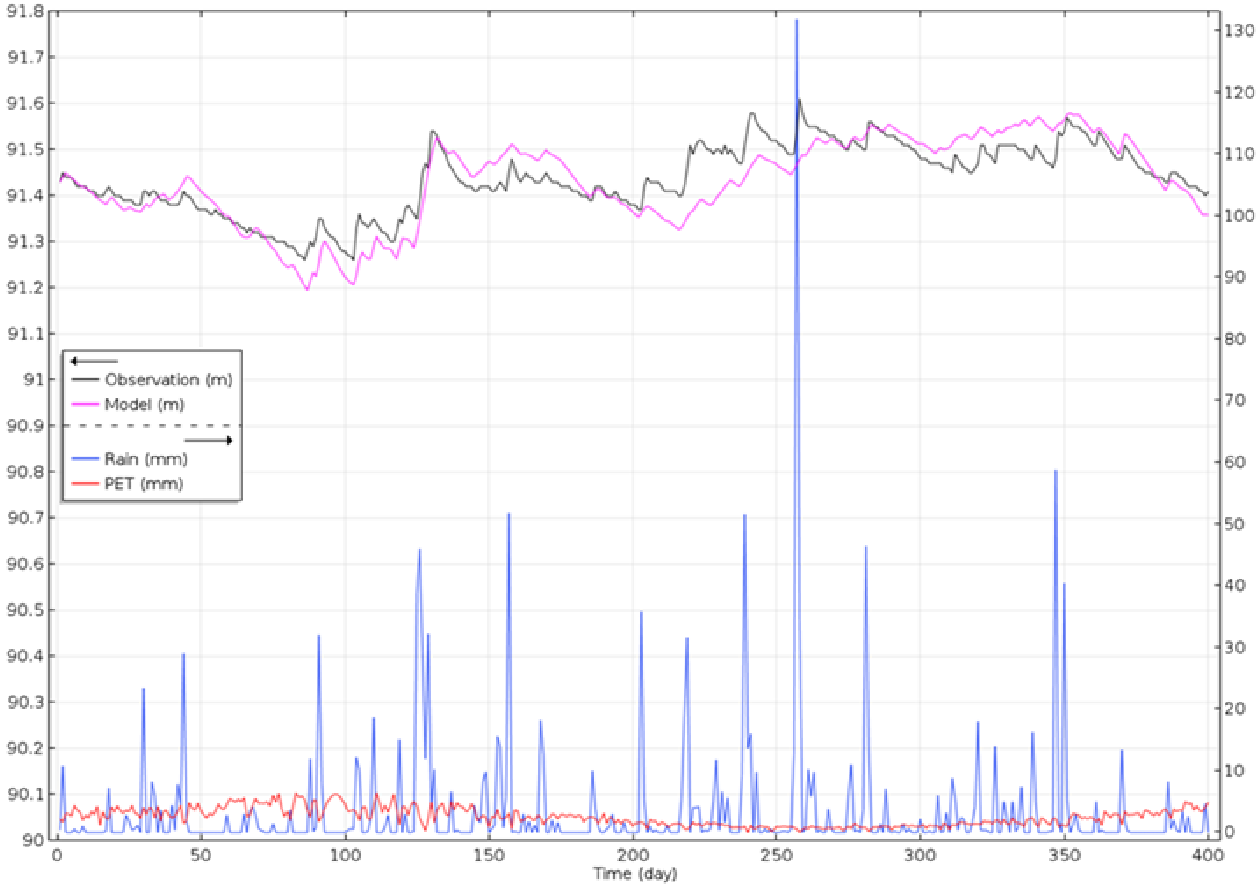

Figure 8. Comparison of modelled and observed water levels at observation bore OB4, Otakairangi Wetland – Whangarei.

6 Applying model to a hypothetical wetland drain

6.1 Site location and setting

Te Hapua Wetland Complex in the Kāpiti Coast District, Wellington Region, was selected as a site to develop a hypothetical land development scenario. This presumes a subdivision consent application for a single lot residential dwelling next to an existing wetland complex. A drain has been proposed as part of the subdivision to lower water levels close to the proposed building site (Figure 9).

Figure 9. Location of hypothetical land development consent application (white boundary) and proposed drain (red line) next to Te Hapua Wetland Complex.

6.2 Data inputs

The following assumptions were considered to estimate the drain setback distance (LD) in Te Hapua Wetland Complex case study;

- Depth to impermeable layer (hS): It was assumed that the depth to the impermeable layer beneath the ground surface is 3 meters,
- Saturated hydraulic conductivity (Ksat): was assessed in two scenarios as moderate (72 mm/hr) and rapid (288 mm/hr). The latter prevents a conservative assessment of drainage setback,
- Drain depth (hD) and water level: Two scenarios were evaluated with different drain depths, specifically 1.5 and 2 meters. The water level in the drain channel was assumed to be 0.5 meters,
- The wetland catchment length (LC) was determined iteratively with LD, by estimating the approximate midpoint between the drain to the northwest and the wetland boundary/edge. This parameter (LC – LD) was estimated as 85 meters based on the topographic map, and the ground was assumed to be flat. See Section A.9 in Appendix A for more detail.
- Land surface recharge (LSR): based on the national land surface recharge map, LSR was estimated to be 399 millimetres per year (mm/year).

A conceptual overview of the model is presented in Figure 10.

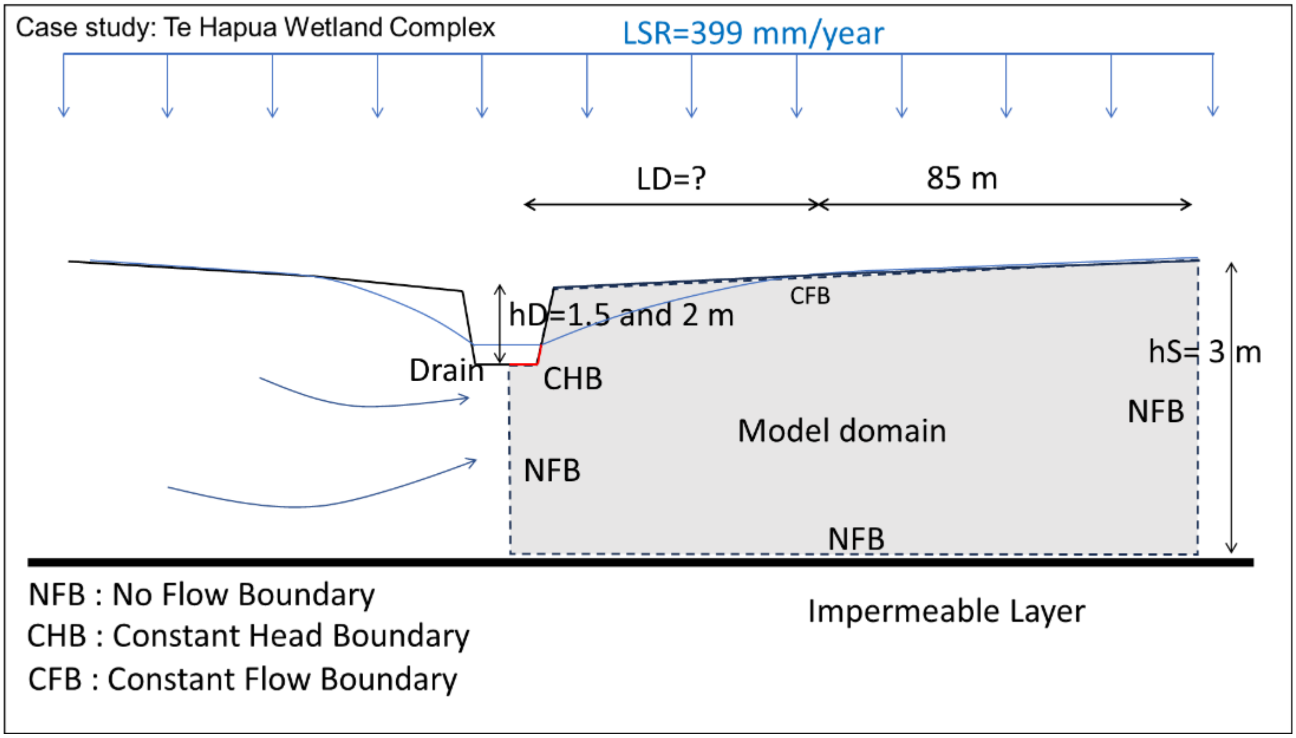

Figure 10. Conceptual model of the groundwater system and drainage components in Te Hapua wetland complex case study.

6.3 Model results

The following sections present the numerical modelling outputs for the hypothetical site, including the estimated setback distance from the drain for different average water level drawdown depths. The scenarios highlight the sensitivity of the model to certain input parameters such as drain depth and soil Ksat, for example, where a higher Ksat results in greater drainage effects and subsequently, a larger setback distance (of the drain from the wetland) would be required.

Further technical detail has been presented in Appendix A Section A.9.

6.3.1 Scenario 1 – Drain depth of 1.5m

In order to evaluate the impact of drains on wetlands and determine acceptable water level thresholds, three levels of effect were assumed: low, moderate, and high. In the low effect scenario, where the average water level drawdown remains consistently below 10 mm, a recommended setback of 132.5 meters is necessary (for the rapid permeability scenario). The setback distance reduces with increasing levels of drawdown and possible effects. Results are summarised in Table 2 and show the sensitivity of the modelling to input parameters such as Ksat, where a moderate drainage of 72 mm/hr would result in the low effect scenario changing from 132.5 m to 51 m.

Table 2: Influence of drains on water levels with varying setbacks to the wetland (drain depth 1.5 m)

Long term average water level drawdown	**Lateral setback distance (LD) from modelling (m)**	
	Ksat – moderate (72 mm/hr)	Ksat – rapid (288 mm/hr)
Low effect: Minimal/no change (<10 mm)	51 m	132.5
Moderate effect: 50 mm	48.6 m	123.7
High effect: 150 mm	42.5 m	103.9

6.3.2 Scenario 2 – Drain depth of 2m

For a deeper drain of 2 meters, the suggested setbacks are provided in Table 3. In the low effect scenario (with rapid Ksat), a setback of 173.1 meters was recommended for maintaining minimal or no change in water levels (<10 mm). With a moderate Ksat (72 mm/hr), the setback decreases to ~82 m for low drawdown effects. This scenario shows that increasing the drain depth from 1.5 to 2 meters resulted in setback distances increasing by a minimum of 30 m, and even greater when Ksat was rapid rather than moderate.

Table 3: Influence of drains on water levels with varying setbacks to the wetland (drain depth1.5 m)

Long term average water level drawdown	**Lateral setback distance from modelling (m)**	
	Ksat – moderate (72 mm/hr)	Ksat – rapid (288 mm/hr)
Low effect: Minimal/no change (<10 mm)	82.1 m	173.1 m
Moderate effect: 50 mm	78.7 m	164.2 m
High effect: 150 mm	70.1 m	144.4 m

These scenarios emphasise the importance of the drain depth and Ksat when considering the setback distances to manage effects on wetland ecosystems.

6.4 Limitations

The new tool has certain limitations that should be taken into account when interpreting the results. A summary of some of these limitations is detailed below, while greater description has been provided in Appendix Section A.2.

- the assumption of a single-layer aquifer system may oversimplify the actual subsurface conditions, which could include multiple layers with different hydraulic properties that are not always homogenous and uniform,
- the model assumes a low permeability layer beneath the wetland, which may not hold true in all conditions,
- aquifer discontinuities or groundwater contributions (i.e., artesian flows) are not accounted for,
- a two-dimensional representation of drainage with flow boundary conditions (i.e., constant head or no flow boundaries) simplifies relatively complex hydrogeological conditions.

Further refinement and verification of the model against field data and more detailed site-specific information can help improve its accuracy and applicability.

7 Summary and recommendations

No readily available tool currently exists in New Zealand that can determine the effects of historical drainage or new drain developments on the water levels of wetlands. This is a significant impediment to protecting and restoring the values of wetlands.

This project has developed a new wetland drain setback tool (WDST) for future application in New Zealand. The tool has been developed and verified using three case study wetlands, and a hypothetical drain development scenario. In all situations where the WDST was applied it performed suitably.

Further development of the WDST is recommended to provide greater confidence in its application and sensitivity analysis for different wetland settings. In particular, this could involve:

- Verification of the drainage model at a greater number and variety of wetland types around the country, subject to different soils and climatic conditions.
  - This is subject to sites having suitable transient water level monitoring data perpendicular to drains.
- Capture of flow out of a wetland drain, to provide additional calibration of the drainage model.
- Soil tests across different wetlands, including infiltration and Ksat, which may be conducted through a range of methods (such as slug tests or double ring infiltrometers).
- Pumping tests, to develop an understanding of specific yields within different wetland types and soil states.

For further details on recommendations to enhance the WDST, refer to Appendix A Section A.10.

7.1 National guidance

Our view is that the WDST has strong potential to provide a standardised national approach for addressing the adverse effects of drains on wetlands in New Zealand.

With additional development, a web-based interface for the wetland model can be developed to enhance accessibility and facilitate effective communication and collaboration among stakeholders. This interface would allow remote access to the model, enabling users to interact with it, input parameters, and visualise simulation results without requiring advanced technical knowledge. Such a user-friendly interface would empower stakeholders to make informed decisions regarding wetland management and conservation strategies based on accurate predictions and insights into flow dynamics.

Expert judgement could then be applied on the model outputs by resource management scientists, such as ecologists and hydrologists, which would consider the confidence in the model results (based on conceptualisation and input data), the sensitivity of the site to changes in water level and resilience (or risk) of new drainage activities.

If a national tool and web-interface is progressed, we propose a minimum of 10 additional wetland sites are used to validate and refine the WDST. We believe this would be achievable within a 12-month timeframe including in collaboration with other agencies including council authorities.

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Appendix A – Modelling background information

A.1 Model conceptualisation

The conceptual drainage model assumes a single-layer aquifer system, even though the subsurface may consist of multiple layers. This simplification allows for a more straightforward representation of the system, focusing on the essential dynamics of groundwater flow and transport.

The soil properties within the model domain are assumed to be uniform and unchanged. This assumption eliminates the need for spatial variation of hydraulic properties, simplifying the model development process. The model treats the soil with consistent hydraulic conductivity, porosity, and other relevant properties.

An impermeable layer is assumed to exist beneath the model domain, acting as a barrier preventing vertical groundwater movement between the model domain and underlying layers. This impermeable layer helps confine the flow within the single-layer aquifer, enhancing the accuracy and realism of the model.

The ground surface is considered to have a gentle slope (i.e., low slope land <7 degrees), although actual terrains may exhibit varying topography. The model assumes a simplified slope to facilitate representation. The slope influences the hydraulic gradient and flow patterns within the aquifer, allowing the model to account for the effects of gravity on groundwater movement.

Different boundary conditions are used in the model to simulate real-world behaviour. The Neumann boundary condition is applied to the ground surface, representing the land surface recharge. The drain within the model domain is assigned a Dirichlet boundary condition, which sets a fixed hydraulic head value to maintain a constant water level. The remaining boundaries of the model domain are considered as no-flow boundaries, indicating that there is no water movement across them.

By integrating these conceptual elements and boundary conditions, the groundwater model provides a simplified yet meaningful representation of the subsurface system. This model conceptualisation serves as the basis for simulating groundwater flow within the defined domain.

Accurately analysing flow dynamics within wetlands and assessing the impact of drains requires robust modelling methodologies. Central to these methodologies is the groundwater equation, which describes the flow of water in porous media based on Darcy's law. This equation serves as the foundation for numerical models used to investigate flow patterns in wetland-drain systems. The groundwater flow equation, incorporating Darcy's law, can be expressed as follows:

$$\nabla \cdot (Ksat\ \nabla H) - Q = Sy \tag{1}$$

In this equation:

- The operator ∇ represents the gradient operator, accounting for spatial variations in the hydraulic head.

- The hydraulic head, *H*, refers to the potential energy of groundwater, representing the elevation to which water would rise in a confined system.
- The hydraulic conductivity tensor, *Ksat*, characterises the ability of the porous media to transmit water, accounting for variations in different directions.
- The term *Q* represents the sources and sinks of groundwater flow, including external inputs and extractions of water.
- The storage term, Specific yield(*Sy)*, captures the change in water storage within the porous media.

By discretising the domain and solving the equations numerically using COMSOL Multiphysics, a powerful simulation software, a numerical model is developed. This model incorporates the groundwater equation as the governing equation and includes additional parameters and boundary conditions specific to the wetland-drain system under investigation.

The combination of the groundwater equation and the numerical model provides a comprehensive understanding of flow patterns in wetlands. The equation captures the fundamental processes of flow in porous media, while the numerical model facilitates practical implementation and analysis. This integrated approach supports effective wetland management by considering hydrological dynamics and optimising conservation efforts.

By utilising insights from the simplified conceptualisation and detailed simulations from the numerical model, wetland stakeholders, including managers and policymakers, can make informed decisions. They can assess the impact of introducing drains, evaluate management strategies, and identify potential challenges or unintended consequences. This integrated approach ensures sustainable wetland development and conservation, promoting the preservation of critical ecosystems while addressing human needs.

In this study, we assume that the groundwater flow is perpendicular to the drain and that the system can be effectively represented in two dimensions. The assumption of perpendicular flow implies that the direction of groundwater flow is normal to the drain. This assumption simplifies the analysis by reducing the problem to a two-dimensional representation, where flow occurs primarily in the horizontal plane. While this assumption may not always hold true in complex systems, it is often a reasonable approximation for certain scenarios, such as flow towards a well or a drainage channel.

A.2 Modelling limitations and assumptions

Additional information on modelling limitations and assumptions is detailed below.

The assumption of a single-layer aquifer system may oversimplify the actual subsurface conditions, which could include multiple layers with different hydraulic properties. An example of this is in undeveloped peat bogs which may have the presence of a higher permeability Acrotelm layer (at the surface) and a lower permeability saturated Catotelm layer (beneath the Acrotelm)[1]. This conceptual simplification could affect the accuracy of the groundwater flow and transport simulations. Additionally, the uniformity assumption for soil properties may not accurately capture the spatial variations in hydraulic conductivity and porosity, especially in heterogeneous environments.

The assumption of a sealing layer beneath the model domain is another simplification that may not hold true in all cases. The presence of discontinuities, artesian flows or preferential flow paths could impact the vertical movement of groundwater and alter the model's predictions. Furthermore, the assumption of a gentle slope for the ground surface neglects the influence of steep terrains or complex topography on groundwater dynamics. This simplification may lead to deviations from reality in areas with significant elevation changes, although it wouldn’t be anticipated that a drain would be excavated on such steep upgradient land under common practice.

Although the model incorporates different boundary conditions to simulate real-world behaviour, the chosen boundary conditions may not fully capture the complexity of the actual system. The Neumann boundary condition representing land surface recharge assumes a uniform distribution, disregarding potential spatial variations in precipitation patterns. The Dirichlet boundary condition applied to the drain assumes a constant hydraulic head, which may not reflect actual fluctuations due to varying water levels. The no-flow boundaries assume impermeable boundaries, disregarding potential lateral or vertical groundwater flows or interactions with adjacent hydrological features.

Lastly, the assumption of perpendicular groundwater flow to the drain and the two-dimensional representation of the system may not hold true in all scenarios. Complex systems with intricate flow patterns or non-uniform drain configurations may require three-dimensional modeling approaches for more accurate results.

It is crucial to consider these limitations when interpreting the model's outputs and making decisions based on the simulated groundwater flow and transport patterns. The intent of the model is to eventually have a high-level tool that provides guidance on possible drainage setback distances with a selection of input data, otherwise trying to simplify a complex phenomenon that would typically require significant investment in time and money to determine site specific values with accuracy.

A.3 Modelling software

The groundwater model presented in this study utilises COMSOL Multiphysics, a powerful simulation software widely employed in various scientific and engineering disciplines. COMSOL Multiphysics provides a comprehensive platform for numerical modelling and simulation, allowing the integration of complex governing equations, such as the groundwater flow equation. By discretising the model domain and solving the equations numerically, COMSOL Multiphysics facilitates the creation of a robust numerical model.

This software also offers a user-friendly interface for defining parameters, boundary conditions, and other simulation-specific settings. With its advanced computational capabilities, COMSOL Multiphysics enables accurate predictions and insights into flow dynamics, supporting informed decision-making in wetland management and conservation efforts.

A.4 Modelling input data for verification sites

Further details on the input data used in each of the three model verification sites is provided below in Table A 1.

Table A 1. Modelling input data and sources of information

Input data	Study Wetlands		
	Moawhitu Wetland	**Queen Elizabeth Park**	**Otakairangi Wetland**
Climate data	Source: Niwa's virtual climate station network (VCSN) data at point 30,691/P157136 . Type: Daily rainfall and evapotranspiration (ET) Duration: 1/1/1972 to current.	Source: Niwa's CLIFLO at Paraparaumu Aero AWS – Station 8567 Type: Daily rainfall and ET (Penman Monteith Method) Duration: 1/1/2010 to current.	Source: Niwa's CLIFLO at Whangarei EWS – Station 40980 Type: Daily rainfall and ET (Penman Monteith Method) Duration: 16/8/2015 to current.
Water level monitoring (verification)	Type and location: 30 - minute intervals at two sites; within drain and 23 m perpendicular to drain. Duration:~10 months (6 July 2017 to 12 April 2018)	Type and location: 30 - minute intervals at two sites; within drain, 65 m perpendicular to drain. Duration:~3.5 years (1 March 2019 to 8 September 2022)	Type and location: 30 - minute intervals at three sites; within drain, 20 m and 100 m perpendicular to drain. Duration:~1.3 years (6 October 2017 to 11 January 2019)
Drain dimensions (hD) and ground surface	Ground survey points from cross sections across drains and through transducer sites. Steep trapezoidal drain dimensions of 3.5 m (w) x 1.01 m (d)	Ground survey points from cross sections across drains and through transducer sites. Shallow trapezoidal drain dimensions of 6.5 m (w) x 1.08 m (d)	Ground survey points from cross sections across drains and through transducer sites. Shallow trapezoidal drain dimensions of 3 m (w) x 1.5 m (d)
Catchment **LC**	LC = 125 m, the midpoint between the drain and the neighboring parallel drain.	LC = 55 m, the midpoint between the drain and the neighboring parallel drain.	LC=200 m has been chosen for this site, taking into account the absence of nearby parallel drains. This distance has been selected to minimize any potential impact on the drain, enabling us to treat the boundary conditions as no flow.
Depth to impermeable layer (hS)	Hand augers identified highly degraded peat and organic matter present 0–3 mbgl, transitioning to clayey SILT with minor sand (3-4 mbgl) then silty CLAY with minor sand (4-5 mbgl).	Hand augers at two locations in QEP identified transition from peat to thin layer of sandy SILT (~3 cm) from ~2.5–3.2 m. Likely the low elevation and coastal setting are influencing vertical drainage rather than a	Since there was no available field data, for modeling purposes, an hS value of 5 m was assumed.

	An hS value of 5 m was adopted in modelling.	notable impermeable layer. An hS value of 2.5 m was adopted.	
Soil hydraulic conductivity (Ksat) – **Validation data only**	Two slug tests conducted at Moawhitu averaged 2.96 x 10^{-8} m/s (0.26 cm/day)	Two slug tests conducted at QEP ~30 m from the drain averaged 4.45 x 10^{-7} m/s (3.8 cm/day) Double ring infiltrometer tests of uncompacted peat in Kāpiti – median Ksat of 9 mm/hr (21.6 cm/d)	Field work was abandoned due to multiple flood events. Ksat adopted in modelling of 1.6 x 10^{-8} m/s (0.14 cm/day)

A.5 Calibration of modelling sites

A transient model was developed for each of the wetlands, and calibrated model parameters to achieve the best fit with the 30–minute timestep water level monitoring data. The calibration was compared against standard modelling performance measures, while also comparing against field data collected during the project (for example, Ksat derived from slug tests and presented in was used to validate the calibrated models Ksat). Acceptable results would indicate that the conceptualisation and equation parameters are suitable for applying to a hypothetical wetland drainage situation, producing estimates of possible setback distances relating to water level drawdown near the wetland.

A.6 National layer for LSR

Daily land surface recharge (the daily precipitation received in excess of the soil water deficit at the beginning of each day) was modelled for each virtual climate station network (VCSN) mesh cell that met slope-based selection criteria.

NIWA have defined VCSN grid points, covering the whole of New Zealand. A rectangular mesh was created, with a VCSN grid point at the centre of each mesh cell. The VCSN grid spacing is 0.05° latitude and longitude, which is approximately 5 km, but varies from north to south. The area of the mesh cells therefore varies from 2,133 ha in the south of the South Island, to 2,545 ha in the north of the North Island.

Recharge was calculated using Aqualinc’s soil moisture and irrigation simulation model, IrriCalc. The model was applied to each selected mesh cell, assuming no irrigation occurred. Model results for the dominant soil and land-use combination for each mesh cell were assumed to represent recharge in that cell.

The recharge modelling was initially done as part of the “Groundwater Atlas” project[7]. However, recharge was re-modelled because the slope-based criteria used to select the mesh cells to be modelled differed from that use for the “Groundwater Atlas” project.

A general description of the IrriCalc model and the key model inputs used for this project are described below.

IrriCalc overview

The method used by Aqualinc to estimate irrigation water use and drainage is an implementation of the internationally accepted soil water balance modelling approach described by Allen et al. (1998)[8]. Aqualinc’s implementation uses IrriCalc to simulate the day-to-day operation of an irrigation system. A rule-based approach to irrigation management is simulated. Application of the irrigation management rule on a daily basis, in response to modelled soil water balance status, determines the timing of irrigation and the amount to be applied. The result of applying the irrigation rule in concert with a daily water balance model is a daily time series of drainage depth and irrigation application depth. The total amount of drainage over a year and of irrigation water used and drainage over a user specified irrigation season, is the sum of the daily amounts.

For the purposes of this project, the irrigation rule was “Never irrigate”.

The version of IrriCalc used for this project has a single-layer soil water balance model that uses the following equation to update the calculated soil water content on a daily basis given daily measurements or estimates of rainfall, irrigation, drainage and actual evapotranspiration.

$$S_{t_2} = S_{t_1} + R_{(t_2-t_1)} + I_{(t_2-t_1)} - D_{(t_2-t_1)} - AET_{(t_2-t_1)}$$

Where:

S_{t_2} = Soil water content at time t_2

S_{t_1} = Soil water content at time t_1

$R_{(t_2-t_1)}$ = Rain between time t_2 and t_1

$I_{(t_2-t_1)}$ = Irrigation between time t_2 and t_1

$D_{(t_2-t_1)}$ = Drainage between time t_2 and t_1

$AET_{(t_2-t_1)}$ = Actual evapotranspiration between time t_2 and t_1

$AET_{(t_2-t_1)} = K_c \times f(S_{t_1,a}) \times ETref_{(t_2-t_1)}$

K_c = Crop factor applicable over time t_1 to t_2

$f(S_{t_1,a})$ = Evapotranspiration reduction function

$ETref_{(t_2-t_1)}$ = Evapotranspiration for a well-watered reference crop between time t_2 and t_1

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[7] Westerhoff RS, Dark AL, Zammit C, Tschritter C, Rawlinson ZJ. 2019. New Zealand Groundwater Atlas: Groundwater Fluxes. Wairakei (NZ): GNS Science. 60p. Consultancy Report 2019/126

[8] Allen, RG; Pereira, LS; Raes, D; Smith, M (1998): Crop evapotranspiration - Guidelines for computing crop water requirements. Irrigation & Drainage Paper 56, Food and Agriculture Organisation of the United Nations, Rome.

The evapotranspiration reduction function is an empirical function that takes a value in the range 0 to 1, depending on the ratio of soil water content on day t_1 to the “field capacity” and the parameter “a”. The parameter “a” is related to the volume of soil water that is readily available to the plant. The empirical function used in IrriCalc is described in Minhas et al. (1974)[9], and has been used in New Zealand by Heiler (1981)[10] and Bright (1986)[11].

Drainage is assumed to occur whenever the soil water content is calculated to be greater than “field capacity”. The volume of drainage is set equal to the volume required to reduce the soil water content to “field capacity”, and it is assumed that drainage occurs within the same daily time period as the rainfall or irrigation that raised soil water content above “field capacity”.

Reference crop evapotranspiration is calculated from daily climate measurements using the Penman-Monteith method (FAO-56), with parameters appropriate for estimating evapotranspiration from a well-watered grass sward of 120 mm height.

Irrigation amounts are either calculated by an irrigation system model on each day of a defined irrigation season or are input as time series measurements.

IrriCalc provides outputs of each component of the soil water balance on each day of the simulation, along with a mass-balance check-sum and the accumulated volume of water used for irrigation.
A crop factor time series for grasslands has been derived from data obtained from Canterbury Regional Council’s lysimeter network (Van Housen, 2015)[12].

Mesh Cell Selection

Land slope was used to select mesh cells where wetlands may occur that might be at risk from constructed drains.

Land slope data were obtained from the Land Resource Information System (LRIS)[13]. All land with slopes up to 7° was identified. The relevant slope categories are:

A = Flat to gently undulating 0-3°
B = Undulating 4-7°

We included all areas with the primary code A and B (i.e., predominantly Flat to Undulating topography), as well as C coded areas that have a secondary code of A or B (i.e., predominantly Rolling topography but with pockets of Flat to Undulating topography).

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[9] Minhas, BS; Parikh, KS; TN Srinivasan (1974): Toward the structure of a production function for wheat - Yields with dated inputs of irrigation water. Water Resources Research, 10:383-393.

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[12] Van Housen, J. 2015. Modelling the temporal and spatial variation of evapotranspiration from irrigated pastures in Canterbury. A thesis submitted for a degree of Doctor of Philosophy at Lincoln University.

[13] https://lris.scinfo.org.nz/, Manaaki Whenua Landcare Research

If the area in a cell that met the above criteria exceeded 1 hectare, the whole cell was included in the analysis. Urban areas were excluded.

Climate data inputs

Daily rainfall and potential evapotranspiration (PET) data were supplied by NIWA from their VCSN. The time period covered by the data is January 1973 – July 2018.

Soils

The soil's profile available water (PAW) is an input to IrriCalc. Data from S-Map[14] was used where available; elsewhere data from the Fundamental Soils Layer (FSL)[15] was used.

S-Map provides PAW values for 600 mm and 900 mm rooting depths. However, the FSL only provides a 900 mm value. The 900 mm PAW values from the FSL were converted to 600 mm for use with IrriCalc.

Soils were divided into the following PAW categories for the national-scale modelling:

- PAW values less than 75 mm were modelled as 60 mm, PAW values in the range 75 – 110 mm were modelled as 90 mm, and all higher PAW values were modelled as 120 mm.

Land cover

Land-cover information was sourced from the Land Cover Database (LCDB) version 4.1[16]. Only areas with vegetative cover were modelled. All vegetated areas were modelled as unirrigated grasslands.

Summary of Key Assumptions

- The topsoil is free-draining.
- Plant canopy development is sufficiently consistent across years to enable the use of the same crop factor time series each year to transform evapotranspiration for a reference crop into evapotranspiration from the land cover of interest.
- All rainfall and irrigation intercepted and retained on leaf and stem surfaces is effective in meeting the evapotranspiration load.

Land Surface Recharge Maps

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[14] https://smap.landcareresearch.co.nz/, Manaaki Whenua Landcare Research
[15] https://soils.landcareresearch.co.nz/soil-data/fundamental-soil-layers/, Manaaki Whenua Landcare Research
[16] https://lris.scinfo.org.nz/layer/48423-lcdb-v41-land-cover-database-version-41-mainland-new-zealand/, Manaaki Whenua Landcare Research

The method described above was used to create a national LSR map, which has been presented in Figure B 1 in **Appendix B.**

A.7 National layer for Ksat

A key input to the drainage setback calculation is the saturated hydraulic conductivity (Ksat) of the soil and underlying strata in the wetland catchment. This section describes the methods used to compile a national scale map of saturated hydraulic conductivity where local data may not be available. The intention is that this map be used to provide default or interim values for Ksat, in the absence of more detailed information on Ksat – for example, from prior catchment scale investigations that, ideally, specifically included site investigations.

Estimation of Ksat from permeability

The New Zealand Fundamental Soil Layer (FSL) originates from a join of features from the New Zealand Land Resource Inventory (NZLRI) and the National Soils Database (NSD). The FSL layer contains a permeability profile attribute, which defines the rate at which water moves through saturated soil[17]. The permeability classes are from Clayden and Webb (1994)[18], and are defined as Slow, Moderate, and Rapid. Table A 2 summarises the classes and likely permeability range. We have assumed that permeability is representative of the saturated hydraulic conductivity (Ksat).

Table A 2. Permeability classes, Clayden and Webb (1994)

Class	Symbol	Permeability (mm/hr)	Assumed Ksat (mm/hr)
Slow	S	<4	4
Moderate	M	4 – 72	72
Rapid	R	72 – 288	288

The soil permeability profile for soil polygons in the FSL may be classified as uniform (S, M, or R), slower with depth (R/M, R/S, M/S), or more rapid with depth (S/M, S/R, M/R).

To obtain conservative wetland setback distances, we assumed the most rapid permeability identified in the permeability class, and we set Ksat as the upper end of the permeability range for that class. For example, if the permeability class was S/R, Ksat was set to 288 mm/hr. Using these assumptions, we calculated Ksat for each polygon in the FSL with permeability data. This excludes land areas classed as estuary, ice, lake, quarry, river, town, or NA in the FSL, as these areas do not have permeability attributes.

Figure A 1 to Figure A 3 show the most rapid permeability class and associated Ksat for the Greater Wellington Region, Selwyn District, and Ashburton District, respectively.

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[17] Manaaki Whenua Landcare Research. 2020. Fundamental Soils Layer Permeability Profile. https://lris.scinfo.org.nz/layer/48105-fsl-permeability-profile/

[18] Clayden, B., & Webb, T. H. (1994). Criteria for defining the soilform, the fourth category of the New Zealand Soil Classification. Landcare Research New Zealand.

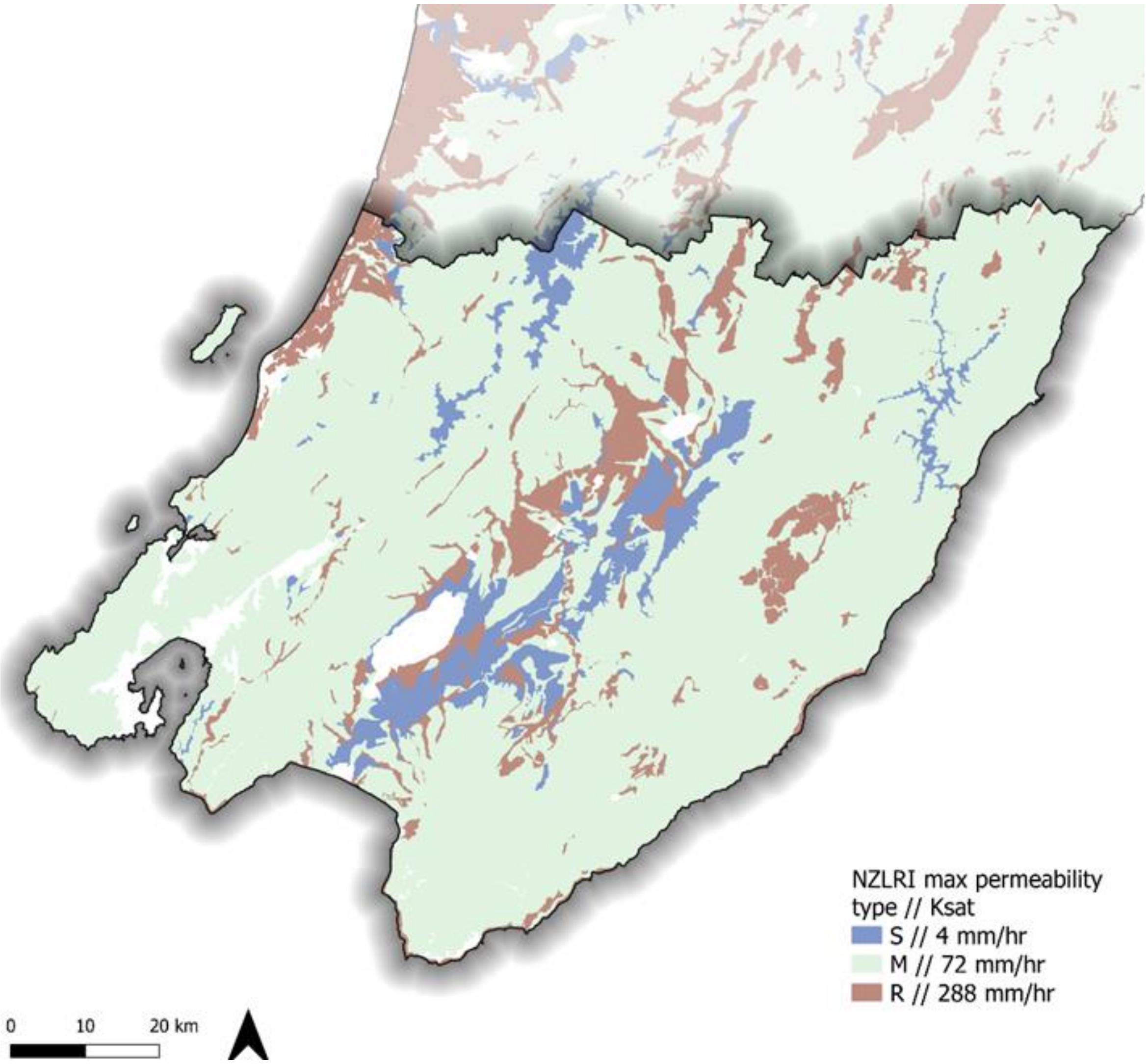

Figure A 1. Map of the most rapid permeability class and associated Ksat for the Greater Wellington Region

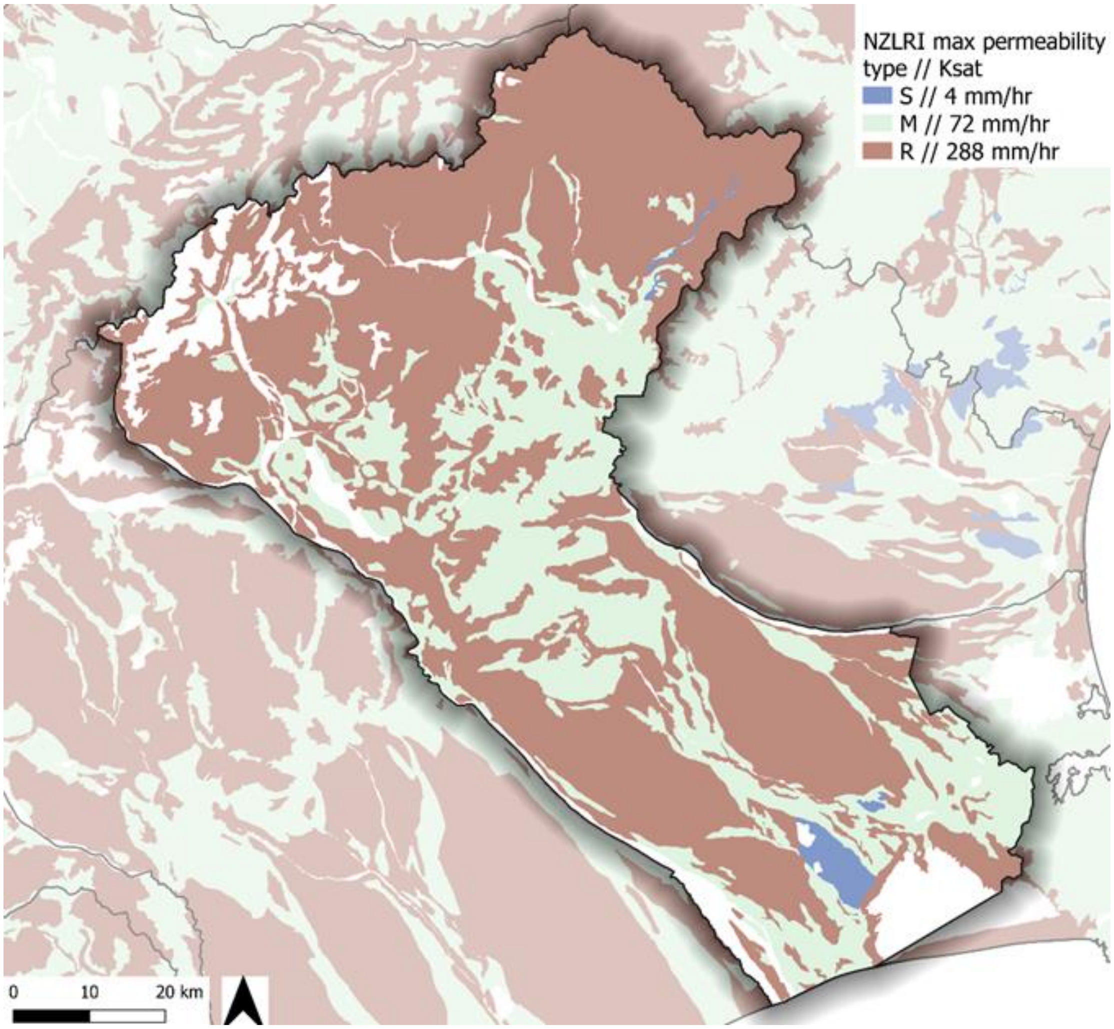

Figure A 2. Map of the most rapid permeability class and associated Ksat for the Selwyn District

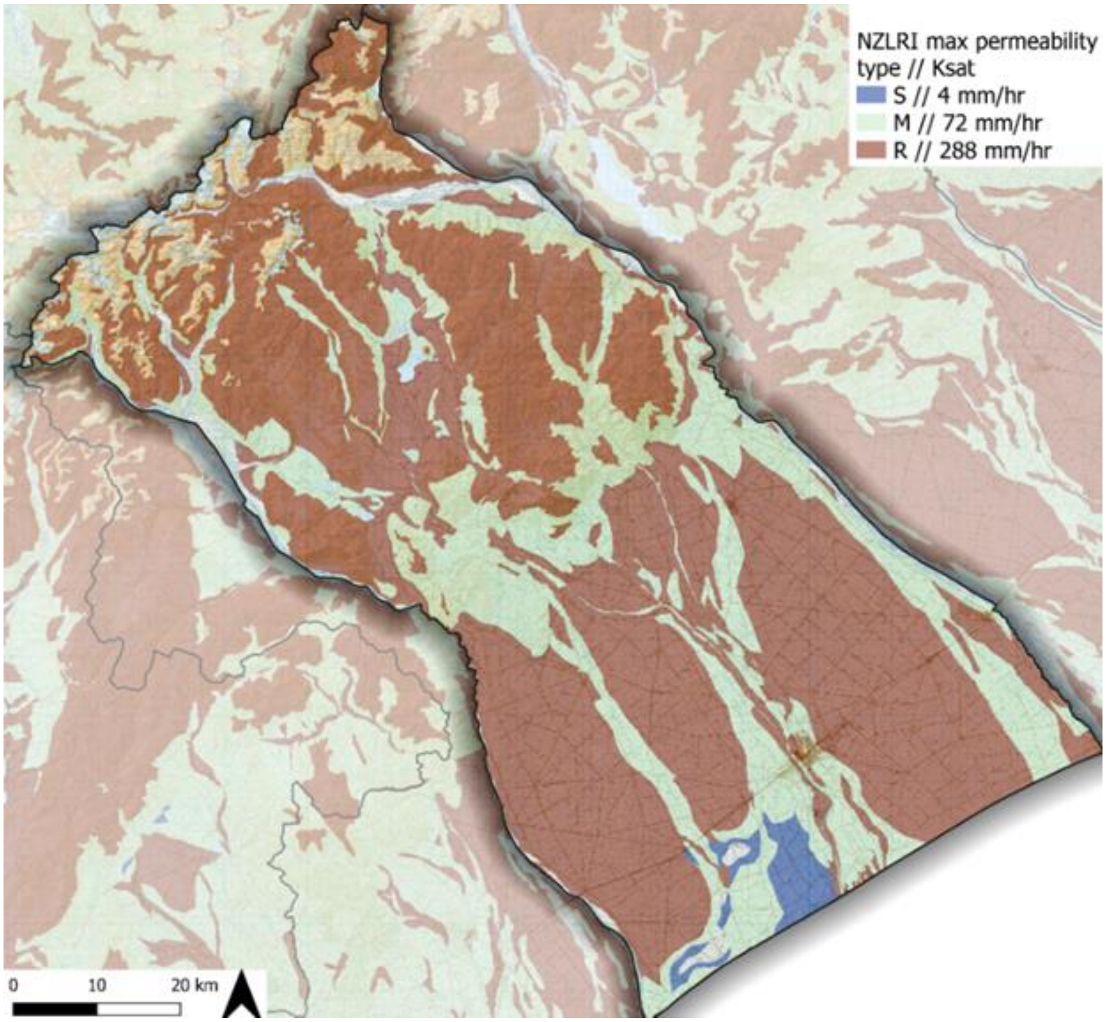

Figure A 3. Map of the most rapid permeability class and associated Ksat for the Ashburton District

Wetland areas where permeability data is unavailable

As noted in the previous section, some areas of the FSL do not have permeability data available. These areas appear as white polygons in the maps above. We explored additional data sources to maximise the amount of Ksat information within wetland extents.

The Ministry for the Environment (MfE) data service includes a layer of wetland extent recorded in 2013[19]. We used this layer to identify the wetland areas which were outside the FSL permeability data coverage.

The wetland layer included attributes with New Zealand Soil Classification (NZSC) information for some areas not covered by the FSL layer, including soil type (e.g., loamy peat) and drainage class (very poorly, poorly, imperfectly, moderately well, or well drained).

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[19] Ministry for the Environment. 2013. Current wetland extent - 2013. https://data.mfe.govt.nz/layer/52676-current-wetland-extent-2013/

However, for some polygons the NZSC data attached to the wetland extent layer was either missing or not meaningful. We overlaid these remaining areas on the most recent (Aug. 2021) S-Map Soil Drainage and Soil Texture layers[20], and joined the soil drainage and texture (peaty, silty, sandy, clayey, or loamy) attributes where available.

The wetland areas covered by each subsequent dataset are summarised in Table A 3. The area falling within each NZSC soil class and S-Map soil texture group is also summarised.

To estimate Ksat for areas without permeability data, we used the area where FSL overlapped the wetlands layer and the S-Map layer to obtain the dominant permeability group in for each soil type/soil texture group. We then extrapolated these soil type-permeability groupings to areas without permeability data. For example, 74% of the ‘peaty loam’ soil polygons in the wetland extent layer overlaid areas where the most rapid permeability classification was ‘M’ (S, S/M, or M/S), and so we set the permeability class for polygons falling in the ‘peaty loam’ soil class which did not have direct permeability data available to ‘M’. The dominant permeability class and associated Ksat for each soil type is summarised in Table A 3.

No polygons of the ‘peat’ or ‘loamy peat’ soil type overlapped with the FSL permeability data, within or outside the MfE wetland extents. We queried the National Soils Database for hydraulic conductivity data for peat or loamy peat soils. We found 14 records for peat soils containing hydraulic conductivity data under 0.05, 0.1, 0.2 0.4, and 1 bar of tension, and no records for loamy peat. Extrapolation of the available data suggested that the hydraulic conductivity with zero tension was around 80–100 mm/hr, which conservatively placed the peat soils in the ‘Rapid’ permeability class.

For the loamy peat areas and the remaining 11% of the wetland area without any soil data, we conservatively assumed the ‘Rapid’ permeability class.

Table A 3. Source of soil data for wetland areas. The area covered by each NZSC soil type from the MfE wetland extent layer and the area covered by each soil texture class from S-Map are also summarised.

Data Source	Area of wetland covered (ha)	Percentage (%) of total wetland area	Dominant permeability class	Assumed Ksat (mm/hr)
Permeability data from FSL	174,336	70%		
NZSC data from MfE wetland extent layer	43,176	17%		
Peat	*29,826*	*69%*	*R*	*288*
Loamy peat	*6,649*	*15%*	*R*	*288*
Peaty loam	*4,113*	*10%*	*M*	*74*
Peaty sandy loam	*1,046*	*2%*	*R*	*288*
Peaty silt loam	*866*	*2%*	*S*	*4*

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[20] Manaaki Whenua Landcare Research 2021. Smap soil drainage and soil texture maps. https://lris.scinfo.org.nz/layer/105955-smap-soil-drainage-aug-2021/, https://lris.scinfo.org.nz/layer/105954-smap-soil-texture-aug-2021/

Peaty clay loam	*317*	*1%*	*M*	*74*
Deep soils	*196*	*0.5%*	*M*	*74*
Peaty sand	*154*	*0.4%*	*R*	*288*
Fine sandy peat	*9*	*0.02%*	*R*	*288*
Silt loam and clay loam	*1*	*0.001%*	*M*	*74*
Drainage and texture data from S-Map	4,653	2%		
Peaty	*1807*	*39%*	*M*	*74*
Silty	*1026*	*22%*	*M*	*74*
Sandy	*948*	*20%*	*R*	*288*
Clayey	*627*	*13%*	*M*	*74*
Loamy	*245*	*5%*	*M*	*74*
No soil data available	27,234	11%	R	288
Total wetland area	**249,399**			

A.8 Additional information on modelling results

Section 5 focuses on the verification of groundwater models at various sites to assess their accuracy in simulating water levels in wetlands adjacent to drains. The verification process involves determining the parameters of the wetland modelling domain, as depicted in Figure 1, such as LD, LC, hD, hS, and an initial estimation of Ksat and Sy, guided by field investigations (if available).

The maximum infiltration capacity concept is utilised to represent temporal variations in LSR. Any rainfall exceeding the maximum infiltration capacity (i-cap) is considered direct surface runoff. Therefore, the calculation for LSR is as follows: if the rainfall is less than or equal to the i-Cap, LSR equals the rainfall; otherwise, LSR equals the i-Cap. Furthermore, the groundwater wetland domain incorporates evapotranspiration (ET).

During the calibration process, the parameters Ksat, Sy, and i-Cap are adjusted to achieve the optimal match between the observed and simulated water table, using performance indicators such as NSE (Nash-Sutcliffe Efficiency) and Pbias (Percent Bias). The verification process provides valuable insights into hydrological processes and enhances our understanding of these complex systems.

A.9 Additional information for hypothetical modelling scenario

The assessment in Section 6 was conducted under a steady state condition rather than a transient model which was utilised for the verification sites (incorporating observed site data). Subsequently, the outputs reflect possible long-term average drawdown conditions or water levels as a response to drainage. Figure A 4 displays the numerical model mesh, providing an example of the spatial discretisation used to divide the domain into finite elements or cells.

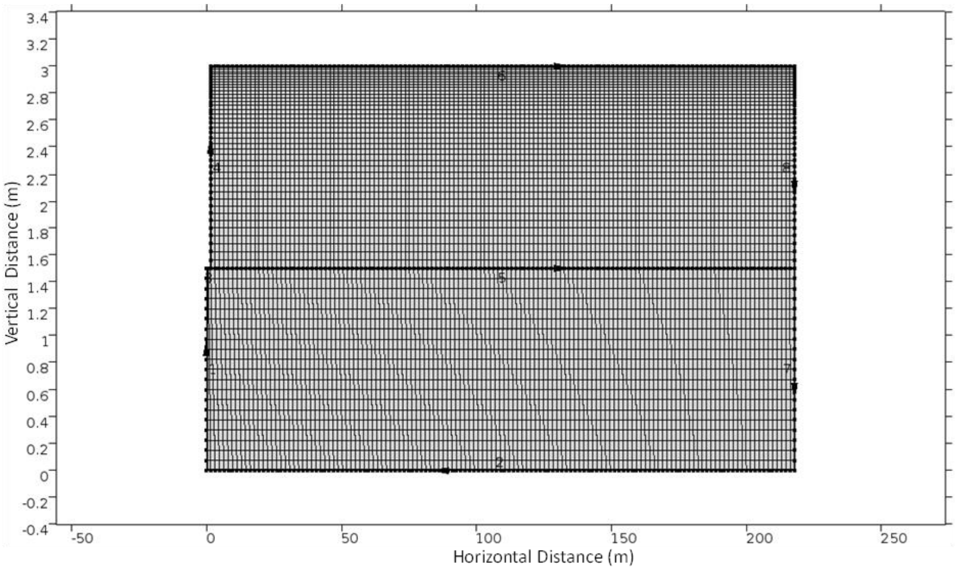

Figure A 4. An example of spatial discretization in COMSOL, illustrating the division of the domain into finite elements.

Results and suggested setback distances

Once the best estimates of input parameters were defined from the model conceptualisation, two scenarios were considered which changed the drain depth and Ksat, as a deeper drain results in a greater drawdown of the water table, while a higher (rapid) Ksat results in greater drainage effects. The objective of each model was to achieve a water level drawdown below 10 mm, 50 mm or 150 mm in the wetland area by changing the drains (LD) location.

LC - LD was identified by selecting the approximate midpoint between the existing boundary drain and the wetland (a length of 85 m). LC and LD were then solved iteratively by modifying their parameters to achieve the targeted water level drawdown above and the LC-LD of 85 m. Remaining model parameters were fixed. The resulting outcome for Figure A 5 for a rapid Ksat with minimal drawdown was an LD of ~133 m, and an LC of 218 m.

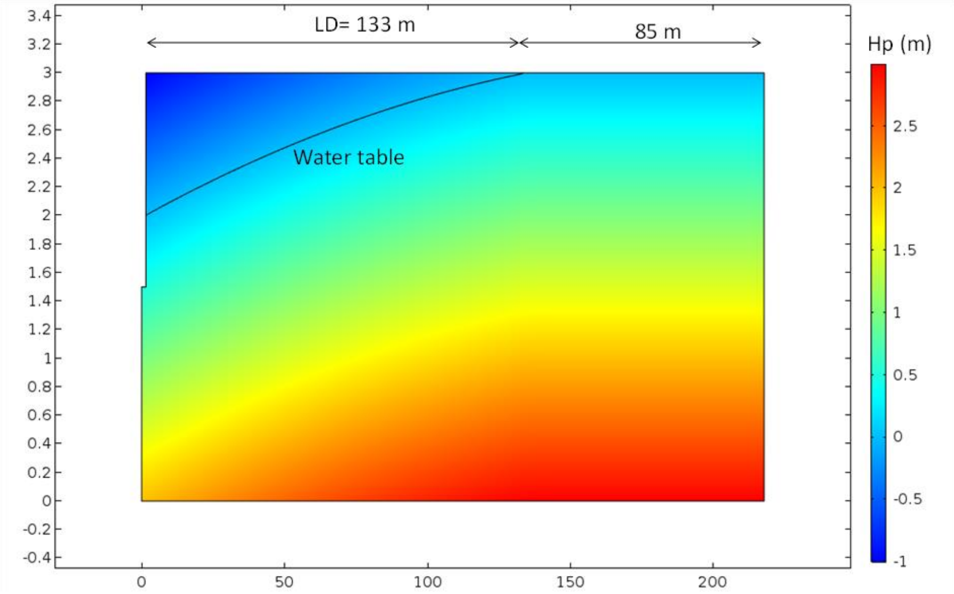

Figure A 5. Model results obtained using COMSOL for a drain depth of 1.5 m. The colour in the figure represents the head pressure (Hp) in meters.

A.10 Recommendations for further model improvements

Wetland type and resilience to water level drawdown

There are many wetland types in New Zealand. The types are well described in Johnson and Gerbeaux (2004)[21]. Each wetland will have its own unique hydrological drivers depending on its topographical and climatic setting, however generally speaking you could classify four main wetland types and their hydrological drivers as:

1. Marsh and swamps – wetlands that have a large mineral soil component, with hydrological inputs from rainwater, surface water and potentially groundwater. Often located in areas that are prone to flood inundation and nutrient/sediment inputs. May have permanent standing water in places, with water tables that fluctuate regularly across the wetland. It is not uncommon to see a water level range of >1.5 m (above ground during flooding in winter to below ground during summer). Vegetation present in these environments are generally more resilient to hydrological variations.
2. Fens – can develop in isolation or on the fringe of swamp and bog habitat. Characterised by hydrological inputs driven from rainfall and groundwater, whether from the shallow unconfined aquifer or in unique situations, artesian groundwater flows. Increasing amounts of organic matter and peat build up, lower nutrient environments and lower water level fluctuations than swamps and marshes (i.e., <1.5 m range over the year)
3. Bogs – take many thousands of years to develop through the accumulation of peat from decaying organic matter. Low nutrient environments and are hydrologically isolated from surface water and groundwater inputs, except during extreme flood events. Rainfall is the

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[21] Johnson, P. & Gerbeaux, P. 2004. Wetland Types in New Zealand. Department of Conservation. ISBN: 0-478-22604-7

primary input. Water level ranges in the centre of large natural bogs can be very low, ranging <0.4 m over the year. Plants present in bogs are uniquely adapted and rare, and can be affected by minor variations in nutrient or water levels due to anthropogenic activities.

Understanding the wetland type in the first instance will help gauge the hydrological drivers and risk and resilience from drainage or excavation activities. Unfortunately, few studies exist that characterise to what extent changes in water levels may impact different wetlands, and their associated plant species. This will also largely depend on the drain location, as a drain that intercepts or provides a flow corridor for surface water to leave a swamp or marsh could actually have significant implications on the wetland health (through extensive drying), despite the plants being resilient to water level fluctuations.

Verification at more wetlands

Three wetland sites were used to verify the conceptual and numerical drainage model. Due to significant weather events in 2023, additional field data was unable to be collected at one of the verification sites (Otakairangi Wetland), and subsequently had to rely on inputs from the other literature and national datasets. Calibration of the QEP model identified that further investigation is needed at this site, including the consideration of the suitability of the water level monitoring bore and whether a new site should be established for re-calibration purposes.

Expansion of the verification sites would be useful, particularly to account for different wetland types (fens and swamps) and climate (South Island, west coast, for example). The purpose of this is to provide a sensitivity analysis of the method to identify limitations and general applicability. This will help inform the development of a national tool and increase confidence among end users.

Incorporation of flows into numerical models

Currently, calibrations have focused on modifying parameters to match the wetlands transient water level at certain distances from a drain. Parameters (such as specific yield) were modified within the bounds of literature values. However, no downstream flow data (from the drain) exists at any sites to confirm suitability of the water balance drainage model. Capturing flow data within the drain for a wetland that has active water level monitoring would provide further confidence when validating the numerical model, as it would be calibrated to both water levels perpendicular to the drain, and to outflows from the drain itself.

However, this is an expensive exercise as may require installation of an Acoustic Doplar Current Profiler (ADCP) to measure velocities within the channel, or installation of a level gauge and establishment of a rating curve through multiple manual flow gauging’s at different water level heights. This will also have challenges depending on the site, due to the presence of macrophytes, low flow velocities and turbid water that may be bound with periphyton, debris or sediment. Such an investment should only be undertaken at sites where adequate data could be collected.

Further soil tests in wetlands

Time and budget constraints limited the amount of soil tests able to be conducted. While slug tests of saturated hydraulic conductivity of soils is a useful and relatively quick method to support the model verifications and allow comparison to the calibrated Ksat, these tests are not true representations of hydraulic conductivity across the wider wetland soils being affected by drainage. This may vary over distance, particularly as there may be transitions from mineral to organic soils depending on the wetland type and vegetation present. Existing drains can also affect soil conductivity, for example, by degrading peat closer to the drain resulting in subsidence, compaction and potentially lower permeability than farther from the site. Subsequently, more tests at a number of locations and distances would allow an average conductivity to be developed for the verification sites.

Future application of this model as a national tool would ideally come with supporting tables from field hydraulic conductivity tests in a range of wetland soils. Testing of wetland conductivity is limited in New Zealand, and developing this literature base would require classification of soil type and a number of hydraulic conductivity tests to be conducted, such as through pumping tests, slug tests or double ring infiltrometers.

A parameter used in the model is specific yield, or effective porosity. There are very few tests in wetland soils, with literature values used in verification exercises being guided from international references. To collect such data nationally would require pumping tests for prolonged durations in bores drilled and installed within a wetland. The bore would need to be suitably installed within the wetland soils, of an orifice that a submersible pump could be deployed and tested for a prolonged duration with nearby observation bores to record water level drawdown over time.

Flow rates are likely to be small from these bores due to low conductivity soils. Currently, the NES-F condition 40 permits scientific research to occur for activities that may have an effect on a wetlands water level (partial or complete drainage), as long as it complies with the conditions. Subsequently, temporary bores may be able to be installed to undertake such tests, although likely will require a resource consent under regional plans (depending on the council).

Appendix B – National LSR and Ksat map

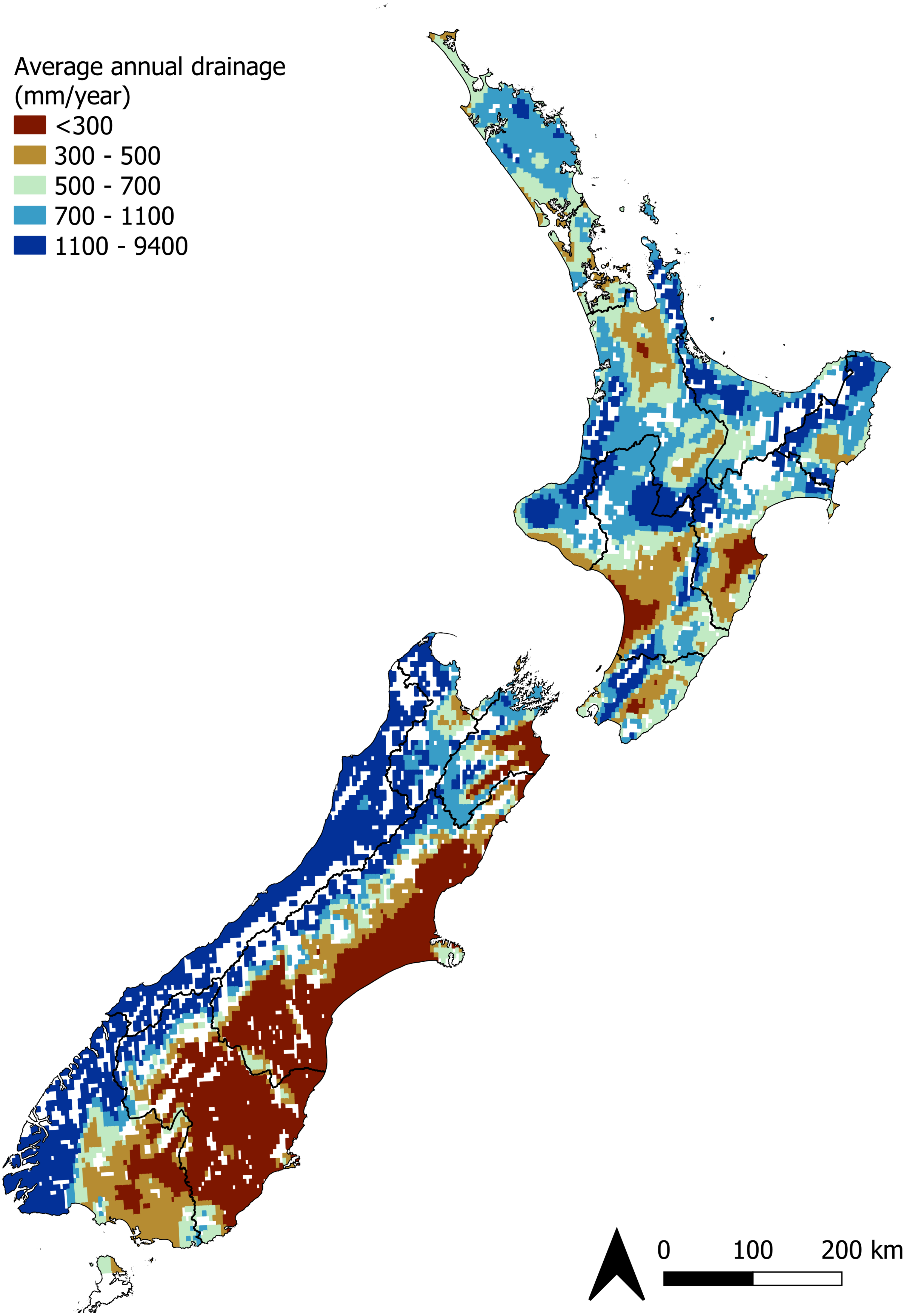


Figure B 1. Map of the daily land surface recharge (LSR), based on the IrriCalc modelling and VCSN data.

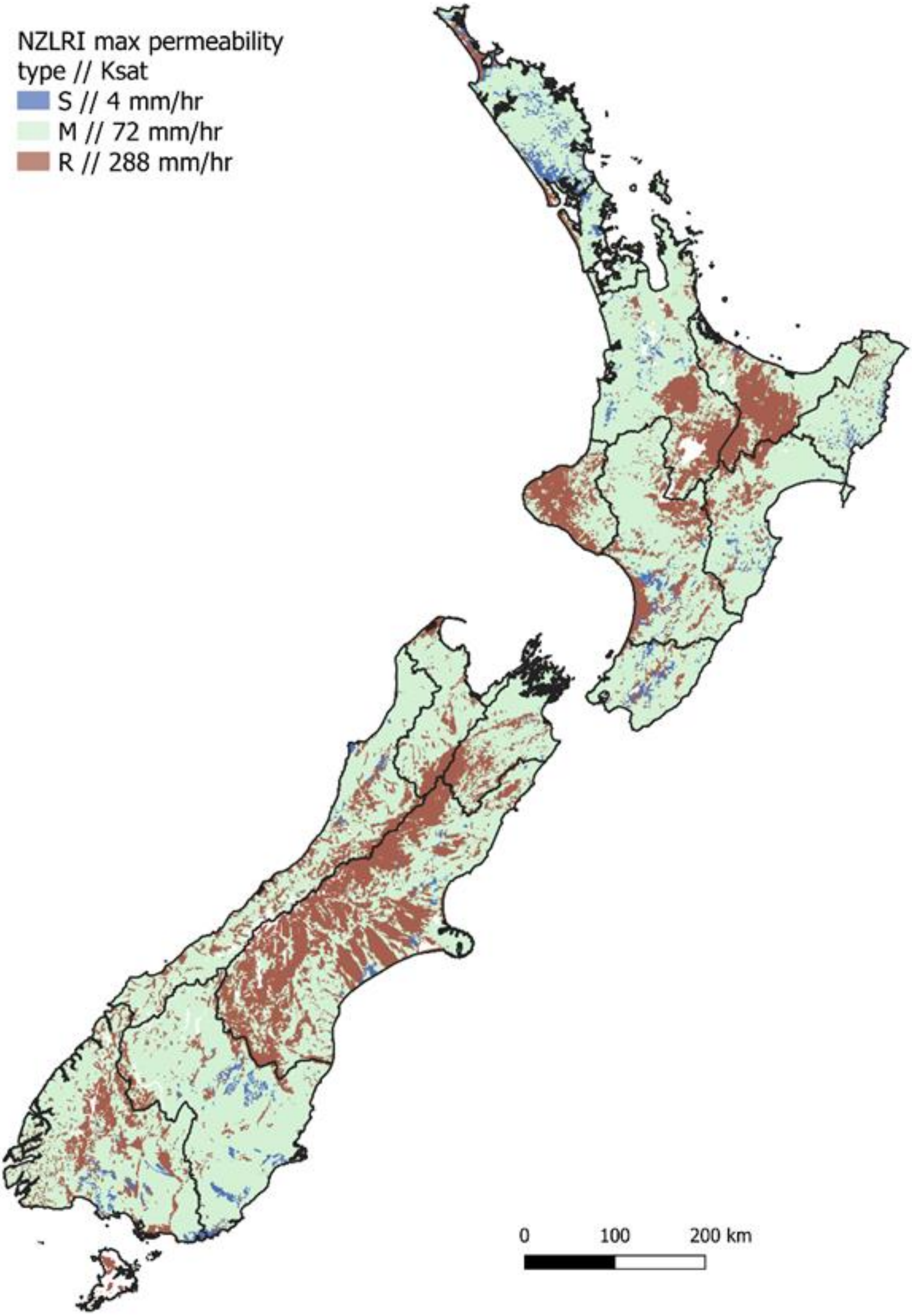
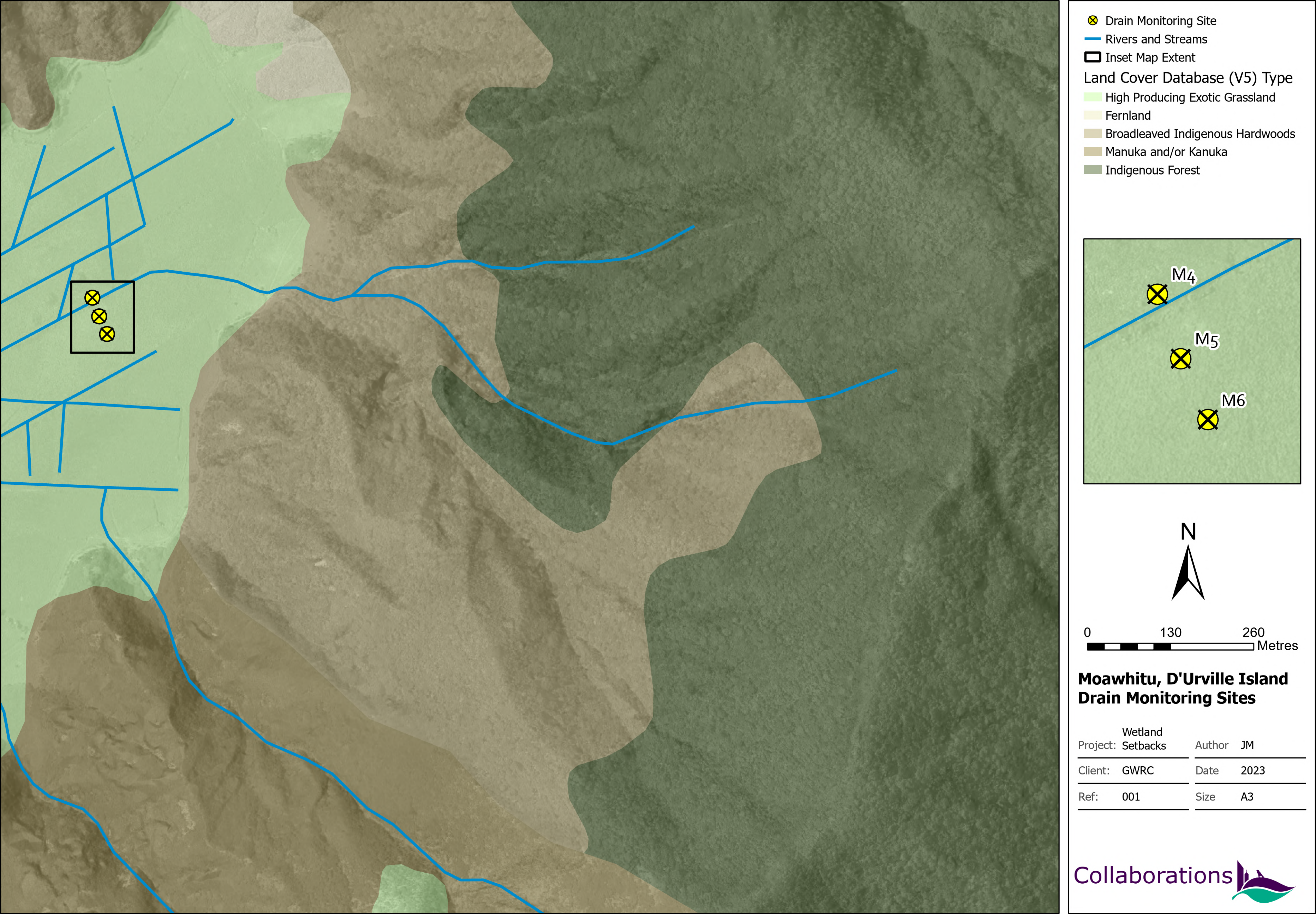


Figure B 2. Map of the most rapid permeability class and associated Ksat, based on the NZLRI permeability layer and the wetland extent layer

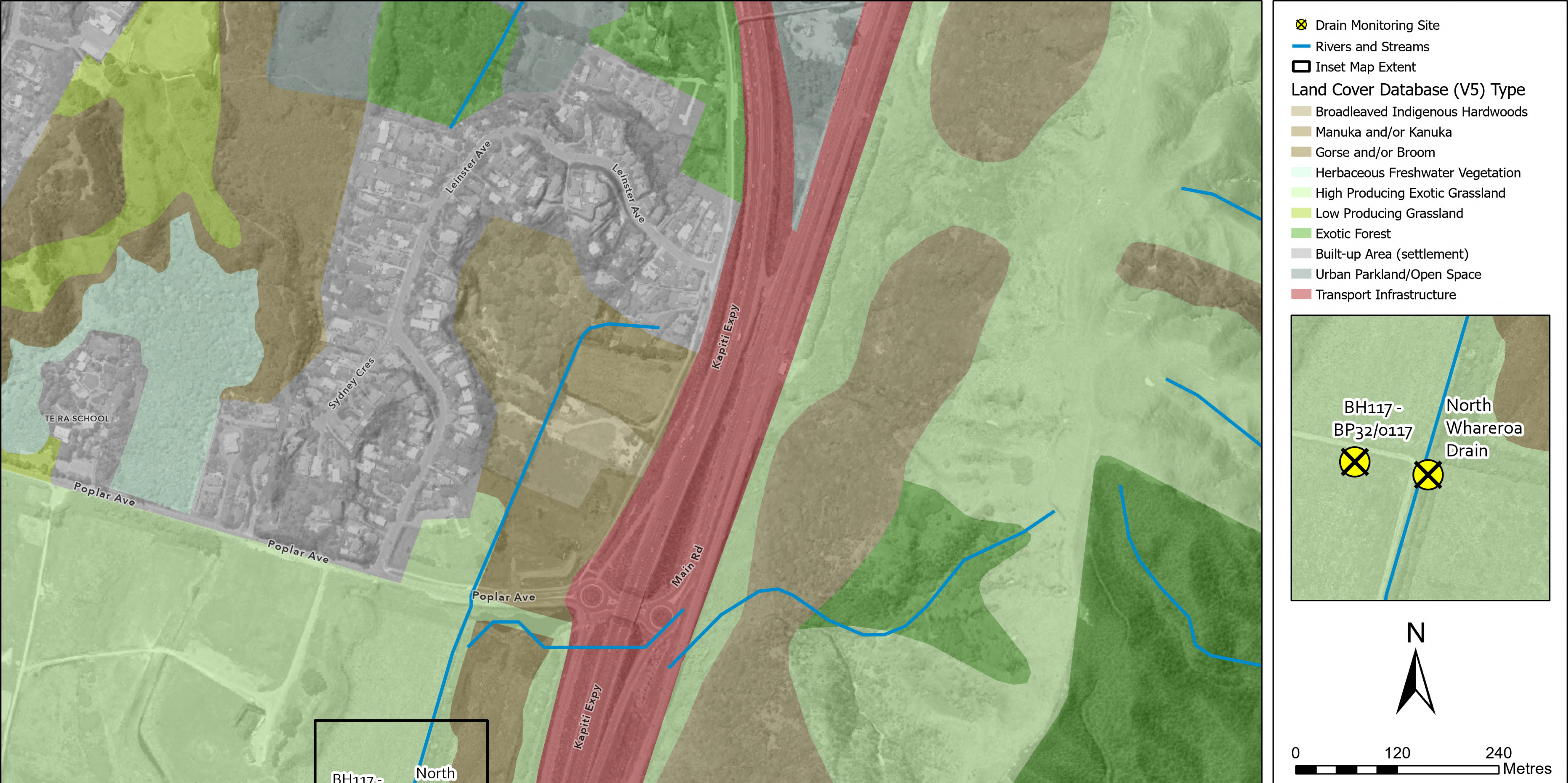
Appendix C – Verification wetland maps



Moawhitu, D'Urville Island Drain Monitoring Sites

Project:	Wetland Setbacks	Author	JM
Client:	GWRC	Date	2023
Ref:	001	Size	A3

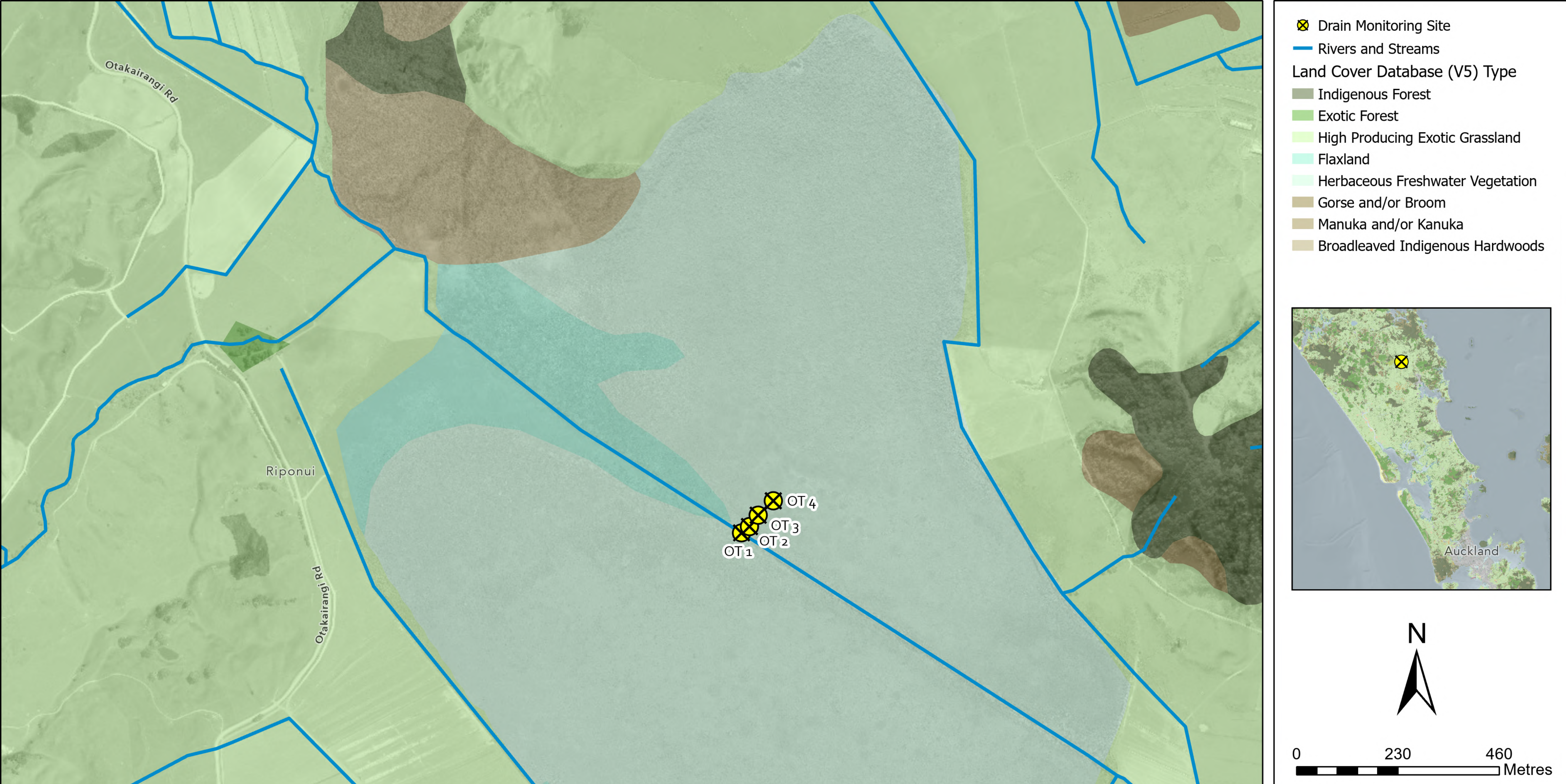
Collaborations



Queen Elizabeth Park, WGN
Drain Monitoring Sites

Project:	Wetland Setbacks	Author	JM
Client:	GWRC	Date	2023
Ref:	002	Size	A3

Collaborations



Otakairangi, Northland
Drain Monitoring Sites

Project:	Wetland Setbacks	Author	JM
Client:	GWRC	Date	2023
Ref:	003	Size	A3

Collaborations