Memo

From	**Richard Measures**
To	Karen Wilson, Environment Southland
CC	Hugh Robertson and Nicki Atkinson, Department of Conservation Chris Jenkins, Environment Southland
Date	21 November 2024
Subject	Review of Waituna Lagoon water balance modelling

Background

Te Rūnanga o Awarua, Department of Conservation Te Papa Atawhai (DoC) and Environment Southland (ES) are in the process of applying for consent to conduct periodic opening of Waituna Lagoon. The proposed consent conditions contain triggers for conducting artificial openings which are linked to water levels measured in the lagoon. Development of the consent application[1] was informed by water balance modelling to predict and compare lagoon levels and opening behaviours under different operating regimes. This water balance modelling was conducted internally by ES.

The Waituna Lagoon water balance model was originally developed for the purpose of forecasting lagoon levels over the short to medium term (days to months) and informing decision making regarding specific openings. The model has then further evolved and been applied to a wide variety of studies, such as considering the effects of climate change, and assessing different opening thresholds/regimes (i.e., informing the consent application).

ES have contracted NIWA to peer review the water balance modelling used to inform the consent application.

Review approach

There is no report available which describes the overall model and its application for informing the resource consent application. For this reason, this peer review has used several sources of information to understand the model workings, its application in informing the consent conditions, and any uncertainties or limitations. Information sources used to inform this peer review included:

- The resource consent application and supporting information[1]. In particular, the 2024 Technical review of conditions for opening Waituna Lagoon[2].
- Informal documentation supplied by ES including notes, draft reports and presentation slides.
- Model code and data supplied by ES.
- Online meetings, phone conversations and emails with model developer Chris Jenkins (Team Leader Hydrological Response, ES).

This review considers the overall design of the model, the details of how each component works and has been calibrated, and how the model was applied to simulate scenarios representing different opening

[1] Te Rūnanga o Awarua, Department of Conservation Te Papa Atawhai and Environment Southland (2024) Periodic opening of Waituna Lagoon to maintain and restore ecological health and cultural values of the lagoon ecosystem. Resource consent application and assessment of environmental effects.

[2] Robertson, H., Atkinson, N, de Winton, M. Schallenberg, M., Holmes, R., Rabel, A., Wilson, K., Jenkins, C., Whaanga, W. (2024) Technical review of conditions for Opening Waituna Lagoon. Prepared for Department of Conservation, Te Rūnanga o Awarua and Environment Southland. Included as Appendix B of the consent application.

thresholds. However, due to available time, and the lack of a single overall report describing all aspects of the model, this review has not exhaustively inspected every detail of the model.

Description of model

As there is no published report describing the Waituna Lagoon model, a high level description of the model has been included here to provide context for the rest of the review.

The purpose of the Waituna Lagoon model is to simulate lagoon levels and opening/closure. To inform the consent application, the model has been applied to simulate multi-decadal lagoon behaviour under different opening regimes. Whilst the model was used to inform assessment of the consent, the model itself does not form part of the proposed consent conditions. All level lagoon thresholds proposed in the consent conditions relate to measured water levels recorded in the lagoon.

The model effectively consists of two components, a water-balance model which is used during periods when the lagoon is closed, and a set of logical rules and probabilities which are used for opening and closure.

Water balance model

When the lagoon is closed the Waituna Lagoon model functions as a water balance model, meaning that at each timestep it calculates changes in the volume of water stored in the lagoon (and hence the water level of the lagoon) based on the differences of inflows and outflows i.e.,

$$\text{Inflow} - \text{Outflow} = \text{Change in storage, } \Delta S$$

The inflows are made up of:

- Tributary inflows, T_i
- Groundwater seepage inflows, G_s
- Precipitation falling directly into the lagoon, P

Outflows are made up of:

- Outflows through the beach barrier (seepage through the barrier when the lagoon level is higher than the sea), B_s
- Evaporation from the lagoon, E

The model can be summarised algebraically as:

$$(T_i + G_s + P) - (B_s + E) = \Delta S$$

The relationship between the volume of water stored in the lagoon, and the lagoon water level, is given by a lagoon level vs volume curve derived from LiDAR data (for lagoon levels higher than water level at the time of the 2019 LiDAR survey) and from measurements of lagoon water surface area (at low lagoon levels).

Of critical importance to the functioning of the water balance model is how each of the input parameters is calculated.

For historic periods, some parameters can be measured or directly calculated from observed data (tributary inflows, precipitation, evaporation). Whilst there is still some uncertainty in the measurement or calculation of these parameters, the approaches used to derive them are well established and considered to be generally reliable. Historic timeseries of these input parameters were derived for the period from 10 March 1977 onwards (since establishment of the Waihopai River at Kennington flow recorder, which is used as a surrogate site to extend records of tributary inflows).

The unknown quantities of barrier seepage and groundwater inflow cannot be directly measured and need to be derived from the difference between the observed storage (from the water level recorder) and predicted storage from the known inputs and outputs for each time step. Lagoon water level data has been recorded at Waghorn Road since 2001. The Waghorn Road recorder is located at the eastern end of the lagoon, near the mouth of Carran Creek, and the recorded water level is affected by wind set-up in the lagoon. Westerly winds can raise water levels at the recorder by approximately 0.3 m or more. Prior to undertaking model calibration, it was first necessary to derive timeseries of average lagoon water level by removing the influence of wind. A relationship between wind speed and direction (as measured at Waghorn Road), and wind-set up, was derived based on periods of data when water level recorders had been deployed at other locations in the lagoon. Wind data recorded at Waghorn Road was then used to remove the wind effect from the Waghorn Road data to produce a cleaned timeseries of average lagoon level.

The period of data from 2001 until 2012 was used for model calibration. For this period, a timeseries of the combined (net) effect of barrier seepage and groundwater inflow was estimated from the difference between the observed storage (from the water level recorder) and predicted storage from the known inputs and outputs for each time step. To separate out the effects of barrier seepage and groundwater it was assumed that barrier seepage was solely a function of lagoon water level, whereas groundwater inflows were a function of monthly average total tributary inflows. Based on these assumptions, the relationships for barrier seepage vs lagoon water level, and groundwater inflows vs monthly average total tributary inflows, were optimised to achieve calibration.

Validation of the barrier seepage and groundwater inflow components was carried out by simulating the period from 2012 to 2017 (i.e., separate from the period used for calibration) and comparing the modelled and simulated lagoon water levels during closed periods (actual opening and closure dates were used in the model). These validation results are shown in Figure 1. Further validation for the period Jan 2017 to June 2023 is presented in the consent application (Figure 18 of the application).

Overall, the model validates well for both periods, indicating high confidence in the water balance calculation during closed periods.

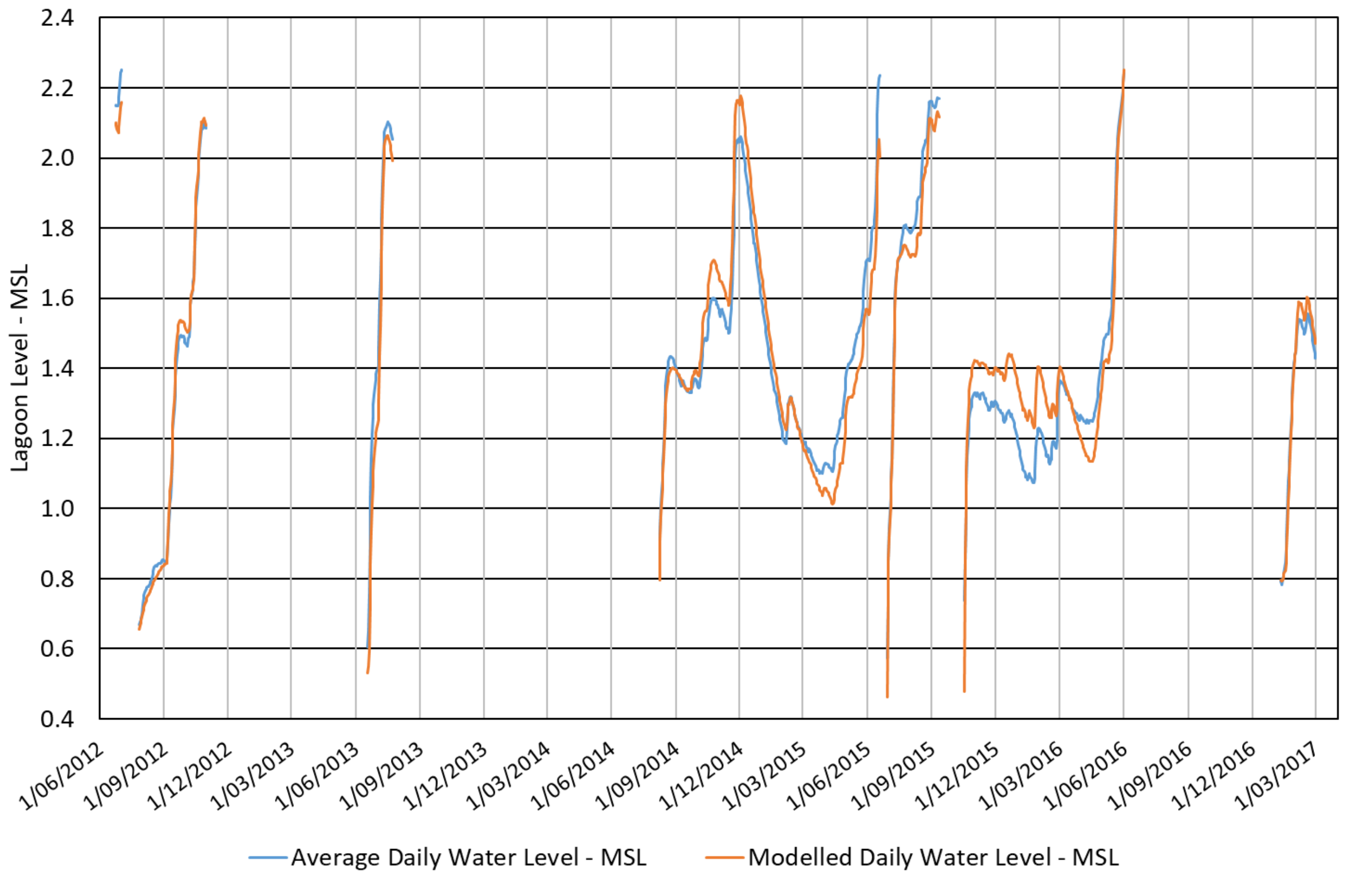

Figure 1: Validation of model ability to reproduce observed lagoon water levels during closed periods (lagoon water level during open periods not shown).

Opening / closing logic

Openings in the model are triggered when pre-defined criteria are met. The model has been used to simulate various opening rules. The rules which relate to the final proposed opening regime correspond to 'Scenario C' described in the technical review of conditions for Opening Waituna Lagoon[2]. The rules modelled in Scenario C were:

- When water levels are above 2.5 m for seven consecutive days an opening is created on the following day.
- When the lagoon has not been open for a period of two years, and the lagoon level is greater than 1.5 m an opening is created (for fish passage).

Similar types of rules were used for other scenarios representing the previous consent condition, other considered options, and the stages of the proposed transitional regime.

Openings are represented in the model by immediately dropping the lagoon level to a fixed 'lagoon-open' water level. For every day the lagoon is open in the model, there is a chance that it can close due to wave/coastal conditions. This chance of closure is represented in the model as a monthly-varying daily-probability which has been calculated from historic data on lagoon closure.

Following closure, the model returns to the water-balance calculation to track lagoon water levels.

Probabilistic simulation of scenarios and presentation of results

To assess the likely lagoon level and opening conditions under each scenario of opening rules, the model was run 30 times for each scenario including random variability (i.e., Monte-Carlo simulation). Each of these model runs (ensemble members) starts from a different (randomly selected) initial condition and simulates 45 years of lagoon level and opening/closure. The initial condition has a 40% probability of being closed, and if closed is assigned a random water level (within the operating regime) and random previous duration of closure (to use when deciding whether a fish passage opening is required). During each simulation, for periods when the lagoon is open, lagoon closure is triggered randomly (according to the monthly varying probability of closure), this randomness is a further source of difference between each simulation. All simulations use the same time series of total catchment inflows (creeks plus groundwater), precipitation and evaporation, taken from the historic record for the period 10 March 1977 to 10 March 2023.

Model results from all 30 simulations of each scenario are aggregated to calculate the summary statistics used in the technical review of conditions for opening Waituna Lagoon. These summary statistics include:

- the average number of openings per year;
- the average number of openings in the 1 September to 30 April period each year;
- the annual average duration of lagoon levels above various thresholds (2.0, 2.2, 2.4 m);
- the average duration of each period when the lagoon level goes above the thresholds;
- the average number of 'events' per year when the lagoon level goes above the thresholds.

Discussion

This section discusses aspects of the modelling I identified as having potential to affect the modelling outputs which were used to support the proposed opening consent. The discussion is split into sub-headings for each aspect. For each sub-heading I have explained the potential issue and discussed its significance before drawing conclusions. A summary/conclusion is presented in a box at the end of each discussion section.

Uncertainty in barrier seepage

The Waituna Lagoon model is automatically run in real-time by ES and, following summer 2023–24, observed and modelled lagoon water levels have diverged. Potential causes of this divergence are increased total catchment inflow into the lagoon relative to recorded flows (e.g., due to rating curve errors), or that the relationship between barrier seepage and lagoon water level may have changed. Preliminary investigations by Chris Jenkins suggest that the barrier seepage may have changed, and an initial estimate of a new barrier seepage function has been developed (Figure 2) which results in improved model performance for 2024. The new seepage curve is highly uncertain, particularly for low to medium lagoon levels due to the short duration the lagoon has spent closed at levels below 2.2 m (following closure of the lagoon on 30 March 2024 the lagoon rapidly filled to approximately 2.3 m and stayed at high levels until it was opened in September 2024). In the future, once more data are available, the new seepage function will likely be able to be refined.

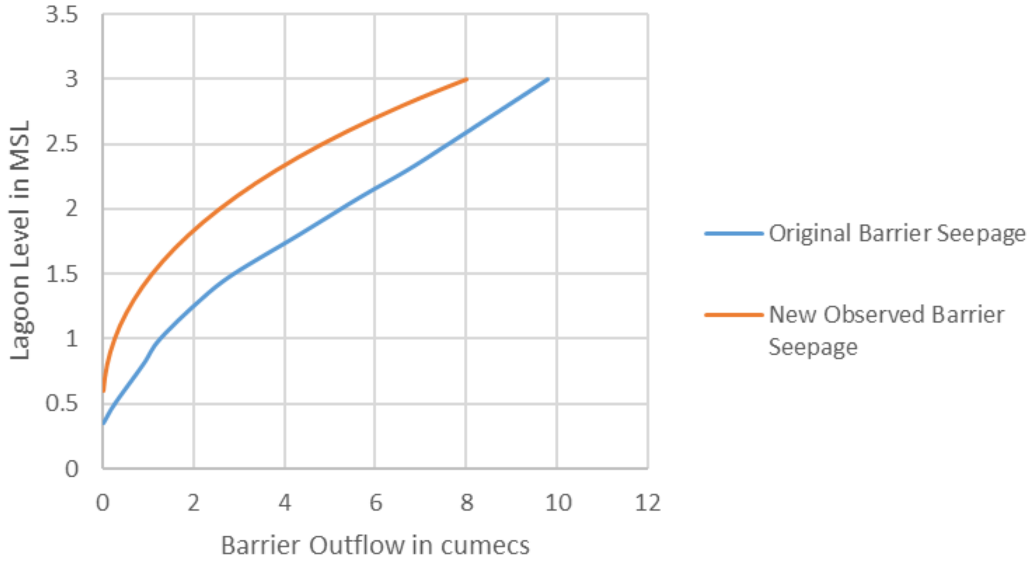

Figure 2: Potential changes in barrier seepage following summer 2023–24.

Based on the newly calibrated barrier seepage function it appears that seepage has reduced by an approximately uniform value of around 2 m^3/s for lagoon levels from 1.5 to 2.5 m (seepage values for lagoon levels above ~2.6 m and lower than ~1.0 m were extrapolated as lagoon levels have not been in this range since the change). I find it surprising that the seepage function would change so uniformly, as I would expect a change in barrier porosity to cause a change in seepage proportional to depth (i.e., a change in slope of the outflow vs lagoon level relationship, reducing flows at all levels by a similar percentage, rather than a shift, reducing flows at all levels by a similar absolute amount). I understand that recent flow gaugings do not show major errors in the inflow gauging station rating curves, but the shape of the shift in the barrier seepage curve (noting that the lower part of the curve is highly uncertain) suggests to me that other potential sources of the divergence between modelled and observed levels should be further investigated.

If we assume that the recent divergence between modelled and observed lagoon levels is due to changed barrier seepage, then it is necessary to consider whether this change is likely to continue, and if so, what effect it has on the conclusions of the modelling used to inform the consent application. The change in seepage is significant, reducing seepage by almost 50% at lagoon levels below 2.0 m, and approximately 30% at 2.5 m. This change would increase the rate at which the lagoon fills, resulting in the requirement for more openings. It would also result in more frequent high lagoon level 'events', but the effect on the average duration of high lagoon level events is uncertain as it makes it more likely that openings will be triggered, rather than the lagoon level naturally peaking and reducing without needing to be opened. It is important to note that these changes will affect all the modelled scenarios, including the scenario representing the previous consent conditions, as well as those representing the proposed conditions.

A source of uncertainty, which was unknown at the time of the modelling, relates to the divergence in model-predicted and observed lagoon levels since summer 2023–24. Initial analysis suggests a reduction in barrier seepage is a potential cause of this change. The potential changes are significant, and if they persist, would have a significant impact on the frequency of openings and high lake level events. This would increase the urgency to have a consent in place for openings (as openings are likely to be required more often). Changes in barrier seepage would affect all modelled opening options, hence they are unlikely to change the relative merits of one set of opening thresholds compared to another.

Other model limitations

There are elements of the model which simplify or exclude processes known to influence the lagoon. These include:

- **Variability in lagoon water level at the time of closure**. The model assumes a fixed water level at the time of closure, whereas real lagoon levels at closure are not always the same. This simplification was assumed because it is hard to develop a function describing the probability of different water levels at closure as closure is a gradual process and it is not always apparent in the historic record exactly when the lagoon closes, and hence what the level was at closure. Furthermore, the water level at closure has very little effect on the timing of subsequent high water levels in the lagoon. There are two reasons for this lack of sensitivity. Firstly, there is little volume difference between typical closure water levels, for example a difference between a lagoon level of 0.4 m and 0.5 m (typical closure levels) only represents 2% of lagoon volume at 2.5 m. Secondly, because of the way barrier seepage is a function of lagoon level, higher lagoon levels experience higher seepage, meaning that the difference in stored lagoon volume (and hence level) resulting from differences in initial water level reduce over time.
- **Wave washover inflows**. It is known that during large wave events washover can enter the lagoon, but the effect of washover is not explicitly included in the model. However, the good performance of the model observed during calibration/validation suggests that any volumes of washover water entering the lagoon do not have a significant effect on lagoon level/volume. That is, if washover volumes were significant we would see increases in observed lagoon level which were not predicted by the model at times of washover.

I am confident that the effect of these limitations is minor and has no significant impact on the conclusions of the modelling.

Representation of proposed consent opening regime

There are some small differences between the modelled scenarios and those proposed in the consent. These differences are:

- **Timing of fish passage openings.** The consent application defines fish passage openings as occurring "*between 1 April and 30 November, provided that the lagoon has not been opened in the previous 24 months, or if the lagoon has been opened during the past 24 months, the timing of the open period did not support upstream migration of threatened or at-risk fish species*"[1], but model scenario C (which represents the proposed final consent condition) simulated fish passage openings using the rule "*if no opening occurred in the previous 2 years, open if the level exceeds 1.5 m*"[2]. This slight difference in the way fish passage openings are implemented may mean the model simulates slightly less fish passage openings than would actually occur under the consent rule, because fish passage openings would sometimes occur when it has been less than 24 months since an opening, if that opening was not between April and November. However, summer openings are rare under the proposed rule, so this situation will occur very infrequently, so the difference is likely to be minor.
- **Openings for ecological and water quality reasons.** The proposed consent conditions allow additional openings if required for ecological / water quality or biosecurity reasons, but no such openings are simulated in any of the modelled scenarios. There is high uncertainty over how frequently such openings may be required, and it is hard to see how these openings could be simulated in the Waituna Lagoon water balance model. Any additional openings for water quality or biosecurity would likely reduce the frequency and duration of high lagoon levels.

These differences are likely to have small effects on the model results for the scenarios representing the proposed consent conditions. These effects are unlikely to significantly change the conclusions from the modelling.

Climate change effects

Climate change is likely to impact Waituna Lagoon hydrology via sea-level-rise effects on barrier seepage rates and lagoon-open water levels, and changed inflows (rainfall, catchment inflows and evaporation). Additionally, climate change may impact the seasonal probability of lagoon closure (via changed wave climate). These effects have not been considered in the scenario modelling, which is based off historic data on inflows, barrier seepage, closure water level and closure probability.

Barrier seepage rates are likely to reduce as a result of sea level rise (because the head difference between any given lagoon level and sea level will reduce), and the water level at the time of lagoon closure will be higher. Relative sea level projections for Waituna Lagoon for 2044 (i.e., at the end of the proposed 20-year consent term) range from around 0.21 to 0.37 m (from a 1995–2014 baseline, including the effect of approximately -1 mm per year vertical land movement[3]). Relative sea level rise of this amount would likely reduce barrier seepage by approximately 1.5 m^3/s at a lagoon level of 2.5 m (i.e., the seepage rate at 2.5 m would likely reduce to the rate experienced historically at ~2.2 m due to the ~0.3 m reduction in head difference between the lagoon and the sea).

Mean annual water discharge into Waituna Lagoon is projected to increase by up to 10% by the middle of this century[4] (i.e., approximately the end of the proposed 20-year consent term). It is very hard to quantify the effect on lagoon closure as a result of changes in wave climate.

The effects of increased inflow and reduced barrier seepage due to climate change over the term of the consent will increase the rate at which the lagoon fills, likely resulting in more frequent openings than predicted by the model. The projected changes imposed by climate (10% increase in flow and 1.5 m^3/s reduction in seepage) are significant. These predicted climate change effects would impact all modelled opening options (i.e., previous opening thresholds as well as proposed) so are unlikely to affect the conclusions from the modelling (i.e. the relative merits of different opening thresholds).

Calculation of closure probabilities

The Waituna Lagoon model uses a monthly-varying daily-probability of lagoon closure to decide when the lagoon closes. These probabilities have been calculated based on the historic record of closures at a monthly level, then converted to a daily probability for use in the model based on the number of days in each month. However, the monthly calculation does not factor in the proportion of the month which the lake was open. The calculation could be made more accurate (and simplified) by considering the proportion of the month the lake was open. Using January as an example, the logic behind the original calculation methodology was:

> *Over 52 years of record, the lagoon closed 3 times in January. During 27 of these years, the lagoon was open during January giving a monthly probability of closure of 3/27 or 11.1%. Converting this to a daily probability based on the number of days in January (31) using probability theory gives a daily probability of closure in January of 0.38% per day.*

The calculation could be made more accurate by changing it to:

> *Over 52 years of record, the lagoon only closed 3 times in January. <u>The total number of days in January the lagoon was open over this 52 year period was 744 giving a probability of closure of 3/744 or 0.40%.</u>*

During February and November no closures have occurred since 1972 (when continuous records begin), so a basic calculation of probability of closure for these months would result in 0% probability (i.e., impossible

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[3] Sea level rise and vertical land movement projections taken from https://www.searise.nz/. Range presented relates to the range from SSP1-2.6 p50 to SSP5-8.5 p83 projections.

[4] Tait, A., Pearce, P. (2019). Impacts and implications of climate change on Waituna Lagoon, Southland. *Department of Conservation: Science for Conservation Series 335*. https://www.doc.govt.nz/globalassets/documents/science-and-technical/sfc335entire.pdf

for the lagoon to close in these months). This is clearly unrealistic, so was resolved during development of the model by making a pragmatic assumption to assume 0.8 historic closures in each of these months in order to compute a closure probability.

The whole period from November to February has low numbers of historic closures, and hence high uncertainty in closure probability. An improved approach would be to aggregate the total number of closures over the November to February period and calculate a single daily probability of closure for all four of these months.

Alternative approaches to modelling the closure process could also be considered, for example a logistical regression model that accounts for inflow, time since opening, and wind (or even wave data), to compute probability of closure. Whilst this would represent a significant improvement in the model, especially if considering the potential impacts of climate change, I am happy that the current monthly-varying probability approach is appropriate for analysis of different options for opening consent conditions.

Figure 3 compares the monthly-varying daily-probability of closure used in the model against an updated calculation using the improved procedure described above (i.e., accounting for the number of days open in the month, and aggregating months with low numbers of observed closures). The changes to probability of closure are small for most months, although are more significant for May and January. To better understand the significance of these differences I calculated the effect on the probability of the lagoon closing at some point during each month assuming it was open at the start of the month (Figure 4). In general, the improved calculation method results in slightly increased probability of closure in most months, this would result in slightly shorter duration openings. The exception to this is the reduced closure probability in January and November. These are the result of aggregating across the November–February period, so are offset by increased probability of closure in December and February.

Overall, the differences in probability of closure as a result of improving the calculation are small and are unlikely to have significant effect on the conclusions of the modelling.

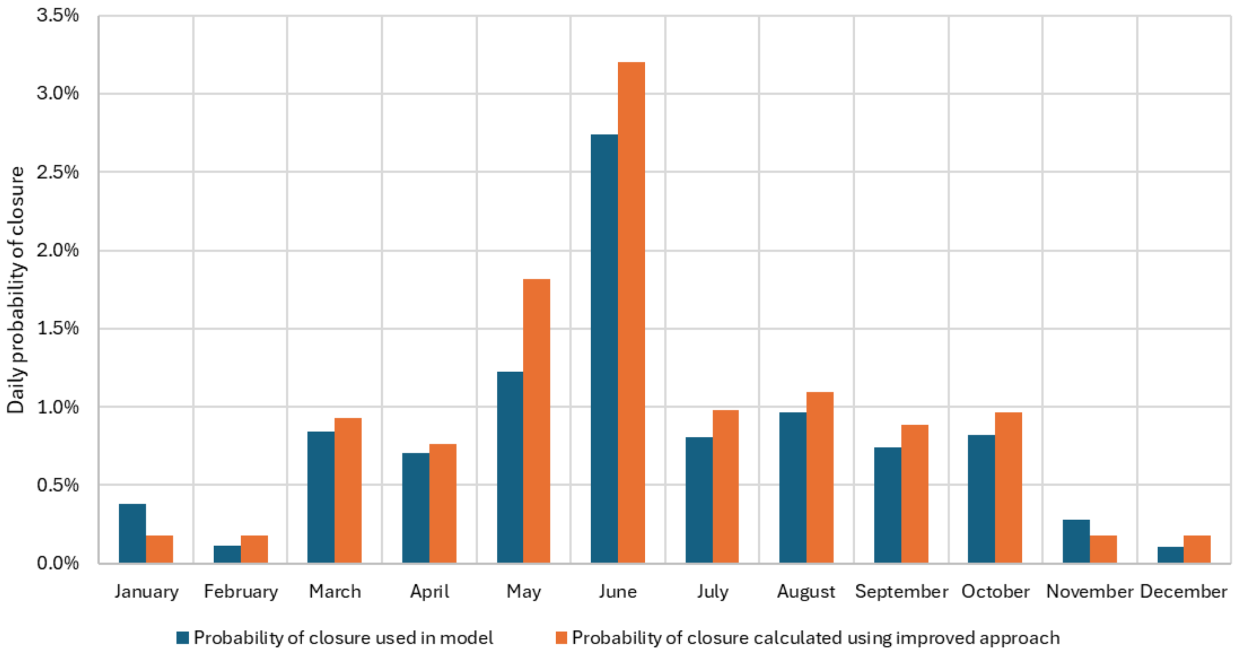

Figure 3: Sensitivity of monthly-varying daily-probability of lagoon closure to changes in calculation methodology.

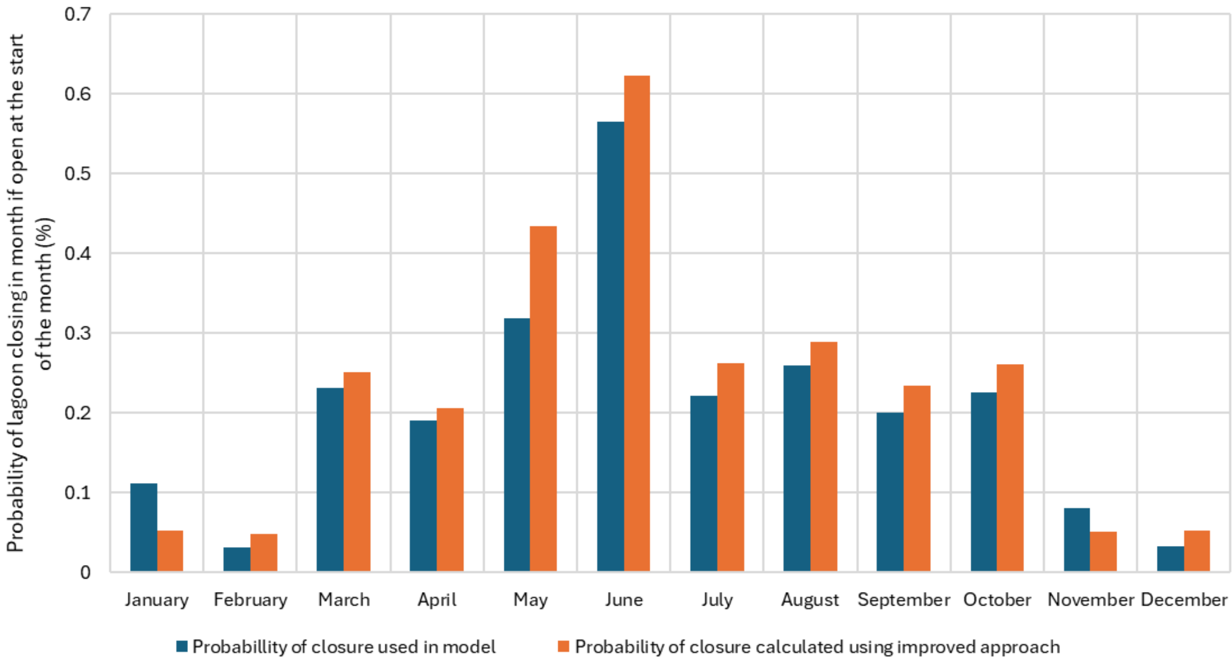

Figure 4: **Effect of improved calculation of closure probabilities on likelihood of closure in different months.**

Conclusion

The Waituna Lagoon water balance model was used to optimise the proposed opening consent conditions by comparing the water level and opening regimes which result from different scenarios. The model does not trigger operational decisions regarding openings, as these are based on measured lagoon water levels (as well as water quality and ecological considerations).

Overall, the model is fit for purpose for the simulation of lagoon water levels and the comparison of different potential opening regimes used to inform the resource consent application.

A source of uncertainty, which was unknown at the time of the modelling, relates to the divergence in model-predicted and observed lagoon levels since summer 2023–24, potentially due to reduced barrier seepage flow rates. Another source of uncertainty in the model results is the effect of climate change and relative sea level rise over the proposed 20 year term of the consent. It should be noted that both of these uncertainties affect all the modelled options for consent conditions, so are unlikely to affect the conclusions from the modelling (i.e. the relative merits of different opening thresholds). As operational decision making does not rely on the model, these model uncertainties will have no effect on the ability to manage the lagoon for ecological or land drainage reasons.

This review has identified several other details of the model which could be improved (as would be expected in any review), but these details are very unlikely to significantly affect the conclusions of the modelling.

Acknowledgements

This review relies on data, figures, discussion and emails with Chris Jenkins. It would not have been possible without his open communication regarding the model and patient answering of my many questions.

NIWA Report No: 2024356CH
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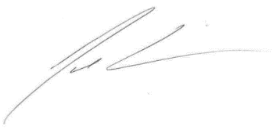
Revision	Description	Date
Version 1.0	Final version sent to client	21 November 2024
Version 1.1	Minor improvements to wording to improve clarity	25 November 2024

Quality Assurance Statement		
	Reviewed by:	Jason Alexander
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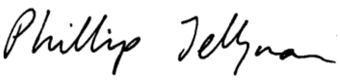	Approved for release by:	Phillip Jellyman