



Earth Sciences
New Zealand

Causes of saline intrusion in the Kaiapoi River

Analysis of monitoring data

Prepared for Environment Canterbury

December 2025

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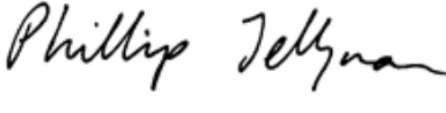
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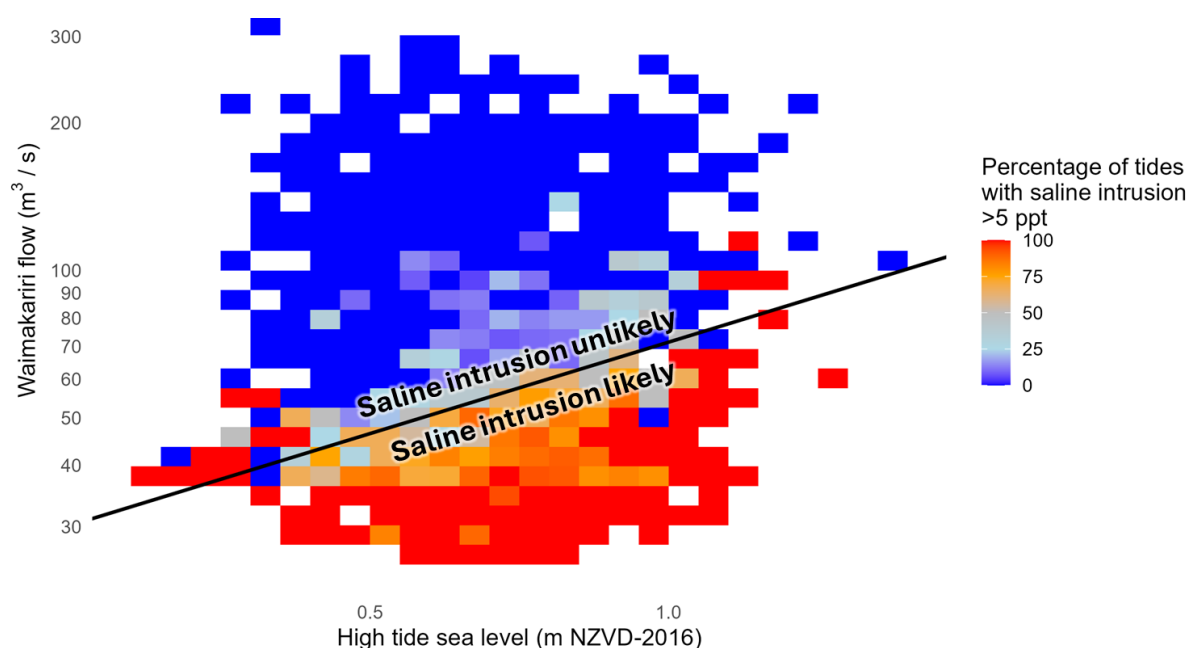
Executive summary

Increased frequency of saline intrusion in the Kaiapoi River has been linked to observations of macrophyte dieback and kākahi (freshwater mussel) deaths in 2024. The purpose of this report is to inform understanding of what causes saline intrusion as a first step towards making more informed management decisions.

The report describes analysis of continuous salinity monitoring data recorded in the Kaiapoi River at the Mandeville Bridge. Salinity data are available since February 2017, although the installed monitoring instruments have gone through several iterations since then and there are uncertainties and gaps in some of the earlier data. Data collection since 2020 has been consistent and data for this period are of good quality.

For each tide where salinity data were available, we identified: peak salinity, average Waimakariri River flow (measured at the Old Highway Bridge flow recorder), average tributary flows (combined Cam River and Cust Main Drain flow data), high tide level (measured at Sumner sea-level recorder), and tidal range. Using this dataset, we carried out statistical analysis indicating that Waimakariri flow and high tide level are strongly predictive of saline intrusion. Tributary flows and tidal range also have smaller, but still statistically significant, effects on salinity.

The combined effect of Waimakariri flow and high tide level on observed salinity are shown in the summary figure below. Under current sea levels, saline intrusion into the Kaiapoi River occurs on almost all tides when flow is less than 35 m³/s, only on approximately 10% of tides when flow is greater than 72 m³/s, and almost never when flow is greater than 105 m³/s. For flows in the range 35–72 m³/s the likelihood of saline intrusion depends on the combination of river flow and tide level, with higher tides required to drive saline intrusion when Waimakariri flows are higher.



Summary figure: Heatmap showing the proportion of observed tides experiencing saline intrusion under different high tide level and Waimakariri flow conditions. Black line is fitted to the data and represents a threshold dividing conditions where the likelihood of saline intrusion is more or less than 50%.

Earthquakes can change river channel bed levels and geometry, potentially affecting saline intrusion. Kaiapoi experienced subsidence during the 2010–11 Canterbury earthquake sequence, and subsidence is likely to increase saline intrusion. The 2016 Kaikoura earthquake had negligible effect on bed levels and is unlikely to have affected salinity.

Analysis of the monitoring data shows that there was a significant change in observed saline intrusion in 2020, coinciding with dredging of the Kaiapoi River. Saline intrusion became more frequent and occurred at higher Waimakariri flows following the dredging.

Saline intrusion is sensitive to high tide level, so sea level rise is expected to increase saline intrusion. We used the relationship between Waimakariri flow, high tide level and saline intrusion to investigate the sensitivity of saline intrusion to sea level rise for a range of river flows. Under current sea levels, a flow of 72 m³/s prevents intrusion on 90% of tides, but with 0.1 m of sea level rise a flow of 77 m³/s is needed to achieve the same effect, and with 0.5 m of sea level rise a flow of 97 m³/s is needed to achieve the same effect.

1 Introduction

1.1 Background

Environment Canterbury (Canterbury Regional Council) has been approached by Waimakariri District Council regarding public observations of emergent and submerged macrophyte dieback and kākahi (freshwater mussel) deaths in the Kaiapoi and Ruataniwha/Cam Rivers during winter 2024. These observations are described in a Waimakariri District Council report (Allen 2024). The report concludes that the cause of the Kaiapoi and Ruataniwha Cam Rivers ecological dieback observed in 2024 is primarily due to increased salinity, with potentially also some effect from frosts.

Environment Canterbury has maintained continuous monitoring of salinity and dissolved oxygen in the Kaiapoi River at the Mandeville Bridge since 2016 (location shown in Figure 1-1). These data are plotted in the Waimakariri District Council report and show that while salinity intrusion has historically occurred during summer months, 2024 experienced much longer periods with regular saline intrusion, including during autumn and winter.

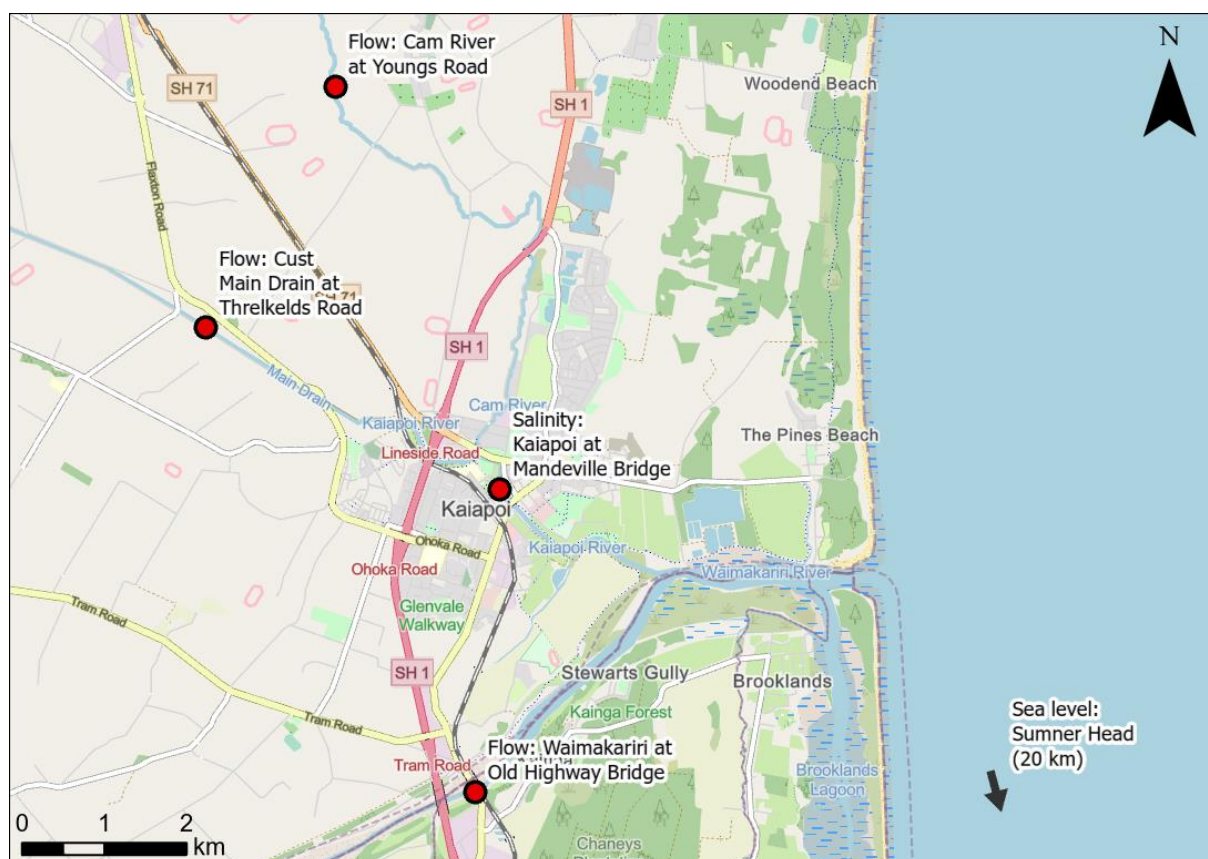


Figure 1-1: Map of the Kaiapoi and Waimakariri Rivers showing the location of monitoring sites used for analysis.

Salinity intrusions were previously investigated by Environment Canterbury in 2018 following previous observations of macrophyte dieback and kākahi deaths over the period 2012 to 2018 (Meredith 2018). They concluded that salt wedge intrusion was the most likely cause of the observed ecological changes (several potential alternative causes were identified but considered unlikely to be the primary cause). The Kaiapoi River is a tributary of the Waimakariri

River and saline intrusion was found to be strongly linked to Waimakariri River flows, with flows less than 40 m³/s associated with saline penetration on every tide and flows greater than 60 m³/s having little saline penetration on any tides. Meredith (2018) hypothesised that bed level changes resulting from the Canterbury earthquake sequence could have allowed increased saline intrusion.

Another cause of bed level changes on the Kaiapoi River is dredging. Dredging occurs periodically to maintain navigation, and we understand that a significant dredging programme funded by an earthquake recovery loan was carried out over the period June–August 2020 (Allen 2020).

1.2 Saline intrusion process

Salinity profiling conducted in 2016 informs our current understanding of the saline intrusion process (Meredith 2018). The profiling showed that salinity intrusion in the Waimakariri and Kaiapoi Rivers generally takes the form of a ‘salt wedge’, with near-bed salinity close to sea water and surface salinity close to freshwater. Seawater has a salinity of approximately 30–35 ppt which increases its density, making it significantly denser than freshwater. The density difference makes it more difficult for the freshwater and saltwater to mix, meaning that the rivers remain stratified with a layer of saltwater near the bed and freshwater near the surface. On an incoming tide seawater pushes upstream along the Waimakariri river bed, whilst the river surface remains relatively fresh. If this salt wedge rises to a level above the bed level of the Kaiapoi River, it can push into and up the Kaiapoi River towards the town.

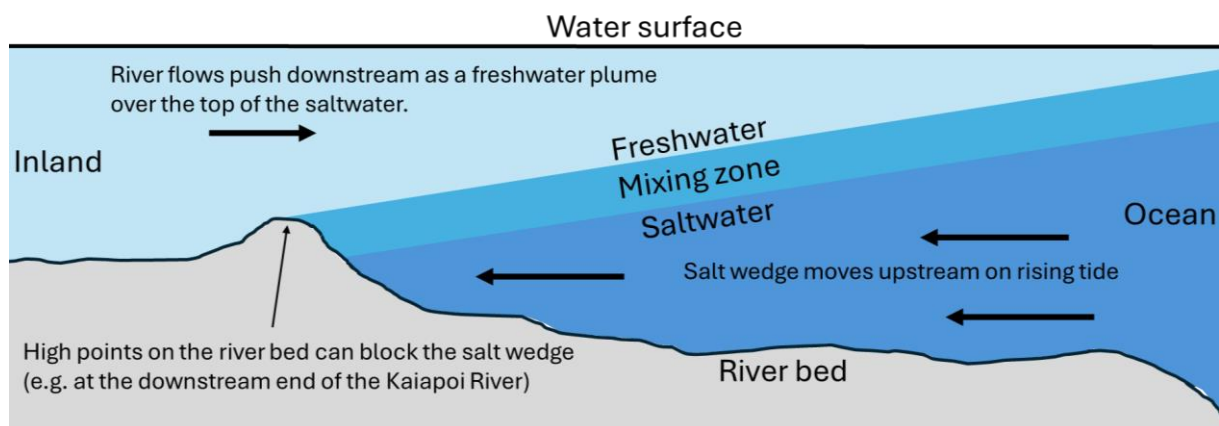


Figure 1-2: Schematic diagram of salt wedge saline intrusion process. Note that in this schematic the vertical scale is very exaggerated, i.e. water depths are approximately 3–8 m whilst the distance from the ocean to the upstream limit of the salt wedge can be more than 5 km.

1.3 This analysis

This report describes analysis of the continuous salinity monitoring data recorded in Kaiapoi River at the Mandeville Bridge. This analysis extends the previous work described by Meredith (2018) by:

- Extending the analysis to include newer data.
- Undertaking a more detailed analysis into the effect of multiple different potential drivers of saline intrusion.

The analysis involved:

1. A site visit to the water quality monitoring station to understand the source of the data, how this has changed over time, and any local effects which could influence observations.
2. Analysing salinity data for the full period available (i.e., 2016–present), including investigating relationships between the peak salinity recorded on each tide and:
 - River flow in the Waimakariri.
 - High tide sea level.
 - Tidal range over the previous tidal cycle.
 - Kaiapoi River tributary flows.
3. Discussing the role of different drivers influence on saline intrusion, including:
 - Canterbury earthquake sequence changes in bed level.
 - Kaikoura earthquake.
 - Kaiapoi River dredging (June–August 2020).
 - Waimakariri River flow.
 - High tide levels and tidal range.
 - Sea level rise.

2 Data

2.1 Salinity data

Continuous salinity monitoring instruments were first installed by Environment Canterbury in February–March 2017, initially as a temporary installation and later as a long term site. Salinity monitoring instruments are located on a bridge pier of the Mandeville Bridge in Kaiapoi. The first sensors to be installed were two AquaTROLL 100 salinity loggers. A “bottom” sensor was installed 30 cm off the riverbed (Site SQ36436, approximately 2 m below low tide level) and a second “top” sensor was installed above that, approximately 30 cm below low tide level (SQ36501). The sensors recorded and stored data locally and data were manually downloaded at monthly intervals during cleaning visits. These sensors were maintained until May 2018 (with a gap in data from October 2017 to January 2018).

Initial analysis of data from these two sensors showed that the bottom sensor provided an early record of saline presence, as it could identify the tip of the salt wedge propagating up the river bed. However, ecological effects were not observed unless a stronger salt wedge had developed (detectable higher in the water column, at the top sensor). Based on this observation all subsequent salinity monitoring installations in the Kaiapoi River have been installed at levels selected to monitor depths in the water column that are most indicative of likely effects on ecology (although sensor levels have varied slightly as described in the following paragraphs).

In November 2019 a Solinst LTC sensor was installed around 1.3 m below low tide level. This sensor was assigned the same site identifier as the original “top” sensor (SQ36501). In November 2021 the sensor was upgraded to a telemetered AquaTROLL multi-parameter sonde positioned slightly deeper. The Solinst data were continued until February 2022 to capture an overlapping period of data allowing the data to be cross-checked for consistency. In September 2025 a custom sensor array was installed to replace the AquaTROLL with both sensor arrays running in tandem to capture an overlapping period of data. As only a short period of record was available from this new sensor array at the time of analysis, we did not include this latest data in our analysis. Figure 2-1 shows the elevations of the different sensors and Figure 2-2 shows a timeline of data availability from the different sensors.

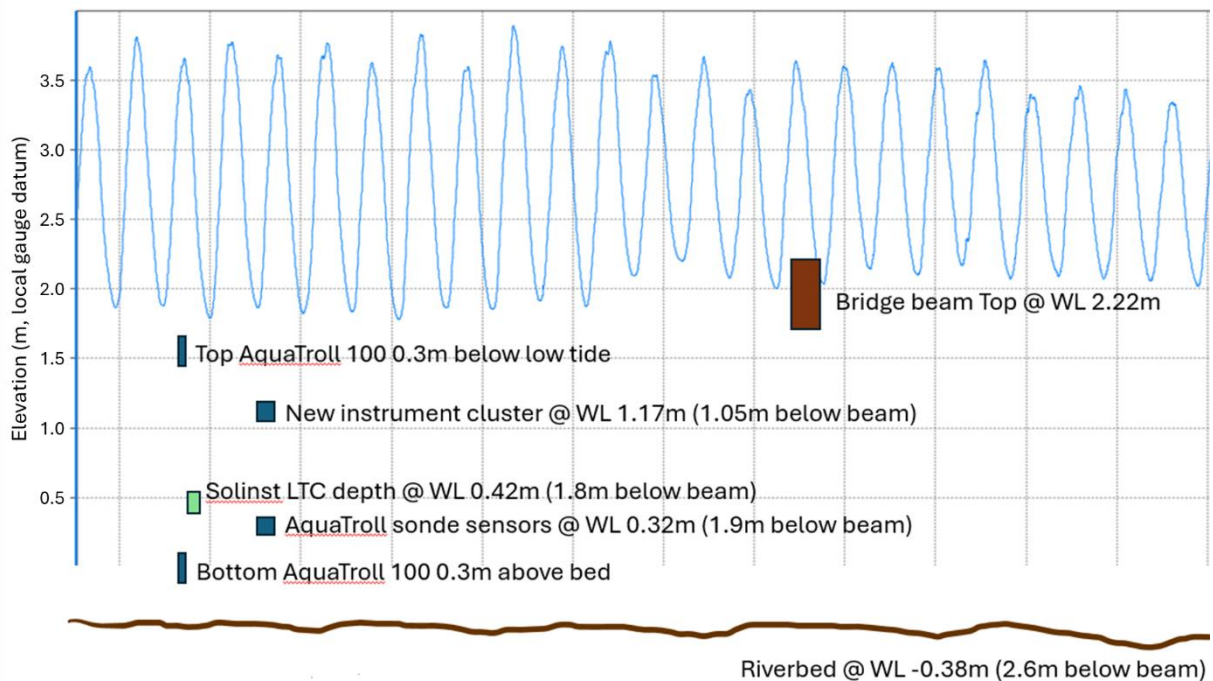


Figure 2-1: Schematic showing the elevation of different salinity sensors installed at the Mandeville Bridge. Blue line shows an indicative period of water level observations showing typical tidal range. Rectangles mark the elevation of the different salinity sensors. Also shown is the approximate bed level, and the level of a major beam on the bridge pier (for reference). All levels in this plot are in a local gauge datum.

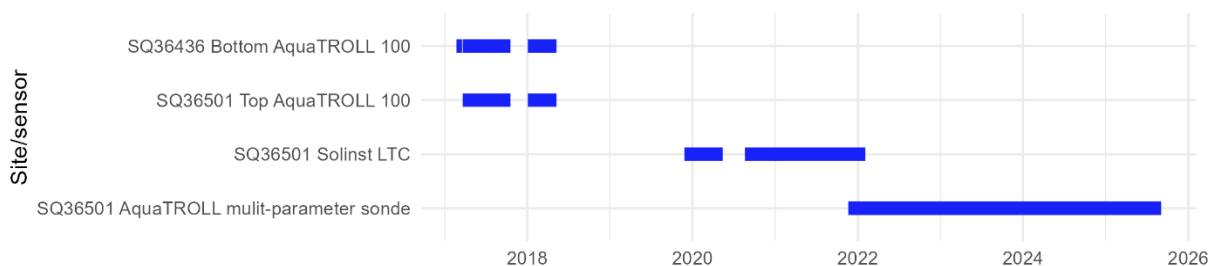


Figure 2-2: Timeline of availability of salinity data from different instruments.

As well as salinity the current sensor array also includes monitoring of water temperature, conductivity, turbidity, chlorophyll-*a*, phycocyanin and nitrate, but these data were not analysed for this report. The instruments are all operated/maintained by Environment Canterbury, recording measurements every 15 minutes and transmitting data via telemetry.

A site visit to the instruments was conducted at low tide on 10 October 2025 when Environment Canterbury were conducting a cleaning/servicing visit. The current sensors appeared well maintained with appropriate procedures for cleaning, calibrating and checking against water sample data. The sensor quality and maintenance regime has generally improved over time meaning that uncertainty associated with the observed data may be higher in the older data.

All the different salinity sensors installed at the site work in a similar way, measuring water conductivity and temperature and calculating salinity using standard calibration relationships.

Salinity was supplied in practical salinity units (PSU), equivalent to parts per thousand (ppt) or grammes per kilogram (g/kg). We verified the supplied salinity data against the supplied conductivity and temperature data, confirming that all the data were consistent (after correcting some very minor issues with units in some of the supplied conductivity data). As there were some periods where conductivity and temperature were in the supplied data, but salinity was missing, we calculated salinity for these periods from conductivity and temperature.

We checked the period of overlapping Solinst LTC and AquaTROLL multi-parameter sonde data to test for consistency between the two sensors. We found there was a bias between the sensors with the Solinst tending to record a salinity 21% lower than the AquaTROLL, although there was also some scatter in the data. It is notable that the highest salinities recorded from the AquaTROLL were approximately 32 ppt, roughly matching seawater, but the highest salinities from the Solinst were less than 25 ppt. This suggests that the AquaTROLL was providing more accurate data. To make the data as accurate as possible for the analysis we scaled up all data from the Solinst (based on the linear fit between the two datasets - red line in Figure 2-3). The scattered points above the black dashed line show times when the Solinst LTC recorded higher salinity than the AquaTROLL sonde. This is unexpected as the Solinst LTC was slightly higher in the water column (see Figure 2-1), so would be expected to experience saline conditions less often than the AquaTROLL sonde. The reason for these scattered points is unclear, but they only represent approximately 1% of the overlapping period.

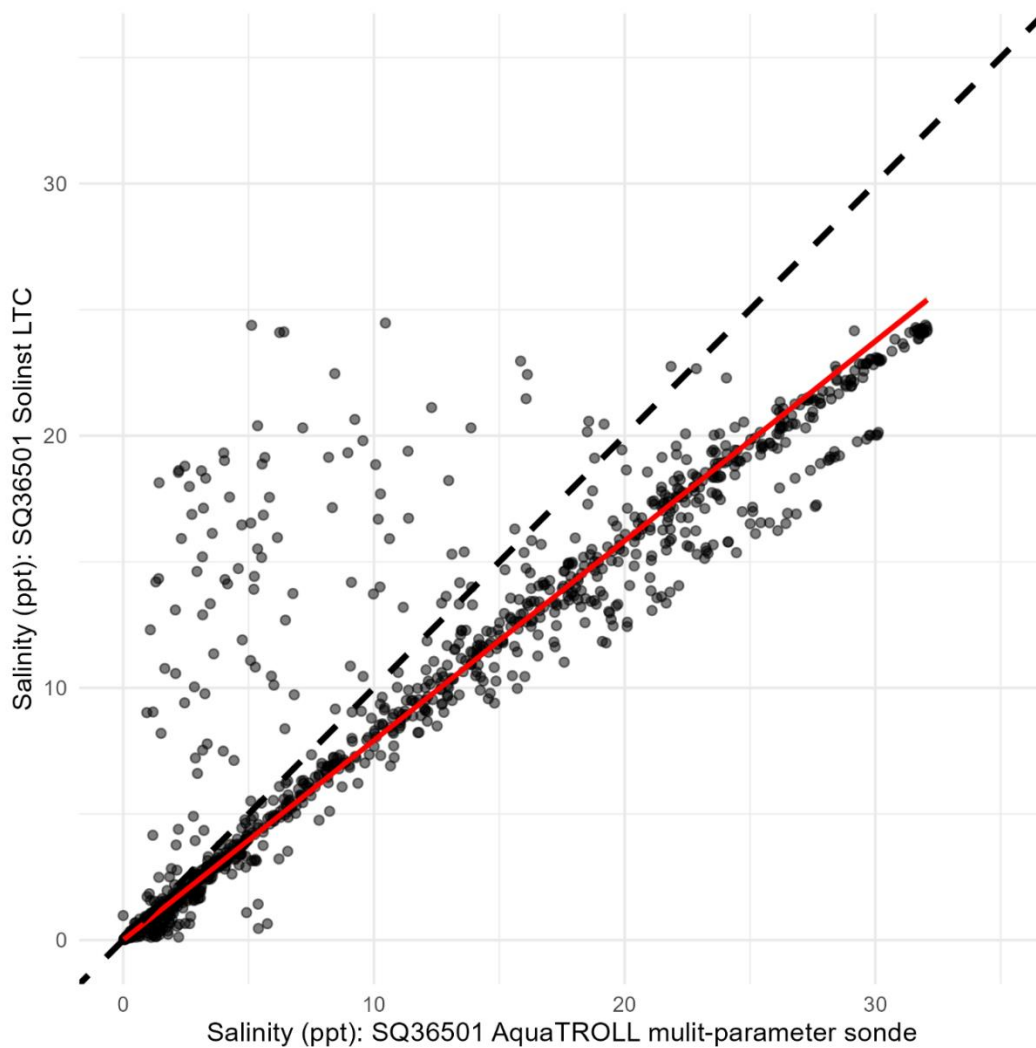


Figure 2-3: Comparison of overlapping salinity data from Solinst LTC and AquaTROLL multi-parameter sonde. Overlapping period from 19 November 2021 to 3 February 2022. Translucent black points represent concurrent measurements recorded at two sensors, black dashed line shows a perfect one to one match, and red line shows a linear fit to the observed data.

We also investigated the effect of sensor elevation on observed salinity by comparing concurrent data from the top and bottom AquaTROLL 100 sensors (Figure 2-4). It is clear that sensor elevation has a systematic effect on salinity, with the bottom sensor often recording saline conditions when the top sensor was recording fresh water. This difference is consistent with the presence of a salt wedge, with salinity moving upstream along the river bed as described in Section 1.2. The systematic effect of sensor elevation on salinity highlights that any differences in sensor elevation between the different sensor installations could bias our analysis and care is needed when comparing data from different installations.

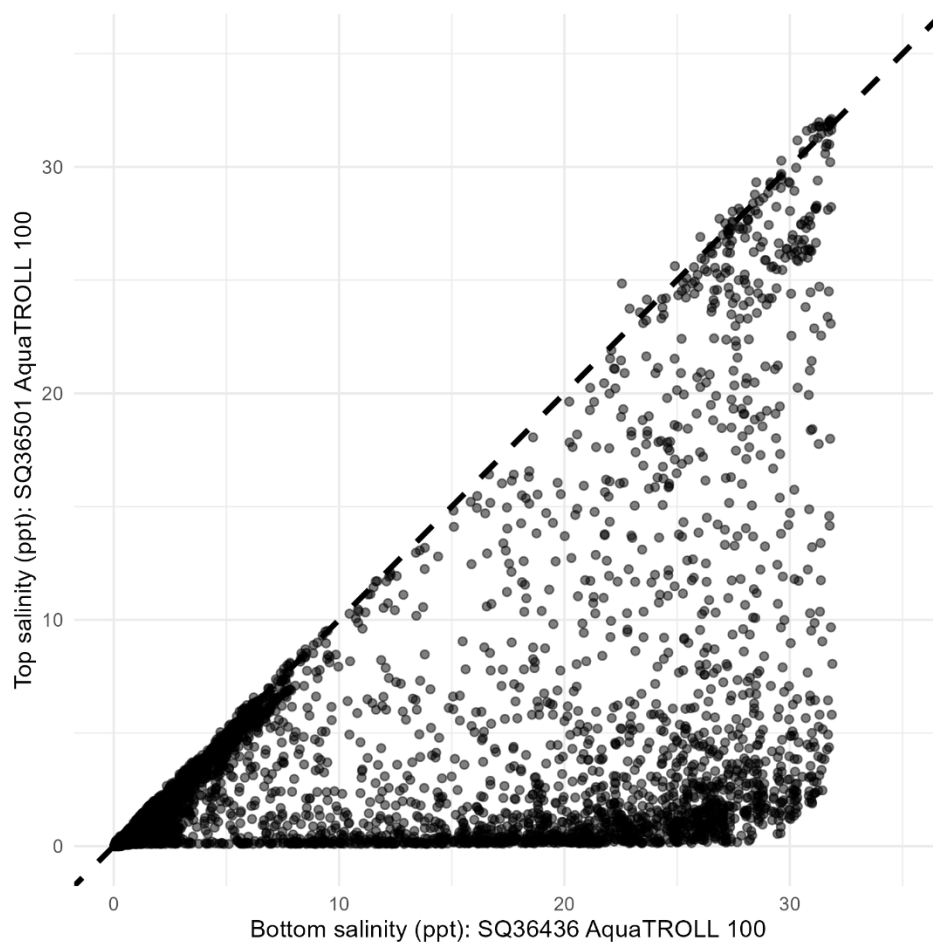


Figure 2-4: Comparison of concurrent data from top and bottom salinity sensors. Concurrent data from 21 March 2017 to 10 May 2018. Translucent black points represent concurrent measurements, black dashed line shows a perfect one to one match.

2.2 Sea level

The closest sea level monitoring recorder is located at Sumner Head (site 66699), approximately 20 km south of the Waimakariri River mouth. Sumner Head is a long term sea-level monitoring site maintained by Earth Sciences New Zealand and has continuous data since 1994. We used 1-minute interval sea level data, which we smoothed to remove noise then identified high and low tides (level and time) to use for further analysis.

We used observed tide data rather than predicted tide levels as observed data includes storm surge and sea-level rise effects. Tide data were analysed in New Zealand Vertical Datum 2016 (NZVD-2016).

2.3 Waimakariri River flow

River flow is monitored by Environment Canterbury at the Waimakariri at Old Highway Bridge monitoring site (site 66401), approximately 3.5 km upstream of where the Kaiapoi River enters the Waimakariri (Figure 1-1). Water level is recorded every 15 minutes at the monitoring site. Flow is derived from the water level record using a “rating curve” established and maintained by regular measurements of flow undertaken at different water levels.

To accurately represent flow the rating curve relies on the river being free flowing, but at high tide the Waimakariri at Old Highway Bridge site is affected by a tidal backwater effect. Environment Canterbury process the observed data to filter out the tide influenced water levels before calculating river flow. We used the best estimate of Waimakariri river flow supplied to us by Environment Canterbury.

2.4 Tributary flow

There is no flow recorder in Kaiapoi as the river is tidal making flow monitoring impractical. To represent tributary flow we used data from two flow recorders within the Kaiapoi River catchment: Cust Main Drain at Threlkelds Road (site 66417) and Cam at Youngs Road (site 66409). The location of these sites is shown in Figure 1-1. Flow data are also available in the catchment from Ohoka Spring at Dalleys Weir (site 66435), but this generally has very low flows and the selected sites are more representative of the catchment as a whole.

Further synthetic flow records are available for other sites within the catchment (Kaiapoi River at Neeves Rd and Ohoka Stream at Kaiapoi River confluence). These data are derived from measured relationships between these sites and primary monitored sites (e.g., Cust Main Drain at Threlkelds Road) and are used for consenting purposes. For this analysis of Kaiapoi salinity data we primarily consider the patterns of flow variation over time rather than the absolute flow values. Whilst these sites are in useful locations we chose to focus on the sites with continuous monitoring as the pattern of flow over time at the synthetic sites is derived from the monitored sites anyway.

3 Analysis and results

3.1 Developing a dataset for analysis

Our analysis focussed on understanding the drivers for saline intrusion into the Kaiapoi River. Peak saline intrusion always occurs close to high tide, so the first step of our analysis was to simplify the continuous monitoring data to a dataset where each entry represented conditions associated with a separate high tide. For each tide we calculated:

- **Observed high tide level at Sumner (high tide level):** As the raw sea level data are noisy (due to the influence of waves/surges etc) we smoothed the raw 1-minute timeseries with a 10-minute rolling average before identifying the tide peaks.
- **Maximum Kaiapoi salinity (peak salinity):** Maximum salinity observed at Kaiapoi within 3 hours either side of the Sumner high tide time.
- **Observed tidal range (tidal range):** We identified low tide levels from the smoothed sea level observations in the same way that we identified high tide levels and calculated tidal range as the level difference between each high tide and its preceding low tide.
- **Average Waimakariri River flow (Waimakariri flow):** We calculated mean river flow over the rising tide (i.e., over the period from the preceding low tide to the high tide). This period was selected as we assumed that it was flow during the rising tide which affected salinity propagation up the river.
- **Average tributary river flow (tributary flow):** We summed flows from Cust Main Drain at Threlkelds Road and Cam at Youngs Road and calculated the mean of the summed flow over the rising tide. As the two flows are highly correlated it is difficult to analyse them separately. Summing the two observed flows was assumed to be proportional to total freshwater flow in the Kaiapoi River at the upstream end of tidal influence.
- **Whether the tide was before or after dredging took place (dredging):** We classified each datapoint based on whether it was before or after dredging was carried out in the Kaiapoi River. Points prior to 1 June 2020 were classified as pre-dredging and points after 1 September 2020 classified as post-dredging. As the dredging took place during June-August 2020 this period was classified as during-dredging.

From 21 March 2017 to 22 July 2025 there are 5831 high tides, of which salinity data were available for 4401. Full data for all variables is available for 4315 high tides.

3.2 Testing for significant drivers of salinity

Using the created dataset, we investigated the strength of relationship between variables (high tide level, tidal range, Waimakariri flow and tributary flow) and peak salinity at Kaiapoi (initially ignoring any effect of dredging). For this analysis we only used data from 2019 onwards due to differences in the sensor elevation of the early top and bottom salinity sensor installations compared to the more recent salinity data. Excluding data from prior to 2019 leaves 3714 high

tides for which all variables were available. Prior to undertaking statistical analysis we checked for correlation between the variables as correlation could make it difficult to separate out their individual relationships with salinity. The results of the correlation check are shown in Figure 3-1. The correlation check showed that:

- There was a moderate positive correlation between Waimakariri flow and tributary flow (Pearson correlation = 0.39).
- There was a strong correlation between high tide level and tidal range (Pearson correlation = 0.78).

The scatter plots in Figure 3-1 also highlight that Waimakariri flow and tributary flow both have very skewed distributions. For this reason, we log transformed the flow data for all our statistical analysis. High tide level and tidal range were normally distributed.

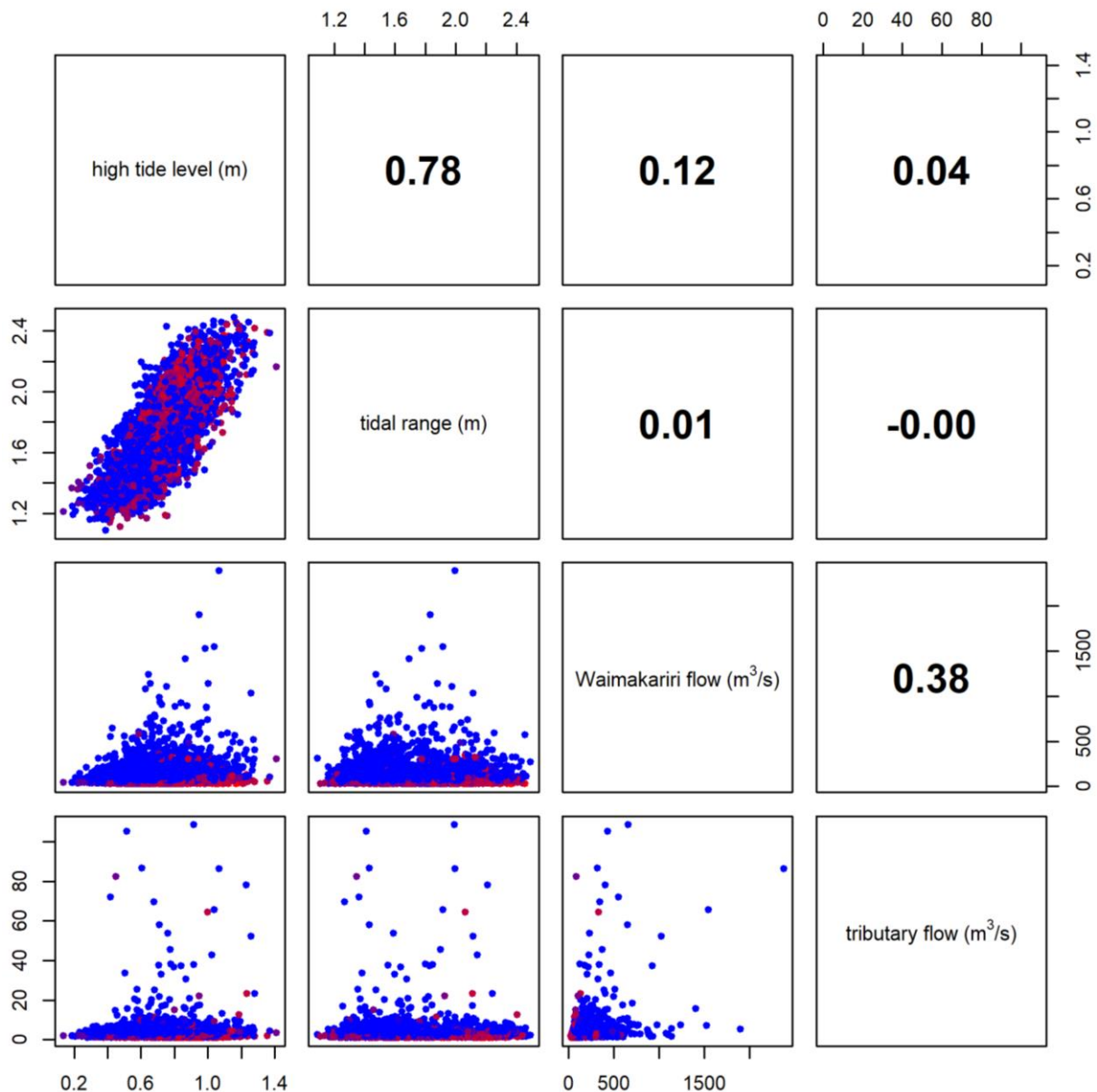


Figure 3-1: Pairwise scatter plot showing correlation between different measured variables representing potential drivers of saline intrusion. Each point represents a single high tide. Points are coloured by maximum salinity observed at Kaiapoi, blue = fresh water, red = saline. Bold numbers are the Pearson correlation coefficient for each pair of variables.

We then checked for multicollinearity to test whether the degree of correlation might influence our ability to separate out the degree to which each variable is independently related to salinity. Despite the correlation between high tide level and tidal range all variables had an acceptable level of multicollinearity (Variance Inflation Factor (VIF) below 3), indicating that each variable contributes unique information, so it is ok to include all the variables into our statistical analysis.

We trialled various approaches to investigate the relationship between each of the variables and the peak salinity. First, we tried fitting a generalised linear model (GLM), but peak salinity is bimodal which means the GLM does not perform well. The distribution of observed peak salinity

is shown in Figure 3-2, it tends to either be close to zero or significantly saline, with few observations between 5 and 13 ppt.

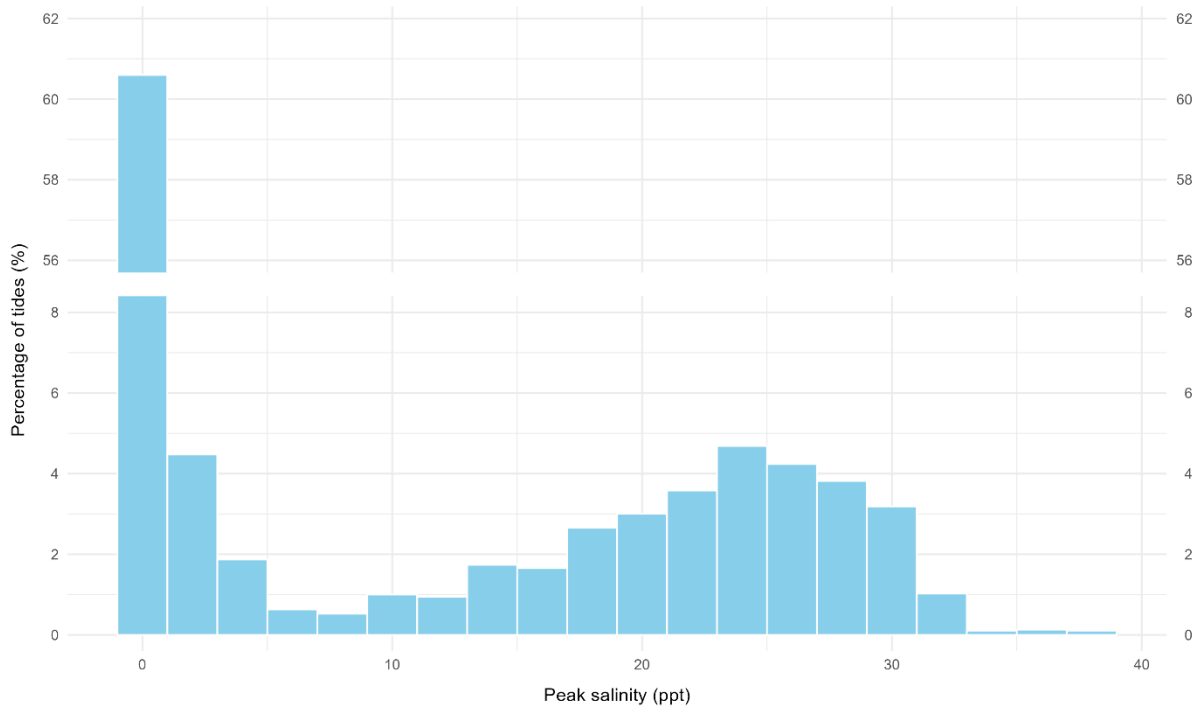


Figure 3-2: Histogram showing distribution of observed peak salinity at Kaiapoi.

We then tested fitting a generalised additive model (GAM). This statistical model assumes that peak salinity can be predicted by summing smooth functions related to each of the variables. Fitting the model involves optimising the shape of the smooth functions describing the partial effect of each of the predictors on peak salinity. Our initial attempts to fit a model were promising, but when checking the model results, we found there is temporal autocorrelation in the residuals. This indicates that the salinity on each high tide is partially linked to salinity on the previous high tide. The presence of temporal autocorrelation violates the assumptions of our initial model, so we modified the model to account for autocorrelation by: (a) adjusting the likelihood to account for first-order autoregressive correlation in the model residuals ($\rho(1) = 0.51$), and (b) explicitly including a smooth function for time within the model (time was expressed in terms of number of high tides since the first data point). Our final model took the form shown in (1) using the ‘bam’ function of the mgcv package (Wood 2025). The resulting partial effect curves are shown in Figure 3-3.

$$\begin{aligned}
 \text{Salinity} \sim & s(\text{high tide level}) + s(\log_{10}(\text{Waimakariri flow})) \\
 & + s(\log_{10}(\text{tributary flow})) + s(\text{tidal range}) + s(\text{tide number})
 \end{aligned}
 \tag{1}$$

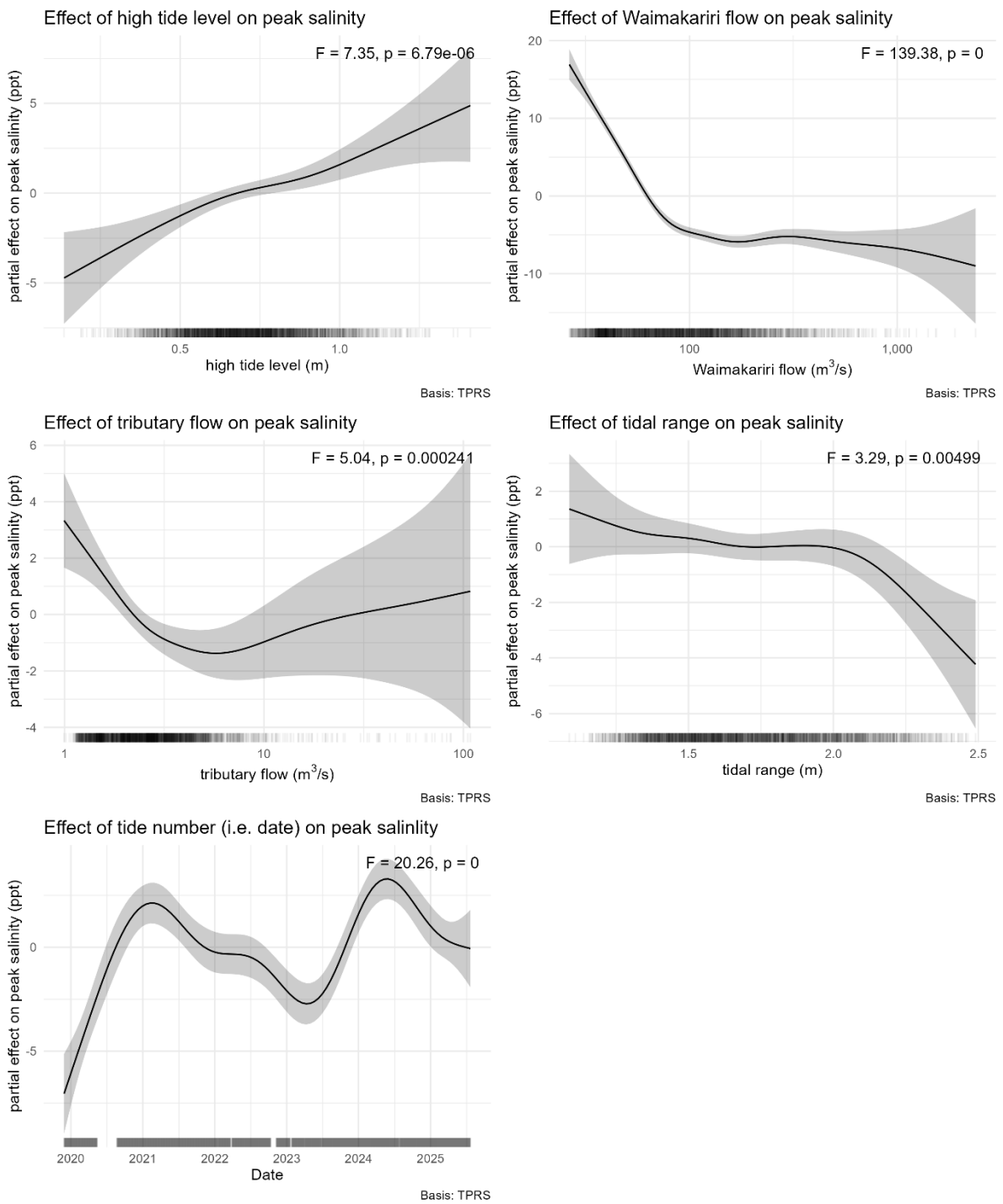


Figure 3-3: Fitted GAM model showing partial effect of high tide level, Waimakariri flow, tributary flow and tidal range on peak salinity. The shaded region shows the 95% confidence interval. Black markers on the x-axis show the distribution of observed data (1-marker per observed tide). The F and p statistics for each parameter are shown in the top right of each plot. The F-value indicates the overall significance of the individual parameter (higher F indicates greater significance), and the p-value indicates the probability that the observed effect of a parameter is due to chance (low p indicates high confidence that the parameter influences salinity).

All variables had very significant relationships with salinity (p-value < 0.005). The partial effect curves (and F-values) show that Waimakariri flow has the biggest effect on salinity, followed by tide number and high tide level. Tributary flow and tidal range have smaller effects.

As expected, higher tide level, lower Waimakariri flow and lower tributary flow are all associated with higher peak salinity. Higher tidal range results in slightly lower peak salinity. At first inspection this seems counterintuitive but because tidal range is considered separately to high tide level, higher tidal range equates to lower low-tide level (for any given high tide level). Lower low tide level potentially allows salinity to flush from the river system more effectively.

The shape of the partial effect curves helps explain the way each parameter influences salinity. For high tide level salinity increases continuously as high tide level increases. For Waimakariri flows up to approximately 75 m³/s increasing flow results in reducing salinity, but beyond this flow threshold there is little effect (as salinities are already low).

The partial effect curve for tide number suggests that there are some temporal changes in the pattern of measured high tide salinity which are not explained by changes in flows or tides. These may be the result of changes in sensors (e.g., type, elevation, drift in calibration), physical changes in the river (e.g., dredging, sedimentation) or other factors. The potential for dredging to have influence salinity is explored further in Section 0.

3.3 Waimakariri River flow and high tide level

Having identified that Waimakariri flow, followed by high tide level, have the biggest effect on saline intrusion (ignoring temporal changes for now) we undertook a more detailed analysis of how they combine to control salinity. For this analysis we only used data from the recent AquaTROLL multi-parameter sonde (November 2021 onwards). We selected these data because they: a) make up the largest part of the salinity record (Figure 2-2); b) are the most reliable; c) are at a consistent sensor elevation; and d) are all from after dredging was completed.

Figure 3-4 shows observed peak salinity plotted against the observed high tide level and Waimakariri flow. Whilst there are clear trends visible in the raw data it is difficult to draw clear conclusions due to the number of data points and the noise present.

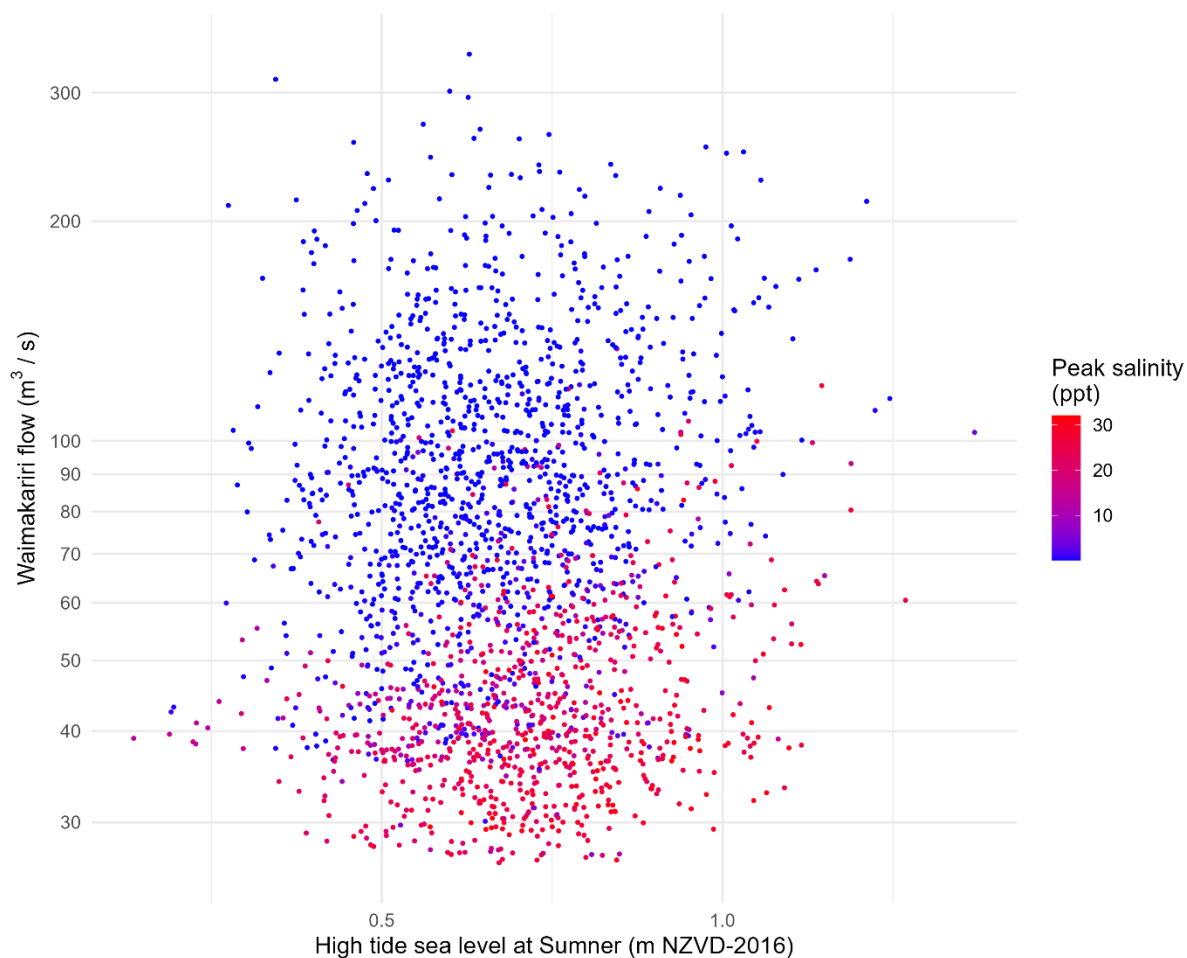


Figure 3-4: Scatter plot showing observed peak salinity versus high tide level and Waimakariri flow. Data only shown from the highest quality period of record since November 2021. Data points from periods where the Waimakariri flow is changing rapidly (more than 100 m³/s in the 24 hours prior to high tide) have been excluded.

We noticed that outlier points often occurred during periods of rapidly changing flow. Rapidly rising Waimakariri flow following a period of low flow with saline intrusion appears to trap salinity temporarily inside the Kaiapoi River, leading to saline intrusion being observed at high tide during high flows. This effect only persists for one or two tides and is part of the autocorrelation identified in the statistical analysis. We filtered out all data points where Waimakariri flow changed more than 100 m³/s in the 24 hours prior to high tide to be able to more clearly analyse the relationship between flow and saline intrusion.

As the salinity data are bimodal, tending to either be close to fresh or relatively saline, we simplified the data by classifying each high tide as either saline or non-saline depending on whether salinity was greater than 5 ppt. The conclusions of our analysis are insensitive to the specific threshold selected within the range of roughly 5–13 ppt as observed salinity is very rarely in this range, tending to be less than 5 ppt or greater than 13 ppt (see Figure 3-2). 5 ppt was selected as it is roughly indicative of salinity sufficient to impact river ecology.

To make the large number of data points easier to visualise we binned the data into discrete bands of high tide level and (log transformed) Waimakariri flow, calculating the number of observed tides in each bin, and the proportion of observed tides which were saline. These

binned data are plotted as a heatmap in Figure 3-5. The heatmap clearly shows the combined influence of high tide level and Waimakariri flow. Some noise is visible close to the upper and lower bounds of observed high tide level, but this represents a very small number of observations.

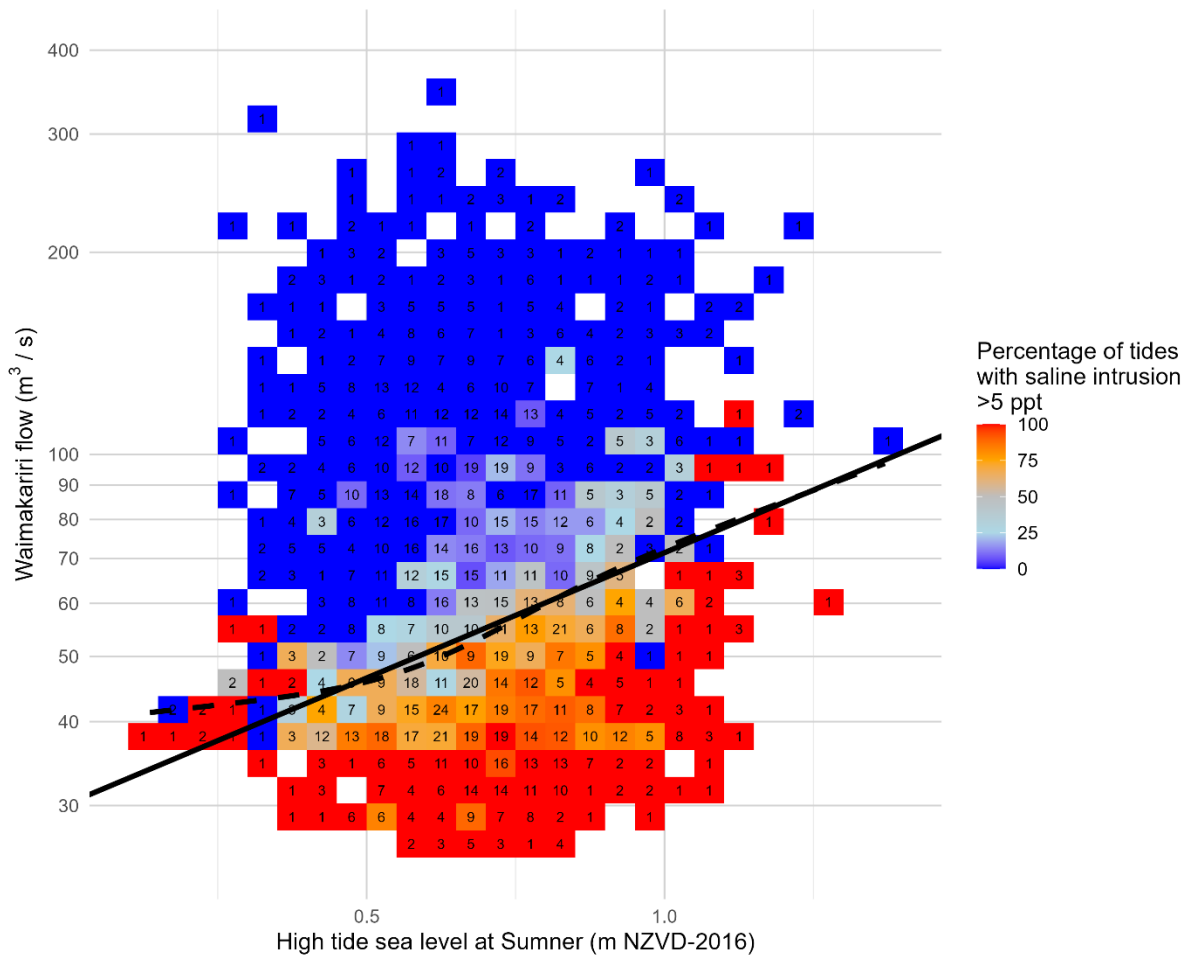


Figure 3-5: Heatmap showing the proportion of observed tides experiencing saline intrusion under different high tide level and Waimakariri flow conditions. Black values show the number of observed tides within each bin/cell. Two threshold lines are shown: the solid line is a fitted linear model, and the dashed line is a fitted non-linear GAM.

To aid in interpreting the data threshold lines were fitted to the observed data, identifying the combinations of high tide level and Waimakariri flow likely to result in salinity (>5 ppt) being observed in Kaiapoi. We tested fitting linear (solid line in Figure 3-5) and non-linear (GAM, dashed line in Figure 3-5) models to determine a threshold, with both models giving very similar results except for close to the lower bound of observed high-tide levels (high tide level less than 0.40 m). Given that very few tides of these levels are observed, and uncertainty of the models is greater at the edges of the fitted data range, we prefer the simpler linear threshold.

Focussing on the effect of Waimakariri flow only, we computed the proportion of observed tides experiencing saline intrusion (>5 ppt) for different Waimakariri flows. This shows that (under 2017–2025 sea levels), saline intrusion occurs on almost all tides when flow is less than 35 m³/s, only on approximately 10% tides when flow is greater than 70 m³/s, and almost never

when flow is greater than 105 m³/s. For flows between 35 and 70 m³/s the proportion of tides with saline intrusion reduces as flow increases.

Figure 3-7 puts these flows into context by showing the observed flow duration curve for the Waimakariri. Flows less than 35 m³/s (i.e. regular saline intrusion) only occur about 5% of the time, while flows between 35 and 70 m³/s (saline intrusion likelihood varies with flow) occur about 40% of the time. Flows in the Waimakariri are influenced by water abstraction, primarily for irrigation. Consent rules progressively restrict abstraction as river flows drop and require that all abstraction cease at flows below 41 m³/s.

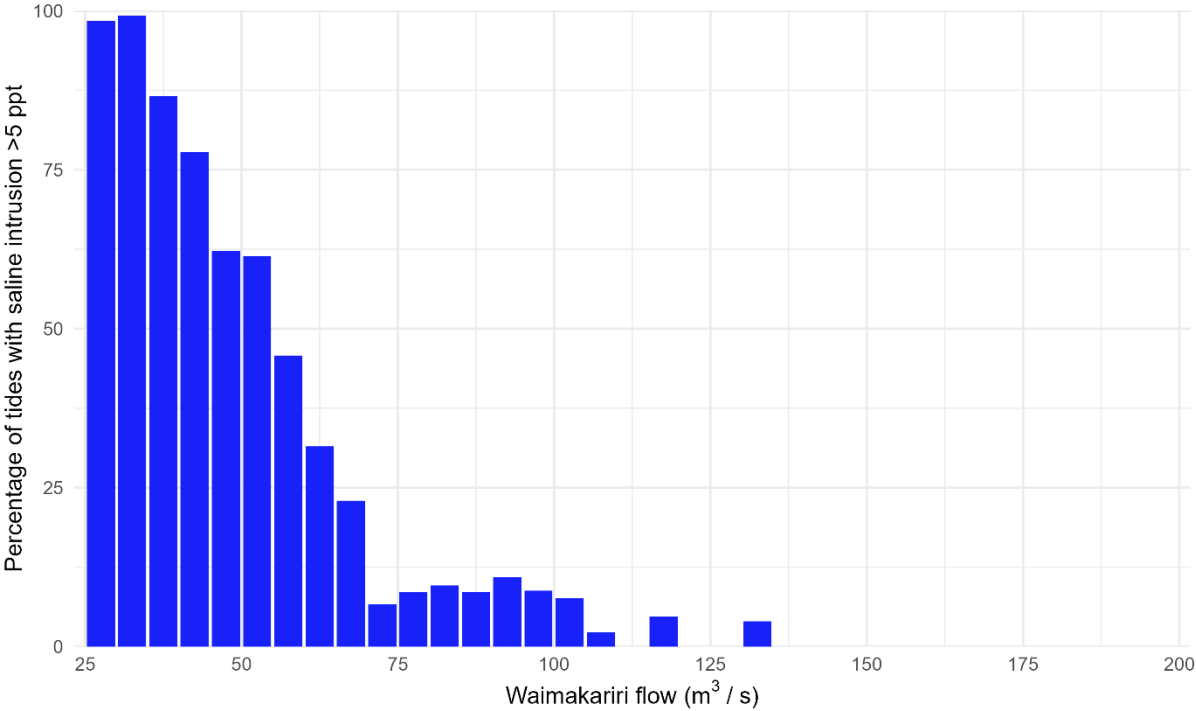


Figure 3-6: Proportion of observed tides with measured saline intrusion for different Waimakariri flows.

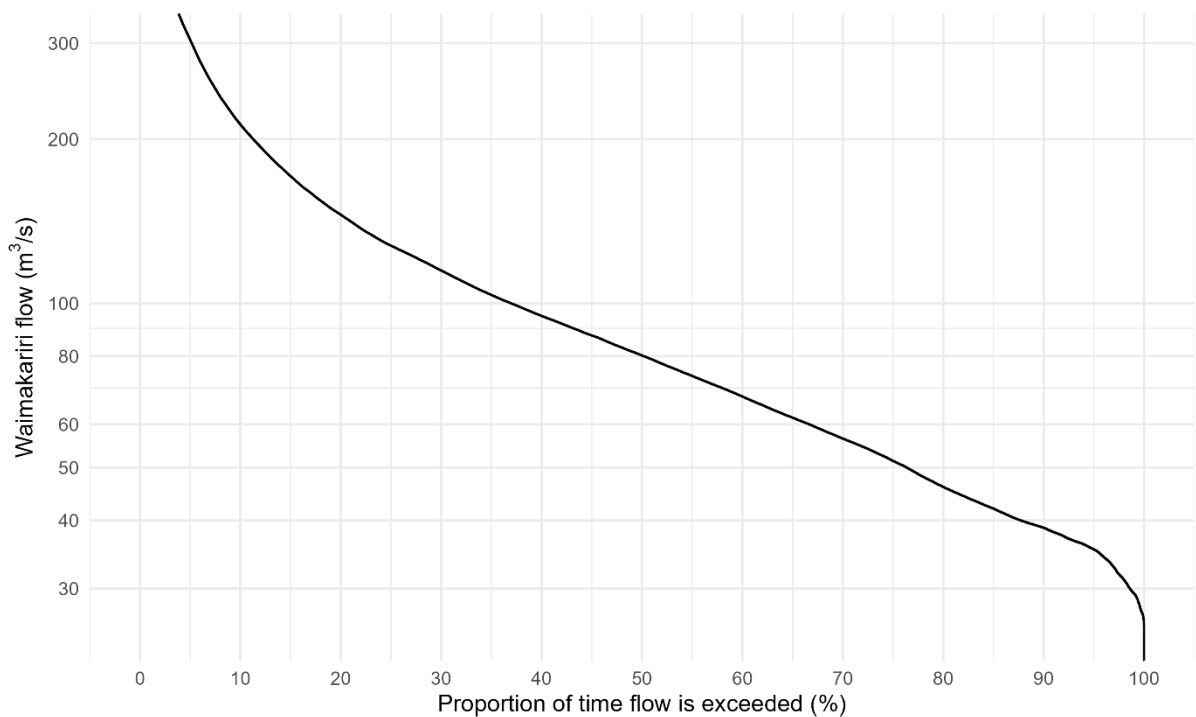


Figure 3-7: Waimakariri at Old Highway Bridge flow duration curve. Flow duration curve calculated for the period 2016--2025.

3.4 Dredging

Dredging has the potential to increase saline intrusion as deepening the channel may make it easier for sea water to propagate upstream. Salinity increases water density and salt water generally propagates along the bed of the deepest part of the channel. High points in the thalweg of the channel (i.e. shallow areas) can block the propagation of a salt wedge (see Figure 1-2). The bed levels at downstream end of the Kaiapoi River, where it meets the Waimakariri, are likely to be an important control on the ability of saltwater to enter the Kaiapoi. The bed of the Kaiapoi River is likely perched above the bed of the Waimakariri with this difference in bed level helping to prevent salinity entering the Kaiapoi River.

To test whether there was a significant change in salinity intrusion from the before-dredging to after-dredging periods, we included a factor which indicated before or after dredging within the GAM statistical model. This allowed us to investigate the role of before/after dredging on salinity while controlling for the effects of high tide level and Waimakariri flow. For this analysis we excluded data from the “during dredging” period. Because salinity is so sensitive to depth we focussed on data from the Solinst LTC sensor only. Data from this sensor spans from before the dredging took place to after so allows us to investigate the effects of dredging without the added complexities of accounting for changes in sensor type or elevation.

There were 326 high tides with available data from the Solinst LTC salinity sensor before dredging and 1006 after dredging (including data from the AquaTROLL Sonde and Solinst LTC sensors as they were at a similar elevation and the data is comparable). The fitted GAM confirmed that dredging had a statistically significant effect on salinity ($p \sim 0$, $t = 7.2$).

The effect of dredging was explored further by repeating the analysis of Waimakariri flow and high tide level effect on salinity separately for the before dredging and after dredging periods

(Figure 3-8). The heatmaps show that saline intrusion is being observed at lower Waimakariri flows and lower tide levels after dredging compared to before dredging.

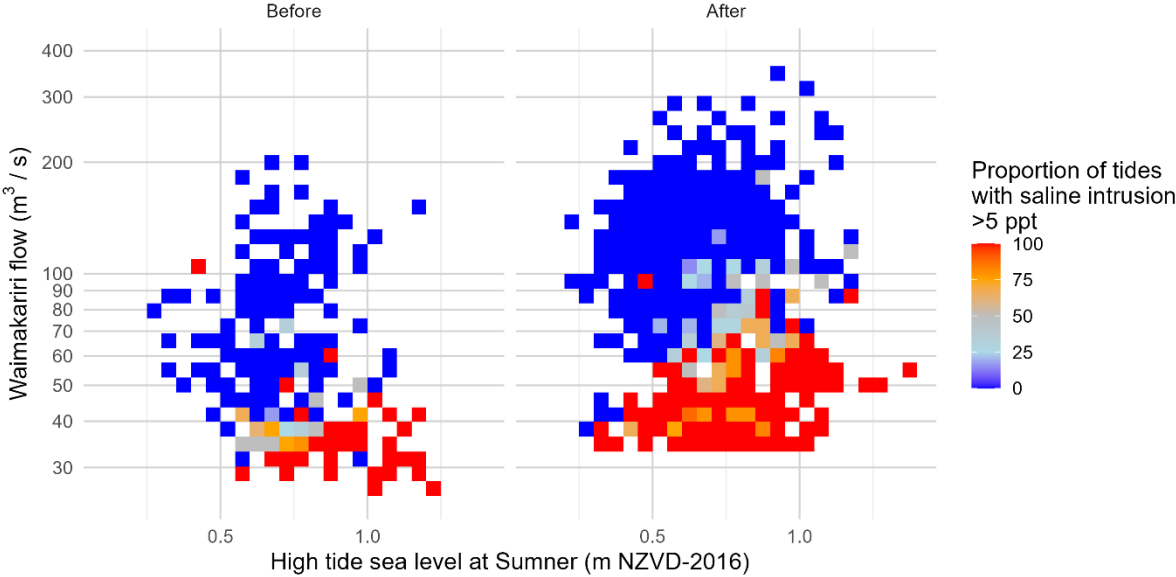


Figure 3-8: Change in observed saline intrusions under different flow/tide conditions from before and after dredging. Data is only shown for the Solinst LTC sensor to avoid any complications due to changes in sensor depth.

Whilst the statistical analysis and heatmaps confirm that saline intrusion is being observed more frequently after dredging took place in 2020, and under lower river flow/tide level conditions, it cannot confirm dredging is the cause of this change. However, the observed increase in saline intrusion is consistent with anecdotal observations and there is a plausible mechanism for dredging to have increased salinity intrusion. The change in observed intrusion for given Waimakariri flow / high tide level conditions is quite large. This finding indicates that there is most likely a real increase in saline intrusion following dredging.

3.5 Sea level rise

Saline intrusion is sensitive to high tide level, so sea level rise is expected to increase saline intrusion. The relationship between Waimakariri flow, high tide level and saline intrusion provides a powerful tool to predict the influence of sea level rise (SLR) on saline intrusions. Sea levels measured at Lyttelton Harbour increased by an average of 2.77 mm/yr over the period 1961–2020 and continue to increase at an accelerating rate as a result of climate change (Bell et al. 2022). Applying the linear threshold in Figure 3-5, in combination with the distribution of observed high tide levels, enables calculation of how the frequency of saline intrusion is likely to change for different river flows, under different amounts of sea level rise. The results of this calculation are presented for a range of flows and sea level rise in Table 3-1. For example, for a river flow of 60 m³/s, 0.1 m of sea level rise would increase the frequency of saline intrusion from 44% of tides to 66% of tides, and 0.5 m sea level rise would mean saline intrusion occurred on every tide. Another way of interpreting the sea level rise effect is to consider how sea level rise impacts the Waimakariri flow required to prevent most intrusion. For example, under current sea levels a flow of 72 m³/s prevents intrusion on 90% of tides, but with 0.1 m of sea level rise a flow of 77 m³/s is needed, and with 0.5 m of sea level rise a flow of 97 m³/s is needed.

Table 3-1: Sea level rise effect on saline intrusion for a range of Waimakariri river flows. High tide level required to cause intrusion has been taken from the straight line threshold in Figure 3-5. The distribution of high tide levels relative to mean sea level taken from observed sea level data for the period analysed (2017 to present) was used to calculate the proportion of high tides exceeding the level threshold. Predictions for the effect of sea level rise greater than 0.5 m are not presented as this takes high tide levels well outside the range of current tides and it may not be appropriate to extrapolate the linear Waimakariri flow/high tide level threshold to these levels.

Waimakariri flow (m ³ /s)	High tide level required to cause intrusion (m)	Proportion of high tides exceeding the level required to cause saline intrusion			
		Current sea level	0.1 m SLR	0.2 m SLR	0.5 m SLR
30	0.153	100%	100%	100%	100%
35	0.252	100%	100%	100%	100%
40	0.351	100%	100%	100%	100%
45	0.451	100%	100%	100%	100%
50	0.550	86%	100%	100%	100%
55	0.649	66%	86%	100%	100%
60	0.748	44%	66%	87%	100%
65	0.847	25%	44%	66%	100%
70	0.946	13%	25%	44%	100%
75	1.045	5%	13%	25%	87%
80	1.145	2%	5%	13%	67%
85	1.244	1%	2%	5%	44%
90	1.343	0%	1%	2%	25%
95	1.442	0%	0%	1%	13%
100	1.541	0%	0%	0%	5%
105	1.640	0%	0%	0%	2%

3.6 Earthquake effects

Earthquakes can cause vertical land movement (uplift or subsidence) as well as lateral spreading and liquefaction, all of which can change river channel bed levels and geometry, potentially affecting saline intrusion. There is no continuous salinity monitoring data available in Kaiapoi from prior to the 2010–11 Canterbury earthquake sequence, or the 2016 Kaikoura earthquake to directly analyse the effect of the earthquakes on salinity intrusion.

LiDAR measurements show that during the Canterbury earthquake sequence areas of Kaiapoi bordering the Kaiapoi River generally subsided (CERA 2012). Subsidence was highly spatially variable with subsidence of more than 0.1 m widespread and more than 0.5 m locally, particularly in areas influenced by liquefaction and/or lateral spreading. The degree of vertical movement is likely to have impacted saline intrusion in Kaiapoi. Any subsidence of the riverbed would be likely to increase saline intrusion (similar to dredging).

Vertical land movements in the Christchurch/Kaiapoi area as a result of the 2016 Kaikoura earthquake were much smaller (subsidence of ~0.01–0.02 m, LINZ 2017) and are not expected to have had a significant impact on saline intrusion.

4 Conclusions

Continuous salinity monitoring data collected from the Kaiapoi River provide a powerful dataset for analysis into the drivers of saline intrusion. Current monitoring data are reliable because they are associated with robust quality control, but the installed sensors have been through several iterations and the earlier data (prior to 2020) has greater uncertainties. The exact elevations of historically deployed sensors are unknown, and measured salinity is sensitive to sensor elevation, this increases uncertainty when comparing data from different sensors/periods.

The occurrence of saline conditions in the Kaiapoi River on any given tide are strongly associated with the combination of Waimakariri River flow and high tide level. Tributary flows and tidal range/low tide level have smaller (but still statistically significant) effects on salinity. The combined effect of Waimakariri flow and high tide level on the likelihood of saline intrusion is clearly shown in Figure 3-5. Saline intrusion occurs on almost all tides when flow is less than 35 m³/s, only on approximately 10% of tides when flow is greater than 72 m³/s, and almost never when flow is greater than 105 m³/s. For flows in the range 35–72 m³/s the likelihood of saline intrusion depends on the combination of river flow and tide level, with higher tides required to drive saline intrusion when Waimakariri flows are higher.

There is a significant change in observed saline intrusion in 2020, coinciding with dredging of the Kaiapoi River. Saline intrusion became more frequent and occurred at lower Waimakariri flows following the dredging. It is not possible to definitively link the observed changes to dredging, however the observed changes are consistent with observations of ecological changes (Allen 2024) and there is a plausible mechanism for dredging to have increased salinity intrusion. We conclude that there is most likely a real increase in saline intrusion because of dredging.

Saline intrusion is sensitive to high tide level, indicating that sea level rise is expected to increase the frequency of saline intrusion. We used the relationship between Waimakariri river flow, high tide level and saline intrusion to investigate the sensitivity of saline intrusion to sea level rise for a range of river flows, finding that even small amounts of sea level rise are associated with notable increases in the frequency of saline intrusion. Under current sea levels a flow of 72 m³/s prevents intrusion on 90% of tides, but with 0.1 m of sea level rise a flow of 77 m³/s is needed, and with 0.5 m of sea level rise a flow of 97 m³/s is needed.

Earthquakes can change river channel bed levels and geometry, potentially affecting saline intrusion. Kaiapoi experienced subsidence during the 2010–11 Canterbury earthquake sequence which is likely to have increased saline intrusion.

5 Acknowledgements

Adrian Meredith and Suz Gabites assisted with understanding the background to this analysis and planning the analysis approach. Hamish Carrad provided the salinity data, coordinated the field trip to the monitoring instruments, answered questions regarding instrumentation and monitoring and drafted Figure 2-1 showing the sensor elevations. This analysis would not have been possible without the ongoing water quality and hydrometric data collection by Environment Canterbury and Earth Sciences New Zealand.

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