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Changes in salinity of a clay soil after a short-term salt water flood event

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ABSTRACT

The effects and subsequent recovery from a short-term salt water flood event were studied on a clay soil. Sea inundation of agricultural land caused marine salt water to pond on the soil surface for up to 144 h. The salinity of the soil, how deeply the salt water penetrated into the soil and how quickly salts washed out of the soil were assessed. Elevated salt content was seen most strongly in the top layer (0–2 cm) of the soil and salt concentrations increased with the length of inundation. Maize crops died if inundated for 24 h or more, while ryegrass pasture died after an inundation period of 36 h or more. Flushing of soil particles with fresh rainwater proved effective at lowering the salt content in the top 2 cm of soil. The salt content was considerably lower after one rainfall event of 35 mm and decreased only slightly more after another 165 mm of rain. The combined effect of sea level rise and land subsidence may enhance saltwater contamination and soil salinisation with potential serious environmental and socio-economic impacts, e.g. compromising agriculture. Using salt tolerant grasses as pasture species in these low-lying areas should be further investigated.

1. Introduction

The thermal expansion of seawater due to ocean warming and water mass input from melting land ice is likely to increase the occurrence of coastal flooding (Church et al., 2013; Nicholls and Cazenave, 2010). A recent event highlights the risks of flooding to pastoral farms within the coastal zone. On Friday, 5 January 2018, a culmination of a king tide (4.4 m and equal to a >1-in- 200 year tide event), strong to gale force winds, warmer than usual sea temperatures and low barometric pressure resulted in sea inundation of agricultural land around the shoreline of Miranda/Kaiaua on the western side of the Firth of Thames, New Zealand (Fig. 1).

Several days of heavy rain prior to the sea inundation further compounded the situation with 140 mm recorded over the preceding 48 h, a 10–20 year return rain event. Between Miranda and Kaiaua, 648 ha of land in a marine clay basin was flooded by salt water for up to 144 h (Craig and O'Shaughnessy, 2018, Figs. 2 & 3). Ponded salt water was removed after the event through open drainage ditches and, to a lesser extent, by evaporation. There was much public focus on damage within the township of Kaiaua but this paper focuses on the impact of the inundation on agricultural land.

Desiccation and death of crops and pasture occurred due to the inundation with salt water. The inundation also potentially increased the salinity of flooded soils. Soil salinity of agricultural lands in New Zealand has rarely been a major problem due to the abundant annual rainfall of 1000 to 8000 mm). There was a body of literature on the impacts of salt water flooding on soils from tsunami and major cyclone events, such as tropical cyclones, typhoons, and hurricanes, these events were much larger than the one at Miranda/Kaiaua, i.e. inundation was usually considerably longer. However, some valuable information was obtained to aid farmers with the recovery process.

One of the main factors after inundation of land by salt water is residual high soil salt content that hampers the development of seedlings and inhibits crop growth (Provin et al., 2009; Tchouaffe, 2007). This high salt content expresses itself in two ways. Saline soils have excessive levels of soluble salts (especially NaCl) in the soil water that reduces the availability of water to plants, thus leading to desiccation and possible death of plants. In contrast to saline soils, sodic soils have excessive levels of sodium (Na^+) adsorbed at the cation exchange sites that can degrade the soil structure through dispersion of clays and slaking of aggregates (Shainberg et al., 2001). Soils can be saline and sodic at the same time.

Soil recovery after inundation by salt water appears dependent on a complex array of factors, including soil texture, soil organic matter content, the level of soil moisture before the surge, rainfall, the availability of transfer pathways for water and the duration of the saltwater inundation (Roy et al., 2014). Sandy soils have higher infiltration rates, while heavy textured soils, which contain much clay and/or silt, often have lower infiltration rates. Soil organic matter aids infiltration by supporting aggregate formation. The duration of infiltration and the availability of transfer pathways for salty water to drain from the affected land appear determined by the relative elevation within the landscape. High salt content on the soil surface and salinity within the soil can be reduced by leaching or overland flow of salty water to drainage ways after rain or freshwater irrigation (Chagué-Goff et al., 2012,

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Fig. 1. Location of the Kaiaua/Miranda area (red oval), Firth of Thames, about 60 km North of Hamilton City, Waikato region, North Island, New Zealand.

Nakaya et al., 2010, Provin et al., 2009, Tchouaffe, 2007). In addition, calcium-based soil amendments, such as gypsum that release Na^+ from clay colloids into soil solution, are commonly used to ameliorate sodic soils (Sandoval et al., 2013). Once Na^+ is released into soil solution, it can then be leached from the soil in drainage.

However, long-term effects can still be expected. McLeod et al. (2010) reported soil salinity persisted in soils of Aceh Province, Indonesia, at levels that could reduce crop production for several years after the 2004 Indian Ocean tsunami, even though there had been >3000–7000 mm of accumulated rainfall over that period to leach salt. Similarly, despite an average annual rainfall in the affected region of 1360 mm, Chagué-Goff et al. (2014) recorded elevated soil salinity in Japan 11 months after the 2011 Tohoku-oki tsunami with salt crusts still covered the area inundated, and Roy et al. (2014) reported about 60% of the affected land was still to recover two years after the tsunami. In contrast, Nakaya et al. (2010) reported most of the soil salinity caused by the 2004 tsunami in southern Thailand was removed by 1000 mm of rain.

The differing behaviour of soil salinity appears largely due to soil texture. The Thai soils were argillaceous with low hydraulic conductivity and electrical conductivity was high only in the surface 2 cm of the soil. In comparison, the Indonesian soils had textures varying from silty loam to silty clay in the top 20 cm and from loamy sand to clay in the subsoils, while the Japanese soils had textures ranging from sand to loam.

Interestingly, soil salinity in inundated soils was reported to increase after the 2011 tsunami due to capillary action and evaporation following long periods with little precipitation (Chagué-Goff et al., 2014).

In comparison with the above literature on the effects from Tsunamis, Provin et al. (2009) reported on the effects of Hurricane Ike on pasture, which inundated agricultural land for up to 240 h. Observations and soil tests made approximately 10 days after the Hurricane revealed some species of pasture survived after inundation for 24–48 h, while Bermuda grass could possibly recover after inundation of up to 96 h. However, many types of forage, such as ryegrass and most clover varieties, were relatively sensitive to higher salinity levels.

There appeared to be few published studies on the impacts and recovery from smaller inundation events where the flood duration was days. As a result, there was limited knowledge of recovery options available for emergency and land management authorities. Waikato Regional Council was one of the agencies that provided support to those affected, undertook assessments and provided guidance. Key questions from affected farmers were what were the long-term effects from the inundation and how long until they could sow new pasture in order to feed their cattle. In addition, the effects of salt water flooding on New Zealand agricultural soils have not been reported. This study investigates the recovery of a clay agricultural soil after salt water inundation for 24–144 h from a king tide/storm surge. The salinity of the soil, how deeply the salt water penetrated into the soil and how quickly salts washed out of the soil were assessed.

2. Methods

2.1. Sampling

Sampling was carried out as part of the emergency support provided to effected inhabitants to aid with recovery. Six initial soil samples were collected on 15 January 2018 (10 days after inundation) from three farms from sites that were under water for 0–144 h (Fig. 4). Three depths were sampled, 0–2 cm, 2–7.5 cm and 7.5–10 cm. The 0–2 cm depth was chosen due to the apparent physical change in the impacted soil and because of practical considerations, especially the effects of

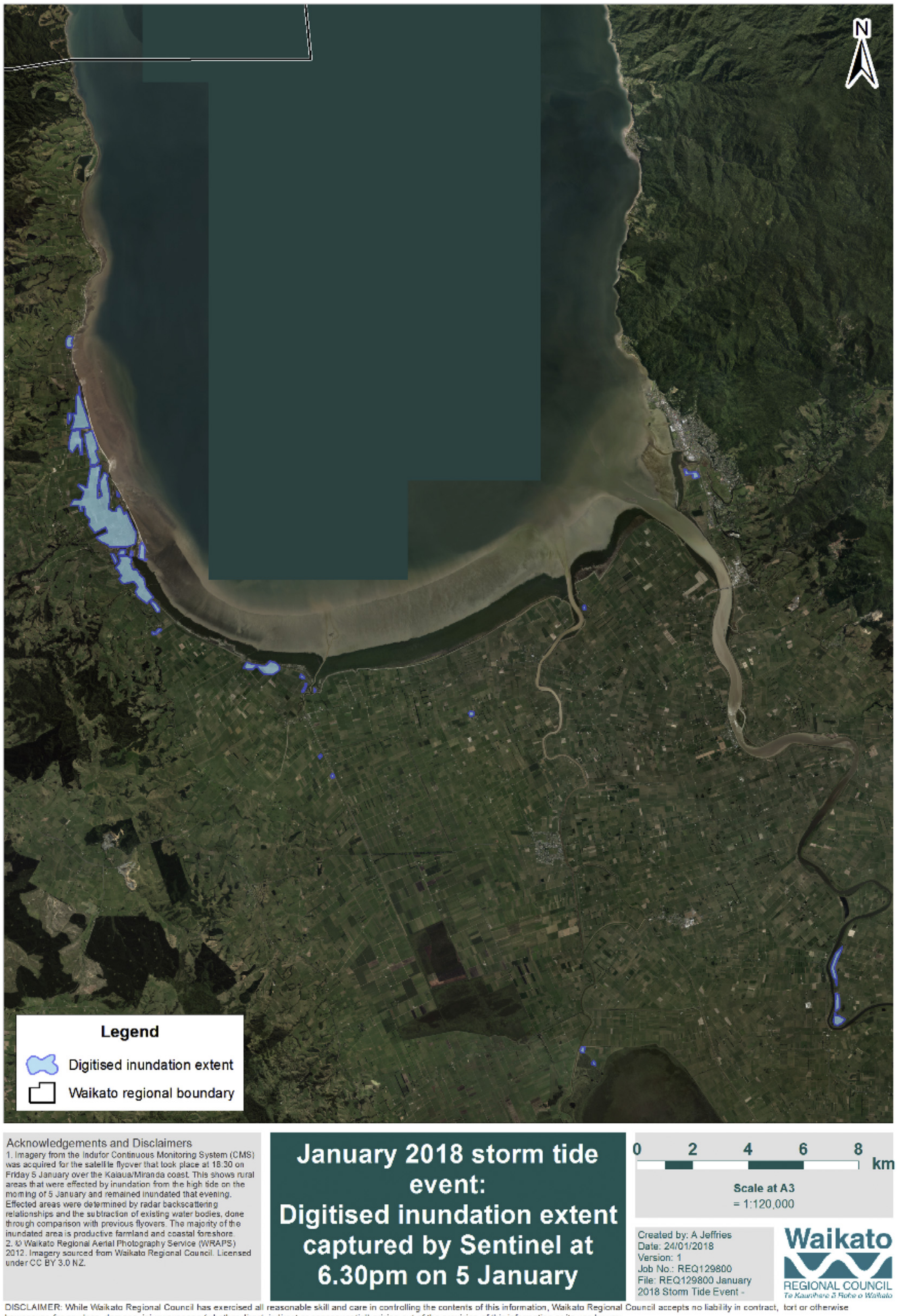

Fig. 2. The Lower Firth of Thames showing areas with detectable inundation remaining as at 18:30 on 5 January. Significant areas remain inundated near Miranda and heading north towards Kaiaua.

cattle treading that distort the soil surface and prevent taking a shallower sample. The other two depths sampled reflect the standard depth for agricultural testing for pastoral soils in New Zealand, which is 0–7.5 cm, while the soil sampler available could sample up to a depth of 10 cm. No rain had fallen since the inundation. Two samples from farms 1 and 3 (F1_0h and F3_0h), and a sample from a roadside reserve that were not flooded were used as non-treatment controls and provided information of the initial state of the soil before flooding.

The pasture at these sites was perennial ryegrass (*Lolium perenne*), which was intensively grazed for dairy production. About 5% of the farmland was maize instead of pasture (Fig. 3) but only sites under pasture were sampled.

Fig. 3. One day after inundation along the Kaiaua/Miranda coast. Overtopping of the coast road is shown by a deposit of white sand in the left middle ground. Relic sand dunes by the road are elevated in the landscape and have already drained.

The soil was Hauraki Clay, derived from estuarine deposited clay (Family: Temuka) for both pasture and maize growing areas, classified as a Typic Orthic Gley Soil in the New Zealand classification (Hewitt, 2010) and an Aeric Fluvaquent, very-fine, montmorillonitic, non-acid, thermic Entisol in the USDA classification (Soil Survey Staff, 2015). Hauraki soils cover an area of 5650 ha and are usually used for high production dairy farming. Table 1 outlines some general properties of this soil. They have relatively high exchangeable Mg levels for New Zealand soils (Metson and Brooks, 1975). Mineralogy is dominated by montmorillonite, with lesser amounts of kaolinite (Gray and Allbrook, 2002). Field evaluation assessed it as clayey (60–70% clay) with weak pedogenesis, slightly firm in the top 12–16 cm increasing to firm below this depth, in agreement with Grey and Allbrook (2002) and McLeod (1992). The Hauraki soil has slow permeability (<4 mm h^{-1}), and is highly vulnerable to bypass flow, waterlogging and compaction (Manaaki Whenua Landcare Reserch, 2015; McLeod, 1992). Therefore, untimely cultivation and grazing when these soils are wet give rise to a rapid and marked loss of soil structure with a reduction in soil permeability and aeration owing to the compaction, deformation and consolidation of the topsoil and upper subsoil.

The length of time the land was inundated depended on its distance from the sea and its height in the landscape, the inundation reaching the 1.95 m mark. The sites located lowest in the basin were about 50 cm above the mean high tide level. Salt crystals were apparent on the soil surface where ponded salt water had evaporated (Fig. 5).

The site showing the highest salinity, which was inundated for about 96 h (Site F1_96h, Fig. 4), was sampled again on the 26th January after 35 mm of rain, i.e. 21 days after inundation. All sites on this farm (Sites F1_0h, F1_36 and F1_96h) were sampled again on the 15th February 2018 after a cumulative total of 200 mm rain had fallen since the inundation, i.e. 41 days after inundation. Additional samples were taken in 10 cm increments from 10 cm to the water table (40 cm on the 25th January and 50 cm on the 15th February) to assess if salt was leaching down the soil profile or rising in association with the tidal watertable (Peat, 2018). The experience of one of the author's (Taylor) was that the watertable in these soils could be influenced by the tide.

2.2. Laboratory analysis

Samples were analysed at Hill Laboratories, Hamilton, an accredited laboratory by International Accreditation New Zealand (IANZ). Samples were air dried at 35–40 °C overnight and crushed to pass through a 2 mm screen. Electrical conductivity (EC) is commonly used as an indicator of soil salinity, i.e. to designate when the soluble salt content of the soil reaches a level harmful to crops (Childs and Hanks, 1975). Electrical Conductivity was measured in a 1:5 soil water extract after 30 min shaking ($EC_{1:5}$, Blakemore et al., 1987). However, the EC of a saturated soil paste extract (EC_e) relates more closely to the soluble salt concentration of the soil solution and hence is more related to plant response than $EC_{1:5}$ (Slavich and Petterson, 1993). Therefore, the electrical conductivity of the 1:5 extract was converted to the electrical conductivity of a saturated soil paste extract using the conversion factor of 5.8 for a heavy clay (Slavich and Petterson 1993).

Exchangeable Ca, Mg, K and Na were measured by a modification of the method in Blakemore et al. (1987). Instead of the original leaching column procedure, an extraction in 1 M Neutral ammonium acetate (1:20 *v*/v soil:extractant ratio, 30 min extraction) followed by determination by ICP-OES was performed (Laboratories, 2018). Levels found were converted to concentrations in the soil on a weight basis using the bulk density of the sample in the laboratory and the Sodium Adsorption Ratio (SAR) calculated.

3. Results

3.1. Initial samples

Salt contents at control sites that were not inundated had low electrical conductivity and SAR, and these remained nearly constant with depth (Figs. 6 & 7). Elevated salt content was seen most strongly in the top soil layer (0–2 cm) of the inundated sites and salt content increased with the length of inundation (Figs. 6 & 7). The highest electrical conductivity and SAR values were found after 96 h inundation. After an inundation period of 50–60 h, soil electrical conductivity exceeded the critical value reported for perennial ryegrass (*Lolium perenne*) of 56 mS/cm (Brown and Berstein, 1953). In comparison, observations during sampling showed ryegrass leaf tissue was brown, apparently desiccated, at sites inundated for 36 h and longer (100% mortality). Also, 10 days after the inundation and before any rain had fallen subsequent to the inundation (i.e. no salt had been washed out of the soil), green tissue was emerging at the base of ryegrass plants in areas inundated for about 24 h. However, all maize crops in the area that was flooded died regardless of time under salt water.

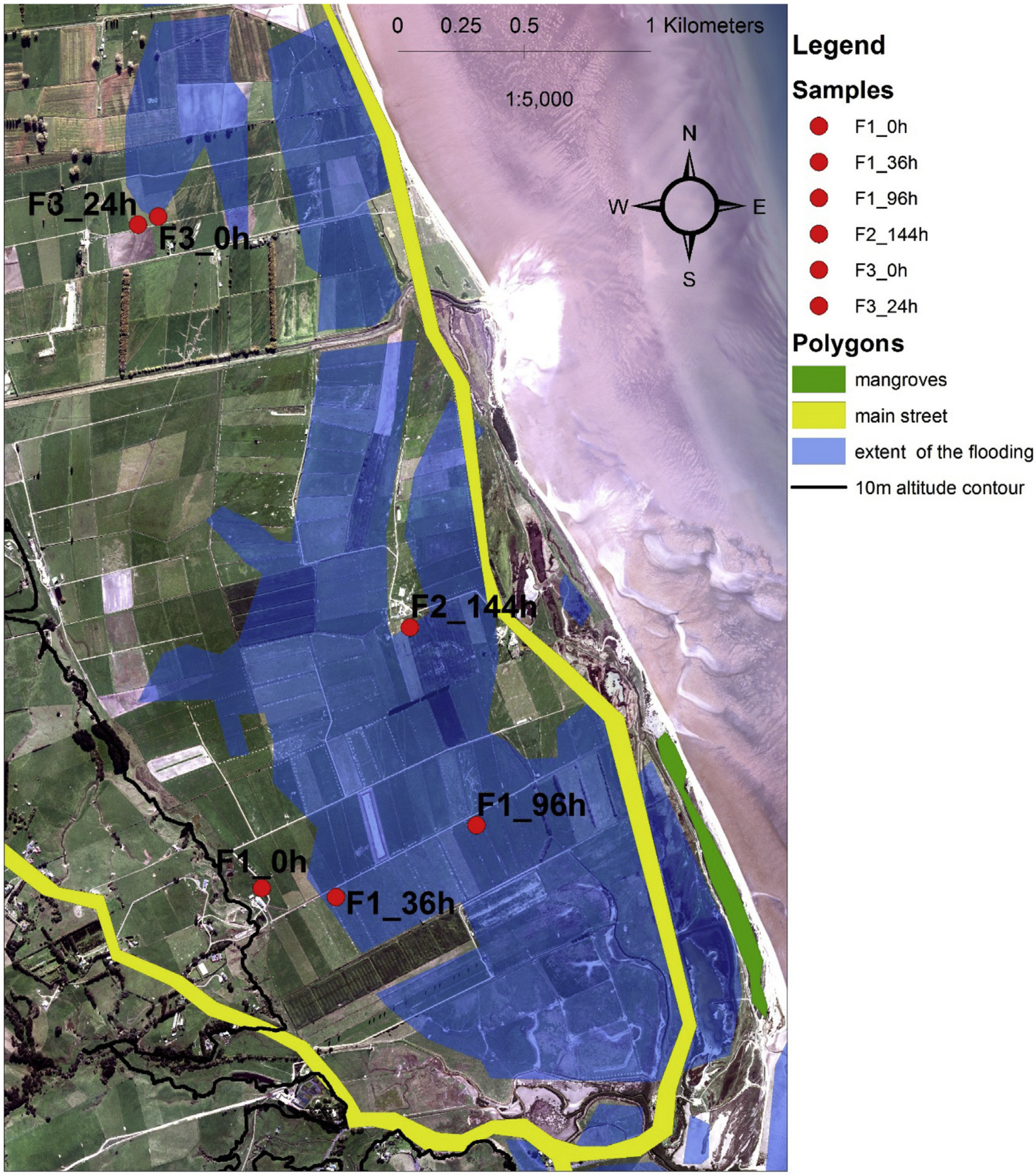

Fig. 4. Location of soil sampling sites on three farms (F1, F2, F3) with different duration of inundation (0 h, 24 h, 36 h, 96 h, 144 h). The flooded area is where there was standing water after the tide had receded.

3.2. Recovery of inundated soil

Electrical conductivity and SAR in the top 2 cm of soil at inundated sites were considerably lower after 35 mm of rainfall and decreased only slightly more after another 165 mm, a cumulative 200 mm of rain. However, electrical conductivity and SAR did not decrease to the levels present before inundation (Table 1) and remained more than an order of magnitude higher than at the control sites. The salt content at depths deeper than 2 cm decreased only very slightly after rain with minimal difference in salt content below 7.5 cm. Electrical conductivity and SAR in soils at control sites did not change with rainfall. As trends are similar for other inundated sites, only the results for site 96 h are presented in Figs. 8 & 9.

Debris flows to lower areas within a field or into drainage ditches were observed. Low areas that were not directly connected to drains continued to have a surface crust of salt. However, none of the sampling sites were within such an undrained low area.

4. Discussion

4.1. Salt in New Zealand soils

As New Zealand has abundant annual rainfall, soil salinity and sodicity in agricultural lands has rarely been a major problem. However, low-lying coastal areas may be impacted by periodic flooding during severe storms and/or during extreme tidal events and saltwater may intrude into groundwater. The frequency at which such events occur is expected to increase due to climate change (Church et al., 2013; Nicholls and Cazenave, 2010). The combined effect of sea level rise and land subsidence may enhance saltwater contamination with potential serious environmental and socio-economic impacts, e.g. compromising agriculture.

4.2. The impacts of salt water flooding

Much of the understanding of the impacts of salt water flooding on soils comes from studies after Tsunami or major cyclone events.

Table 1
Selected chemical and physical properties of the Hauraki clay and clay loam soils.

Depth [cm]	Electrical conductivity [mS cm^{-1}]	Sodium Adsorption ratio	Sodium [me/100 g]	Magnesium [me/100 g]	Calcium [me/100 g]	Potassium [me/100 g]	CEC	pH	Carbon
Farm 1 in 2017 (previous to flood)									
Depth (cm)									
0–7.5	n.d.	0.10	0.40	6.74	27.6	1.71	40	6.6	n.d.
0–7.5	n.d.	0.14	0.52	7.06	21.2	1.18	33	6.3	n.d.
0–7.5	n.d.	0.10	0.36	7.00	20.8	1.66	38	6.0	n.d.
0–7.5	n.d.	0.14	0.51	6.11	22.0	1.24	34	6.2	n.d.
McLeod, 1992									
Depth (cm)									
0–13	n.d.	0.13	0.56	7.22	23.4	1.16	39	5.6	7.9
13–23	n.d.	0.18	0.76	8.51	19.4	0.94	33	5.9	2.3
23–38	n.d.	0.21	0.88	9.93	19.0	0.92	34	6.0	0.9
38–71	n.d.	0.34	1.41	11.7	20.7	0.73	36	6.1	0.5
71–116	n.d.	0.37	1.54	9.80	21.1	0.67	33	6.5	0.4
Unflooded reserve									
Depth (cm)									
0–2	0.2	0.06	0.23	6.80	16.5	0.98	42	5.6	10.2
2–7.5	0.1	0.05	0.18	4.65	9.2	0.46	29	5.3	7.7
7.5–10	<0.1	0.06	0.2	4.73	8.6	0.37	28	5.3	5.9
10–20	<0.1	0.05	0.17	4.26	6.9	0.35	24	5.4	4.1

n.d. = not determined.

However, both tsunami and major cyclones also cause physical damage to soils and plants due to the energy released as currents and winds. Sediment deposits have been used to identify the landward extent of tsunamis and major cyclones (Dominey-Howes et al., 2000; Tunbridge, 1981). This process is called high-energy sedimentation. Unlike tsunami and major cyclonic events, which left thick deposits that made it difficult to identify the original soil surface, the current inundation only left thin deposits of silt (<1 mm), thus was a relatively low-energy event.

The salinity status of the inundated farmlands in tsunami and hurricane events was reported to depend on soil texture and therefore on the infiltration rate of the soil, anticipant soil moisture and the duration of the inundation, as well as the relative physical position (elevation) of the farmland (Roy et al., 2014; Provin et al., 2009). Similarly in the present flood event, the length of time the land was inundated depended on its height in the landscape. Thus, the sites that were not inundated were > 2 m above the high tide mark, while the sites longer under water were in a basin and about 0.5 m above the high tide mark (Fig. 3). Subsoils at sites close to the sea had elevated sodium and EC levels compared to subsoil at control sites (Figs. 8 & 9 compared with Figs. 6 & 7). Although this elevation in sodium could be due to sodium moving down through the soil, it could also be due to the effects of high tides pushing salt up through the soil (Peat, 2018). Sites at lower elevation and close to the sea could be vulnerable to salt from salt groundwater during king tide and other tidal surge events.

Elevated soil salinity was seen in only the top 0–2 cm layer, which is consistent with results from tsunami inundated soils with similar texture (Roy et al., 2014; Nakaya et al., 2010).

Electrical conductivity concentrations were closely correlated with Exchangeable Na and SAR ($R^2 = 0.974$ and 0.965, respectively. Amendment with lime or gypsum is the standard management practice for reducing sodicity. However, exchangeable Na, SAR and EC decreased markedly in topsoils after rain, even without amendment, indicating the soluble salt fraction is dominating exchangeable Na.

Nevertheless, SAR and electrical conductivity in the soil profiles did not return to pre-flood or control values even after 200 mm rain (Figs. 8 & 9). The electrical conductivity after rain was still 20 mS cm^{-1}, which may affect the germination of salt sensitive plants, such as maize. The remaining SAR levels may be further reduced by amendment with gypsum to provide Ca ions to exchange with the Na ions on the soil exchange sites. Released Na^+ would then be available to leach in soil drainage water. Lime would also supply calcium ions but is not

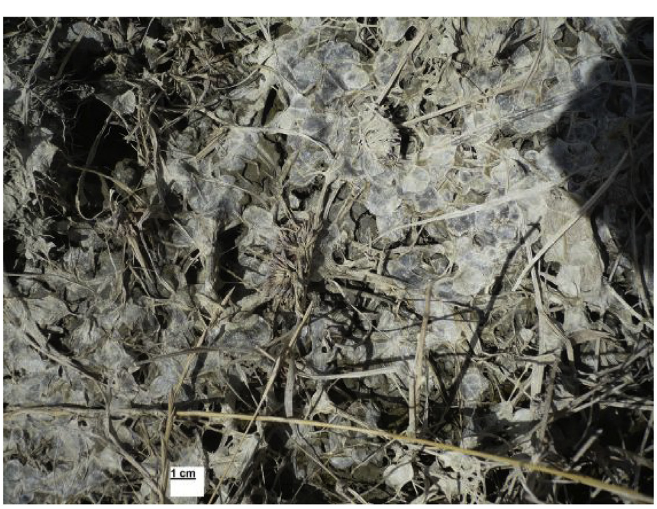

Fig. 5. Formation of salt crystals on the surface of the soil, site F2 144h on the 15th January 2018.

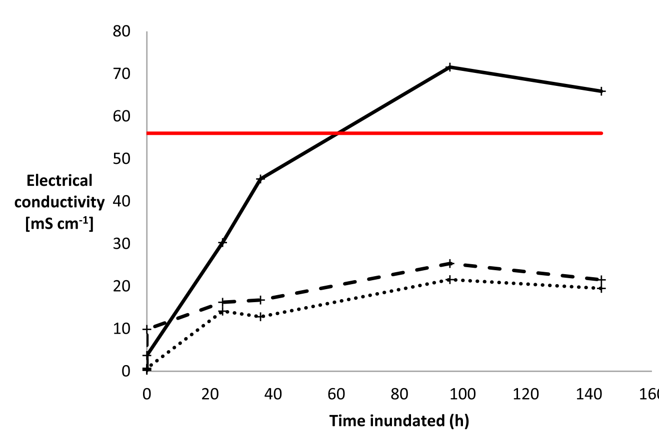

Fig. 6. Electrical conductivity (ECe) for three different soil depths and different lengths of inundation by salt water. Sites closest the sea were inundated the longest.

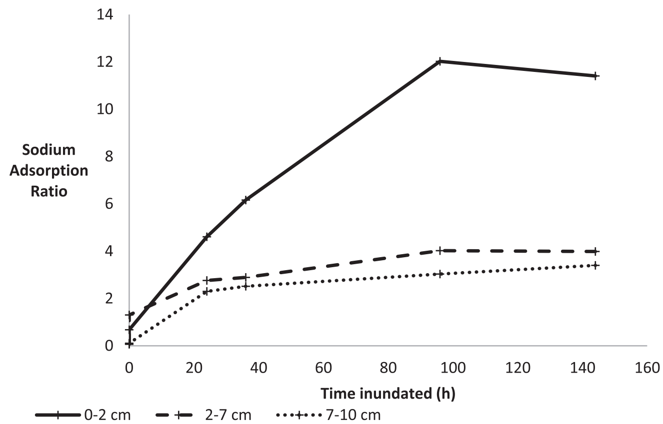

Fig. 7. Soil sodium adsorption ratio for three different soil depths and different lengths of inundation by salt water. Sites closest the sea were inundated the longest.

recommended as application would raise the soil pH above the agronomic optimum for pasture.

The formation of salt crystals on the soil surface was due to evaporation of salt water that had ponded on top of the soil because of the low infiltration rate. Hot sunny weather after the inundation event caused considerable evaporation of the ponded water, leaving salt crystals on the soil surface. The salt crystals were easily dissolved by rain and washed away as shown by the considerable decrease in soluble salt content of the 0–2 cm soil depth after one rainfall event of 35 mm. Debris flows showed rain became overland flow with salty water washing off into nearby ditches and low areas within a field. The presence of salt crusts observed in undrained low areas may affect the germination of replacement pasture.

The soluble salt contents of the 0–2 cm samples further decreased only slightly with subsequent rainfall, and were similar to the salt contents of the deeper soil depths. In comparison, soluble salt content decreased only very slightly at greater depths even after accumulative 200 mm rain, consistent with little drainage and/or indicating a return to equilibrium for these coastal soils. These results are consistent with the general consensus that flushing of soil particles with freshwater is the best option for treating saline soil in lowland fields (Chagué-Goff et al., 2012; Nakaya et al., 2010; Provin et al., 2009; Tchouaffe, 2007).

4.3. Soil cracks and soil saturation

The soil was clearly dry at sites F1 0h and site F3 0h with large cracks in the soil at the initial sampling, i.e. 10 days after rain. However, sites that had been inundated appeared near saturated with no open cracks apparent. These inundated sites remained clearly moist for subsequent samplings, at 21 and 41 days after inundation. The weather during this time consisted of periods of hot dry summer weather with occasional intensive rainfall events.

The antecedent water content of the soil is likely to have had an impact on the penetration of Na down the soil profile. Deep cracks are commonly found in this montmorillonite-dominated soil when it is dry over summer and these cracks may have provided a route for salt water to penetrate deeper into the soil. However, heavy rain occurred immediately before the inundation event and this rain is likely to have caused soil clays to swell and close the cracks. Therefore, it is not surprising that salt was only elevated in the 0–2 cm samples.

4.4. Time under salt water

Rye grass survival was observed for sites inundated for 24 h or less but not for sites inundated 36 h or longer. Maize was very sensitive to salt water and no maize survived in the inundated area. In comparison, Provin et al. (2009) reported some species of pasture survived after inundation for 24–48 h, while Bermuda grass could possibly recover after inundation of up to 96 h. Although these are different species, these results show the potential for utilising salt tolerant grass for low-lying areas that are becoming more prone to salt water inundations.

5. Conclusions

The combined effect of sea level rise and land subsidence may enhance saltwater contamination and soil salinisation with potential serious environmental and socio-economic impacts, e.g. compromising agriculture. The inundation by salt water along the Kaiaua-Miranda coast impacted soils and plants, with the length of time the land was inundated depending on its height in the landscape. Similarly, the longer the land was inundated the greater the resultant salt concentrations in the soil. Pasture was died after an inundation period of 36 h, while ryegrass in areas inundated for <24 h recovered. All maize died if inundated by the sea regardless of the time the crop was inundated.

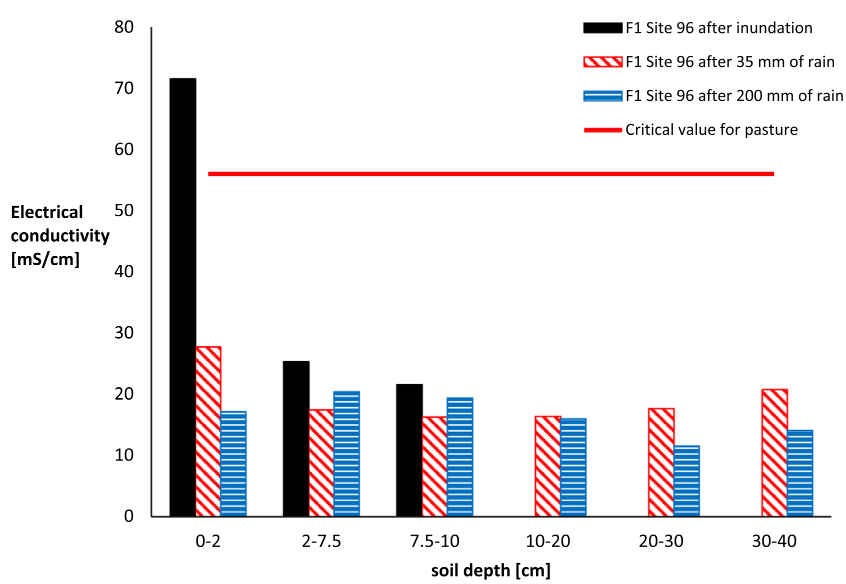

Fig. 8. Soil salt content indicated by electrical conductivity (ECe) for seven different soil depths for site F1 96 after inundation (0–2, 2–7.5 and 7.5–10 cm soil depths) and after two rainfall events (0–2, 2–7.5, 7.5–10, 10–20, 20–30 and 30–40 cm soil depths).

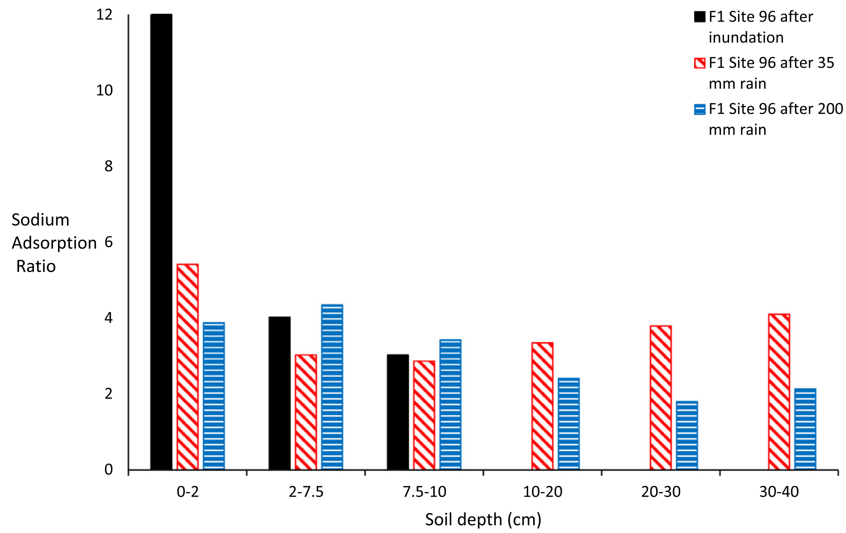

Fig. 9. Soil Sodium Adsorption Ratio for seven different soil depths for site F1 96 after inundation (0–2, 2–7.5 and 7.5–10 cm soil depths) and after two rainfall events (0–2, 2–7.5, 7.5–10, 10–20, 20–30 and 30–40 cm soil depths).

Flushing of soil particles with fresh rainwater proved effective at lowering the salt content in the top 2 cm of soil. The salt content was considerably lower after one rainfall event of 35 mm and decreased only slightly more after a cumulative 200 mm of rain.

Farmers should be prepared for similar events in low-lying coastal areas with drainage systems in place to remove salt water quickly once the event has past. Hollows and basins in fields should be directly connected to drains to avoid ponding. Using salt tolerant grasses as pasture species in these areas should be further investigated.

Acknowledgements

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Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version, at doi:https://doi.org/10.1016/j.geodrs.2019.e00239. These data include the Google map of the most important areas described in this article.

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