.Geomorphological Assessment
and
Management Considerations
for the Pukekuke Lagoon
Natural Heritage Restoration Project

A report prepared for the Department of Conservation

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GLOSSARY

Anticline: A dome-like hill formed by geological folding of underlying sedimentary strata.

Beach: Accumulation of unconsolidated materials (sand, gravels) along a coast, encompassing the inter-tidal area plus the area immediately landward that is affected by wave uprush (swash) and seaward affected by the wave backrush. This cross-sectional extent is also termed the **foreshore.**

Blowout: A trough excavated in foredunes by enhanced wind flow typically funnelled through topographic constrictions or gaps in vegetative cover which causes the dune crest to "blow out". An advancing lobe of sand spills downwind.

Coastal progradation/accretion*:* Refers to the seaward displacement of the shoreline when the beach builds out in response to a surplus of sediment (a positive sediment budget). The Manawatu coast has a history of net progradation. Coastal accretion is part of the same process but strictly refers to the build-up in elevation of a beach or dune surface rather than to the outward movement of the shoreline.

CSL: Coastal Systems Ltd. www.coastalsystems.co.nz

Deflation area: A landform of varying size and shape (basin, plains or flats) that forms when sand is removed by wind action. Damp sand just above the water table limits the vertical extent of a deflation surface.

Drift potential: Total onshore sand-moving wind energy may be measured by calculating the drift potential (Freyberger, 1979). The value for the Pukepuke area is classified as high.

Dune Phases: Coastal dune fields develop through a series or phases of widespread dune activity separated by periods of dune stability and soil formation.

ENSO: El Nino Southern Oscillation is a quasi-regular (3 to 7 years) climate change caused by variation in sea-surface temperature in the tropics that causes change in mid latitude wind (and wave) conditions toward stronger winds from the westerly quarter, wetter on the NZ west coast and drier on the NZ east coast.

Foredune: A sand dune located immediately landward of the beach and aligned parallel to the shoreline at the time of formation. Pioneering sand grasses such as marram and spinifex are critical to foredune development as these trap sand blown from the beach and enable ongoing dune growth.

Georeference: Refers to plans, vertical aerial photographs and other images that are digitized then transformed to a common set of map co-ordinates so images can exactly overlay each other and thus be directly compared and characteristics measured. There are several different co-ordinate systems available. The most common in use in New Zealand at the present time is the New Zealand Transverse Mercator 2000 (NZTM).

http://www.linz.govt.nz/data/geodetic-system/datums-projections-and-heights/projections/new-zealand-transverse-mercator-2000

Holocene: The current warm period that began approximately 10,000 years ago. Prior to this the temperature was cooler (temperature 5-10 degrees cooler 20,000 years ago) and sea-level over 100 m lower due to extensive ice cover.

IPCC: International Panel on Climate Change is the international panel of scientists which regularly prepare reports on the effect of greenhouse gas induced climate change

LIDAR: Light Detection and Ranging, is a remote sensing method that uses light in the form of a pulsed laser to measure ranges (variable distances) to the Earth. These distances are converted to elevation and each point recorded along with its corresponding location derived from GPS to enable high resolution three-dimensional data to be collected of the Earth surface.

Littoral: A zone extending from the high tide mark to the offshore limit of wave and current-driven sediment transport. Littoral drift refers to sediment thus transported alongshore.

Marine processes: Wave, wind and associated currents which drive change (sediment transport) in the tidal and subtidal zones.

MWD: Ministry of Works and Development. The Ministry was in charge of government development, including hydrological and coastal monitoring and research, until its disbandment in 1987.

Parabolic dune: A typically U, or V-shaped sand dune with an elevated convex nose, that may reach 10s of metres in height, with lower trailing arms, sometimes exceeding a kilometre in length, separated by an intervening basin from which sand is eroded, funnelles between the sidewalls (the throat) where it becomes airborne and deposits in the nose area. This landform often originates at the foredune, but then disassociates itself from the coast as it migrates inland, often for several kilometers, before being arrested by river/streams, or perhaps stabilizing during an extended period of low wind and high rainfall i.e. conditions constraining wind erosion while promoting vegetation growth. Anthropogenic intervention has resulted in stabilization during more recent times.

Post-glacial marine transgression (PGMT) The retreat and shrinking of Pleistocene ice sheets, ice caps, and mountain glaciers following the last glaciation (ice age) resulted in the addition of enormous quantities of water to the oceans; as a consequence global sea-level rose by over 100 m and shorelines retreated landward (transgressed) by several kilometres. This transgression lasted about 10,000 years

Pleistocene: A period lasting some 2.5 million years (up until the Holocene). The Pleistocene is characterized by repeat glaciations which caused sea-level to fluctuate over a range of about 120 m, more recently during 100,000 year cycles

Regression modelling: Statistical techniques for investigating relationships between variables.

Relict coastal dunes*:* Dunes that developed in the past that are now stabilised by vegetation and no longer active.

Risk: The potential for losing something of value. In risk management it is expressed in terms of the combination of the likelihood of occurrence of a hazardous event with the consequence of the event.

Shoreline: The fringe of a water body. Where that water body is the ocean the shoreline is also called the coastline.

Sand dune: A mound or hill of sand that forms when sand, being transported by wind or water flow, is deposited as flow characteristics change. With coastal sand dunes, wind flow typically interacts with vegetation to cause deposition, with different types of vegetation having different aerodynamic properties and thus characteristic dune shapes. The valley or trough between dunes is referred to as a slack or swale.

Sand plain: a flat or gently undulating area where sand has been removed by deflation processes. Also referred to here as a *deflation plain or sand flat* and sometimes referred to as *dune slacks*.

Stable dune: A sand dune that is able to resist wind erosion, typically one that has a continuous/uniform cover of vegetation.

Surf zone: That coastal area affected by breaking wave processes.

Unstable dune: A sand dune that is affected by erosion. Such a dune typically has a lack of vegetation or discontinuous vegetation.

Transgressive dune field: An assemblage of sand dunes migrating downwind. Several such fields occur along the west coast of the North Island.

Transverse dunes: These are transgressive dunes that, in contrast to parabolic dunes, are aligned at right angles to the predominant *wind resultant* (see definition below). They are roughly shore-parallel in the Manawatu-Horowhenua districts and are largely relict dunes. They developed when there was limited vegetation and an abundant source of sand, and normally exhibit a relatively gentle windward slope and a steep leeward slope.

Wellington Vertical Datum 1953. Vertical datums relate to mean sea level (MSL) based on tide gauge data at 13 ports around the New Zealand coast. As sea-level changes over time and between these ports, it is necessary to specify the datum when used. LINZ have tables of relative differences between datums and to update the datums.

http://www.linz.govt.nz/data/geodetic-system/datums-projections-and-heights/vertical-datums/tidal-level-information-for-surveyors

Wind resultant: A measure of the long-term effect of winds of varying strength, duration and direction upon the net direction of sand transport.

1 INTRODUCTION

1.1 BACKGROUND

The Department of Conservation (DOC) manages Pukepuke Lagoon Conservation Area, located between Himatangi Beach and Rangitikei River and some 1.9 to 3.7 km inland from the coast (Figure 1). Pukepuke is a stewardship area under the Conservation Act with the Department's management goal driven by its Natural Heritage Outcomes Model as detailed in DOC's Statement of Intent 2015-2019. In particular, that the Pukepuke Lagoon Conservation Area is conserved to a healthy functioning state by 2030 and that a plan be developed to restore its natural heritage.

Pukepuke has a range of scientific attributes (landforms, flora and fauna) along with significant historical, cultural and recreational values. While there is a desire by DOC to work in partnership to restore Pukepuke Lagoon Conservation Area, there is no recent cohesive documentation for integrated management at Pukepuke. As the first step in the Pukepuke Lagoon Natural Heritage Restoration Project, DOC (Manawatu) has commissioned Coastal Systems Ltd (CSL) to prepare a broad backgrounding geomorphological assessment.

Pukepuke Lagoon became a wildlife management reserve in 1968 vested with the Ministry of Internal Affairs and managed by the Wildlife Division (Service). The Service prepared a management plans in 1977 (Turner) and an expanded (draft) plan in 1987 (Aviss). These plans background the site resources (land, water, flora, fauna cultural and public use), and (the 1987 plan) sets out 3 objectives and 29 Policies to conserve, manage and enhance the diverse wildlife and biological populations and allow for public use (p11,12). The Plan notes that "if not managed, as with other shallow wetlands, the natural reclamation process, will eventually cause the lake to dry and the Service would not have done its job". The Plan states that the natural process was being spear-headed by encroachment of raupo and the Service had an ongoing programme for its control. Access has remained restricted and is credited with its diversity and relative good health. The Plan also mentions a substantial amount of management-orientated research had been undertaken by the Wildlife Service Research Section and research facilities at both Massey and Victoria Universities. Another difficulty the Service faced was managing the lagoon water level for wildlife as this could conflict with the optimal regime required by adjacent agriculture. Despite the Service attempting to do so, the reserve was not gazetted under the Reserves Act (1977).

Following governmental restructuring in 1987, the Wildlife Service was absorbed within the newly formed Department of Conservation, and DOC took over control of Pukepuke Wildlife Reserve, renaming it the Pukepuke Lagoon Conservation Area.

The Pukepuke catchment was a Hydrological Representative Basin study between 1969 and 1983 administered by the Ministry of Works and Development (MWD). Some of the extensive hydrological data collected during the study were used in the 1970s as a basis for future water resource allocation by the Regional Council (then the Rangitikei-Wanganui Catchment Board), and more recently as a basis for a water balance and groundwater capture-zone assessment by the Regional Council.

As will be described later in this report, the lagoon formed relatively recently in its present location, having earlier occupied a much larger adjacent area to the northwest that was gazetted as a Native Reserve (Section 378) in 1869.

1.2 GEOMORPHOLOGY and TERMS of REFERENCE

"Geomorphology" is the study of the origin and evolution of topographic and bathymetric features created by physical, chemical or biological processes operating at or near the Earth's surface. Geomorphologists seek to understand why landscapes look the way they do, understand landform history and dynamics, and to predict changes through a combination of field observations, experiments and modelling. Geomorphologists draw on a range of associated disciplines such as geography, geology, biology/chemistry/physics, anthropology, hydrology and geotechnical engineering.

Geomorphological assessments currently underpin a range of environmental studies/investigations including defining the coastal environment, civil engineering investigations, natural character assessments, outstanding landform and landscape identifications, hazard assessments, coastal management investigations and Tangata Whenua interests.

For this Pukepuke Lagoon assessment, the Terms of Reference were as follows:

1) What landforms are there? Provide a description of the current landforms, associated processes and their geographical setting;
2) Why are these landforms there? Provide an explanation in terms of their evolution and formative processes;
3) How will they change? Predict how the landform and associated processes may change in the future;
4) Initial recommendations relating to the restoration management project, and
5) Preparation of a "reader-friendly" report.

1.3 APPROACH

This assessment began by searching for both historical and contemporary information concentrating on survey (cadastral) maps, vertical aerial photographs and satellite imagery, historical maps and other technical information/reports and books. Maps and aerial imagery were "georeferenced" to the same scale and orientation so they can be exactly overlaid and compared.

In May, 2017, an oblique aerial photo survey was also carried out as well as a set-up meeting with interested parties including representatives from DOC, Horizons Regional Council, the Manawatu District Council, local iwi and landowners, Marianne Watson of Hydronet, and Jacobs New Zealand Ltd staff who were about to undertake out a hydrological groundwater assessment on behalf of the Regional Council. This meeting was held soon after CSL were commissioned and resulted in a plethora of background information additional to that upon which the geomorphological assessment was initially expected to be based. As such, a more thorough and wide-ranging study of the natural and developmental history, hydrology and vegetation was able to be undertaken resulting in more comprehensive initial recommendations - termed "considerations". A site inspection was carried out in August, 2017.

Section 2 describes the present geomorphology in the vicinity of the Pukepuke Lagoon Conservation Area including the wider geography and controlling processes. Section 3 describes the landform evolution from pre-colonial time, through historical time (since records were available) to the present. Section 4 considers how the Conservation Area may change in the future. A detailed summary is provided in Section 5, and Section 6 contains several “considerations” (initial recommendations) for the Pukepuke Lagoon Natural Heritage Restoration Project.

A Glossary of technical terms and acronyms has been included to assist the reader with technical wording.

Finally, a matter of terminology. The original lagoon within the Native Reserve and the associated main outlet stream to the coast were referred to as the Pukipuki Lagoon and Pukipuki Stream respectively in early plans and documentation, while the current lagoon/conservation area/stream are referred to as Pukepuke. This distinction has been upheld in the present report.

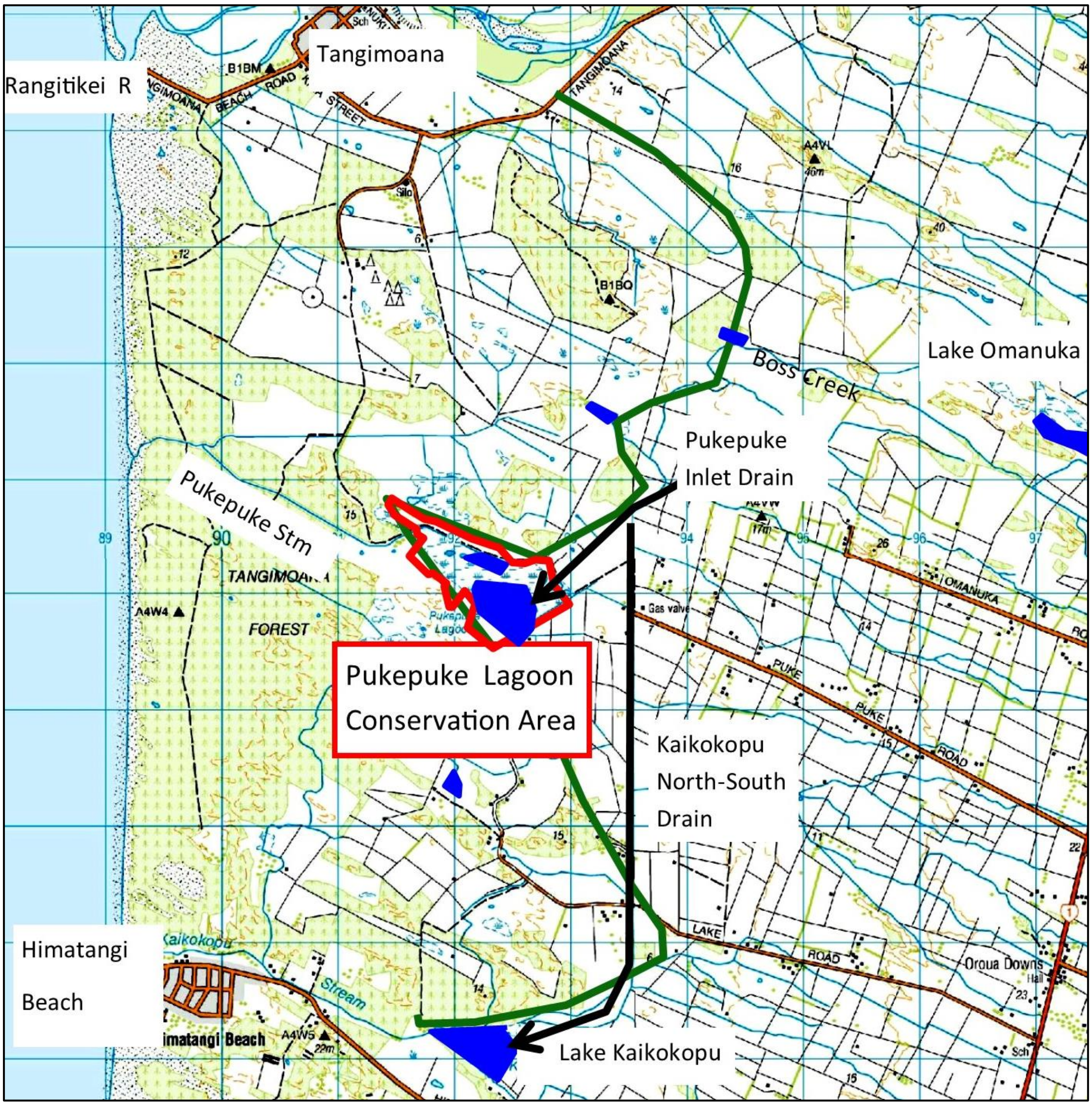


Figure 1 Location map of the Pukepuke Lagoon Conservation Area (red boundary). The green line defines the landward limit of most recent sand dune advance and the blue areas are water bodies.

2 PRESENT GEOMPROHOLOGY

2.1 SETTING

Pukepuke Lagoon lies at the margin of a belt of stable sand dunes (which extend inland from the coastline some 3 to 5 km) and an ancient sand plain (Figures 1 and 2). Several such water bodies (shallow sand dune lakes) lie along this margin (Figure 1) with Pukepuke being the largest and thus of potential significance. The sand plain gently slopes up to the crest of the Himatangi Anticline (a low relief dome-like hill) whose long axis approximately aligns with State Highway 1. A topographic profile from the coast to inland beyond the anticline crest is shown in Figure 3 with the lagoon, the Kaikokopu North-South Drain (described below) and crest marked. The spikes on the left side of the profile represent the coastal dune belt and the ground slope in this area 1 in 2000. By comparison, the relative uniformity of the sand plain up the anticline is evident in the centre-right of Figure 3 with the average ground slope 1 in 250. The existence of the water bodies and swamps along the dune margin result from impeded drainage by the dune system and emerging groundwater. The numerous dune swales and deflation areas result in seasonal marshes developing within the dune system and some of these can be seen in Figure 2.

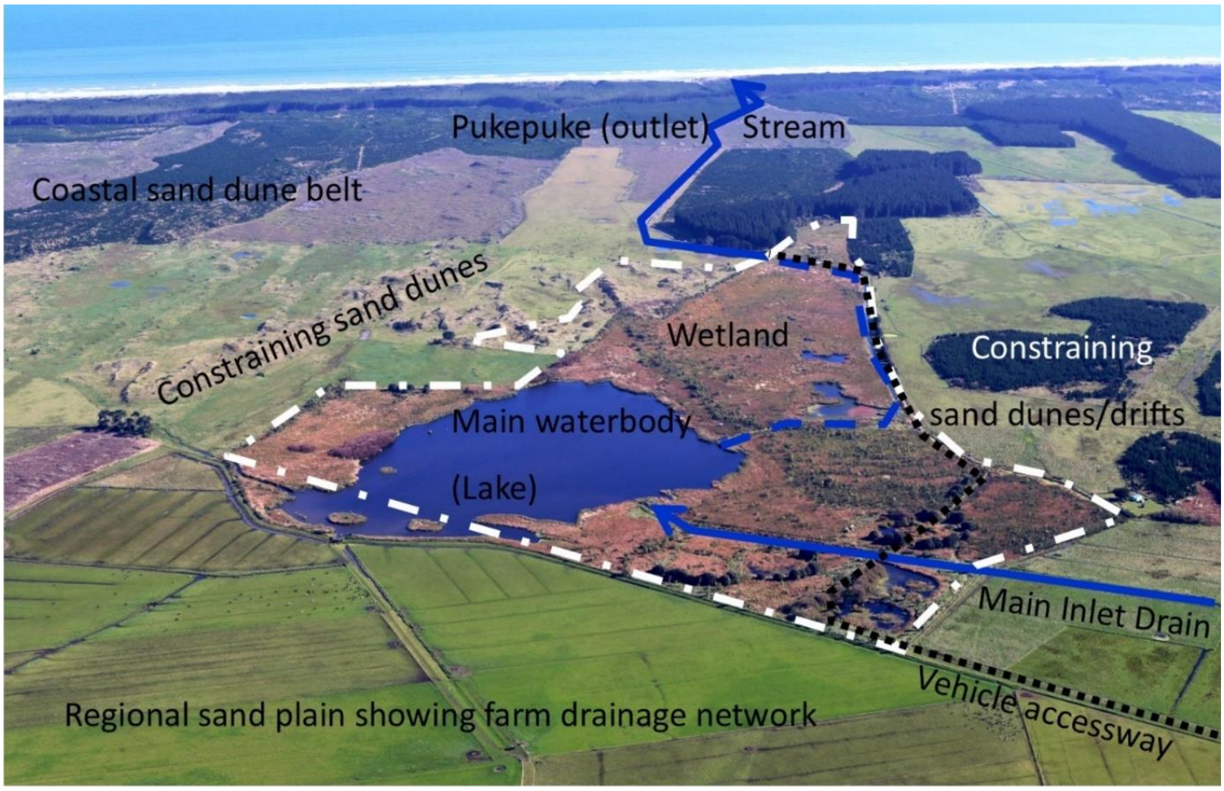


Figure 2 Pukepuke Lagoon Conservation Area (white dashed line) with main features marked. In addition, the blue lines mark the inlet and outlet drainage with the dashed blue line depicting the internal connecting drain. Photography by Lawrie Cairns Aerial Photography 9.5.2017

This region is underlain by fine sand (the residual of previous dune migrations), to a depth of 8 to 40 m which is then underlain by impermeable clay (Mark-Brown (1978) which is likely a wave cut terrace into Pleistocene marine sediment. Localised deposits of river gravels from previous migrations of the Rangitikei River also occur together with some clay and iron pan layers at shallow depth (Jacobs, 2017). As a result, an upper level unconfined aquifer (recharged by rainfall) underlies the entire drainage area (Mark-Brown, 1978).

Extensive use is made of the shallow aquifer for agriculture and domestic waste disposal, soakage from septic tanks effluent and spray irrigation from diary shed wash (Fowles, 1982). The present report has not investigated more recent, or projected, land use/water allocation.

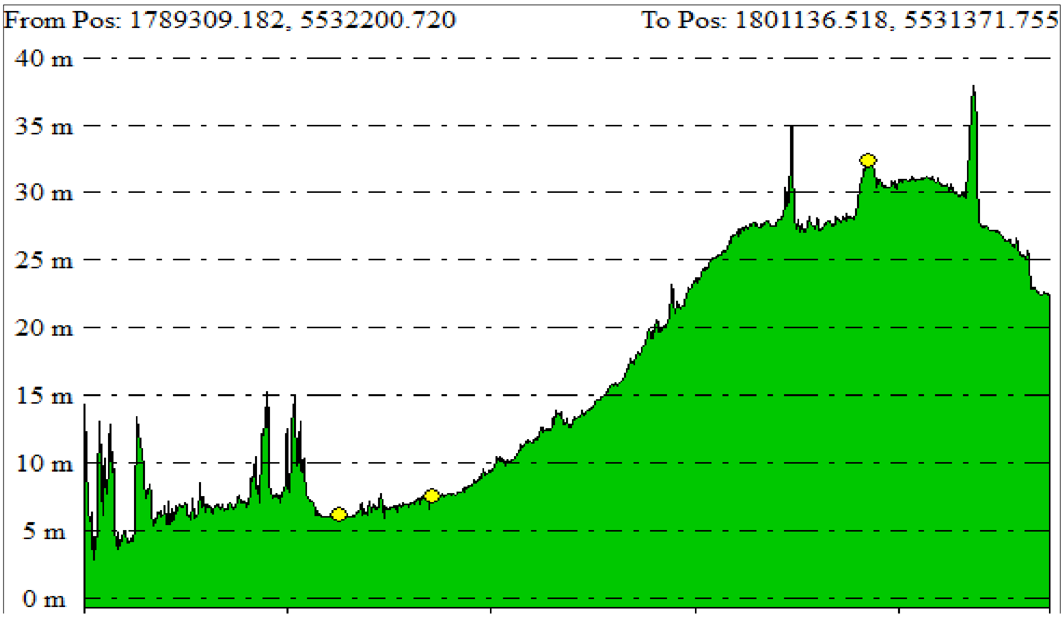


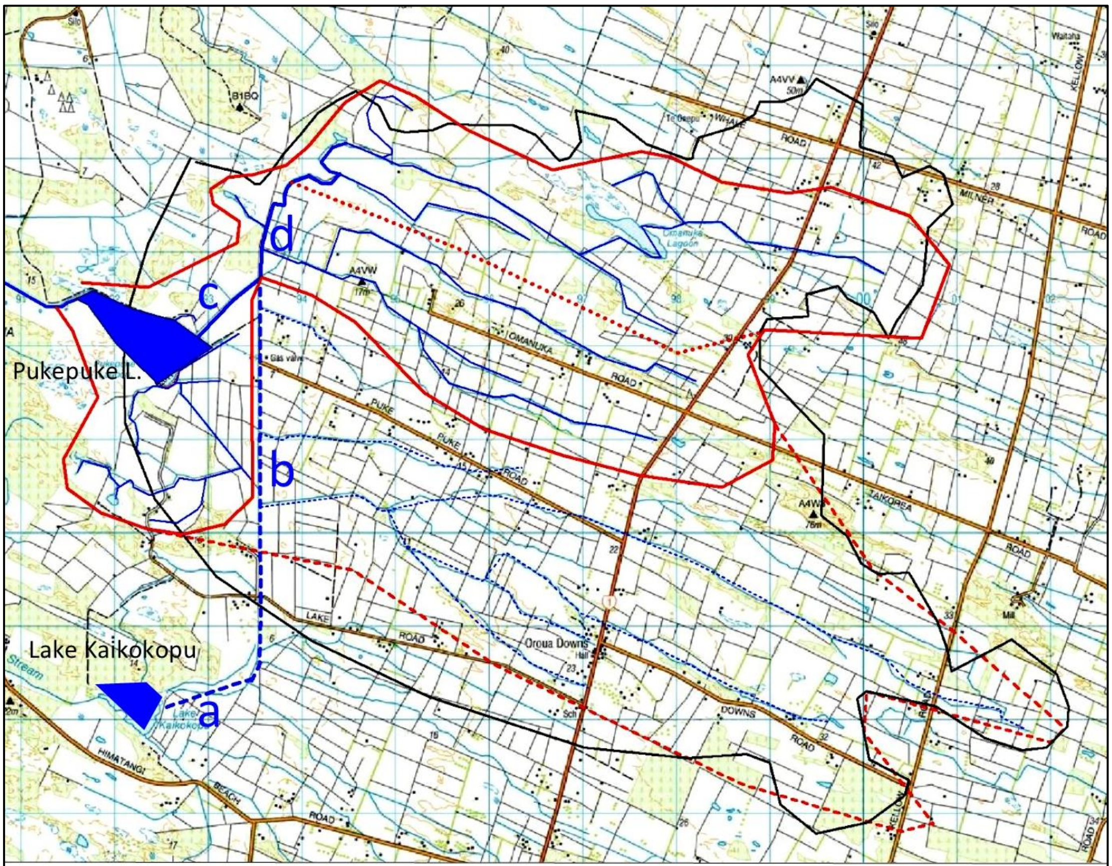
Figure 3 Section from coast to crest of the Himatangi Anticline (see Glossary). Yellow dot on left locates the Pukepuke Lagoon, the middle dot located the Kaikokapo North-South Drain and the dot on the right locates State Highway 1 near the crest. Note the coastal dune signals (spikes) between Pukepuke and the coast, and also some dunes at the top of the anticline – these being much older (explained in text). Source: LIDAR provided by Horizons Regional Council.

The lagoon's catchment has been modified by agricultural drains, as indicated in Figures 1 and 2, which have truncated 2086 ha of natural basin surface area, leaving a catchment area focused on the north and west of 2330 ha (Figure 4). However, as described in Section 3, the northern subcatchment of the Omanuka Lake/Boss Stream (approx. 1670 ha) was not part of the original "Pukipuki" Lagoon catchment. Note that these catchment areas have been derived from topographical maps and digital terrain modelling with the current area being similar to that derived for the earlier MWD's Representative Catchment Study.

Two main drains are depicted in Figure 4 by the thick blue lines. The thick bold line marked "c" represents the Pukepuke Inlet Drain which collects water surface and streamflow (shallow groundwater) from the northern catchment (via drain "d"). The thick dashed line marked in Figure 4 is the interceptor drain which channels water from the original Pukipuki central/southern catchment across into Lake Kaikokopu and is referred to in this report as the Kaikokopu North-South drain. In some plans this drain is subdivided into Conlan's Drain ("b" in Figure 4), and the Hunia Diagonal Drain ("a" in Figure 4). Further details about the drains are provided in Section 3.

A dense network of secondary channels and farm drains flow into the main drains (Figures 2 and 4) with this network having developed over time.

The recent groundwater assessment by Jacobs (2017) defined the present Pukepuke capture zone based on piezometric levels (equilibrium water levels as detected in wells), and derived an area of 4876 ha which is depicted by the black line in Figure 4.



Red bold: Pukepuke surface catchment, **Red dashed**: surface catchment diverted into Kaikokopu. **Red dashed:** original Omanuka/Boss catchment, **Black line**: Jacobs (2017) groundwater capture zone, **Blue thick line**: main drains into Pukepuke Lagoon (c = Pukepuke Inlet Drain, d = Northern Intercept Drain). Blue thin lines: Pukepuke drainage network. **Blue thick dashed lines:** main drains into Lake Kaikokopu (b = Conlan's Drain, a = Hunia Diagonal Drain) and in this report the full length of a + b is referred to as the Kaikokopu North-South Drain, Blue thin dashed lines: drainage network diverted to Kaikokopu.

Figure 4 Catchment boundaries, main drains (named a,b,c,d) and drainage network.

2.2 PUKEPUKE LAGOON CONSERVATION AREA

2.2.1 General

The Pukepuke Lagoon Conservation Area covers approximately 80 ha and consists of a main waterbody, referred to here as the lake, and several smaller water bodies or ponds, surrounded predominantly by wetland (~50 ha) and a small area of sand dune (~10 ha), as well as having a 350 m long inlet channel and a 1.1 km long outlet channel[1] (see Figures 2 and 5). The Conservation Area has a somewhat "bulbous" landward end some 900 m wide, and a seaward directed "tail" orientated SE to NW seaward, with this long axis measuring some 1.8 km.

It is noteworthy that most water bodies in this region are referred to as lakes, but Pukepuke and nearby Omanuka have always been referred to as lagoons. A broad definition of lagoon is a shallow body of water separated from a larger body of water and early surveyors may have seen Pukepuke and Omanuka in this way.

The large waterbody (lake) is located at the landward end of the Pukepuke Lagoon Conservation Area and measures some 400 m across (SW to NE), 600 m along the seaward axis, has a perimeter of 1.9 km and has an area of approx. 16 ha with 0.6 ha outside the Conservation Area (Figure 2). Along the northern side of the Conservation Area are three water bodies with the largest (1.4 ha) closest to the lake. The Conservation Area also has several ponds at its eastern end which range in size from 0.2 and 0.4 ha. Some of the ponds were excavated in 1970-71 and used for herbicide trials on raupo control by the Wildlife Service – this is discussed further in Section 3.

A map showing the lake bathymetry was included in Fowler (1982); however, the survey appears to have been adapted from an earlier (1953) report and reduced to the MSL-based elevation datum (Wellington Vertical Datum 1953) used for the lagoon's hydrological equipment. For the present exercise, the uppermost (shoreline) contour has been discarded as this has changed considerably during the intervening 65 years (described further in Section 3). However, the remaining contours may well still demonstrate the basic shape (morphology) of the lake bed so have been included in Figure 5. The deepest point of the lake is at the seaward end with the bed having an overall oval shape and some widening at the eastern (inland) end – broadly in keeping with the shape of the lake shoreline. The recorded maximum depth of 1.3 m equates to approximately 5 m above MSL.

The composition of the lake bed is described by Jacobs (2017) to consist of sand and is likely underlain by silt/iron pan which maintains levels to a certain extent. However, areas of sandy gravel were also noted. Indeed, these materials have been described as underlying the wider drainage area by Mark-Brown (1978). It is also noted that the lack of muddy sediments prevented collection of suitable samples for pollen analysis by Massey University Geography students in the 1990s (Flenley, pers comm.). This was our first indication that the lagoon had a relatively young age.

2.2.2 Hydrology

As noted earlier, Pukepuke Lagoon was the focus of a Representative Basin study from the late 1960s to the early 1980 by the Ministry of Works and Development (MWD). The lake level was monitored by an automatic recorder, numerous groundwater wells were established about the lagoon and within the catchment and these were monitored manually, and a v-notch weir established at the outlet for measuring discharge (Hydronet, pers comm). Some of the key monitoring sites are located in Figure 6. It is noted that there appears to have been no streamflow/main drain monitoring, so modification to the Pukepuke hydrological regime by catchment diversion and drainage has yet to be assessed.

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[1] All measurements in this report are taken from maps, plans, aerial photograph and satellite images georeferenced off 2011 LINZ ortho vertical aerial photography.

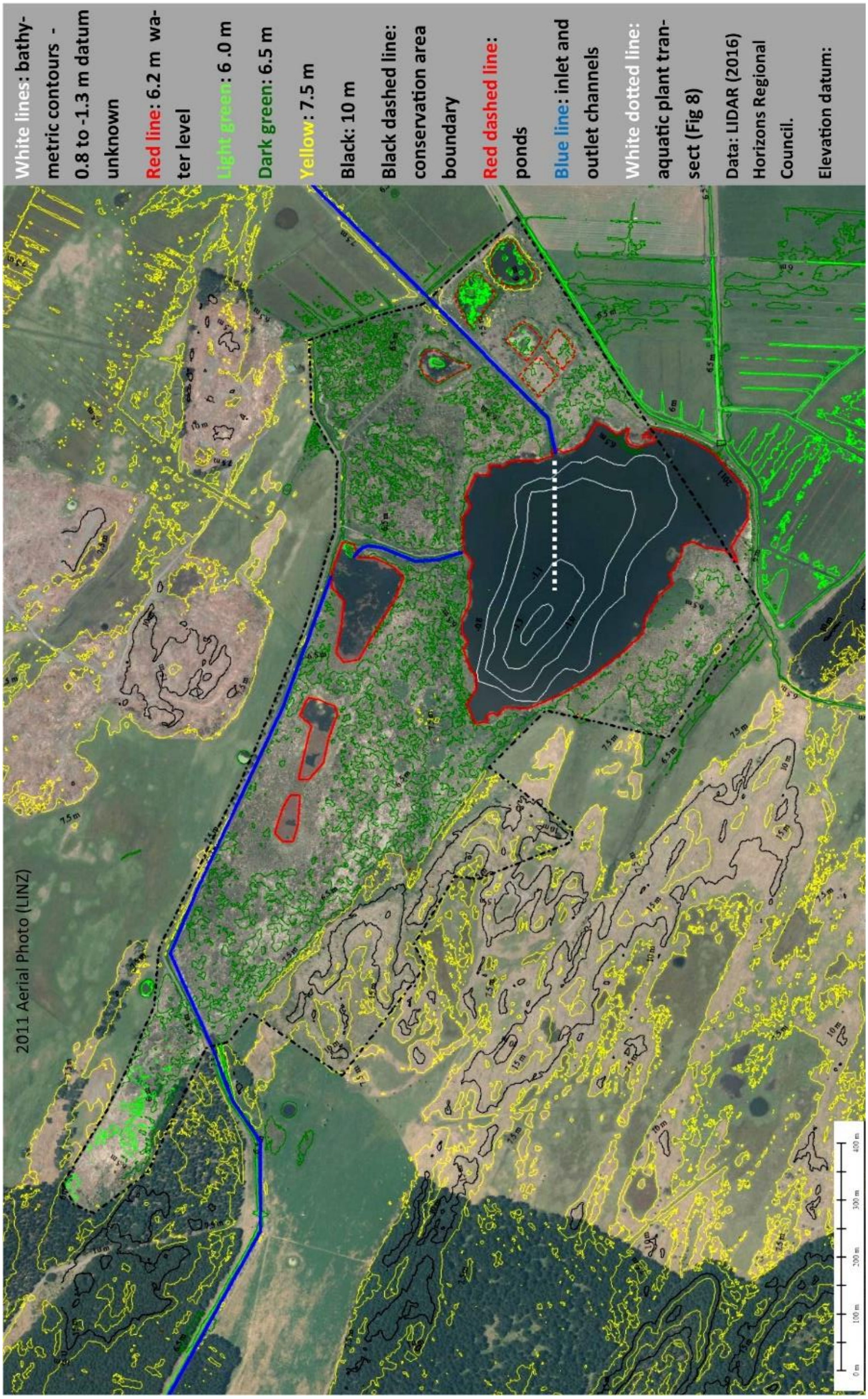

Figure 5 Contour lines depicting key levels in the vicinity of the Pukepuke Lagoon Conservation Area.

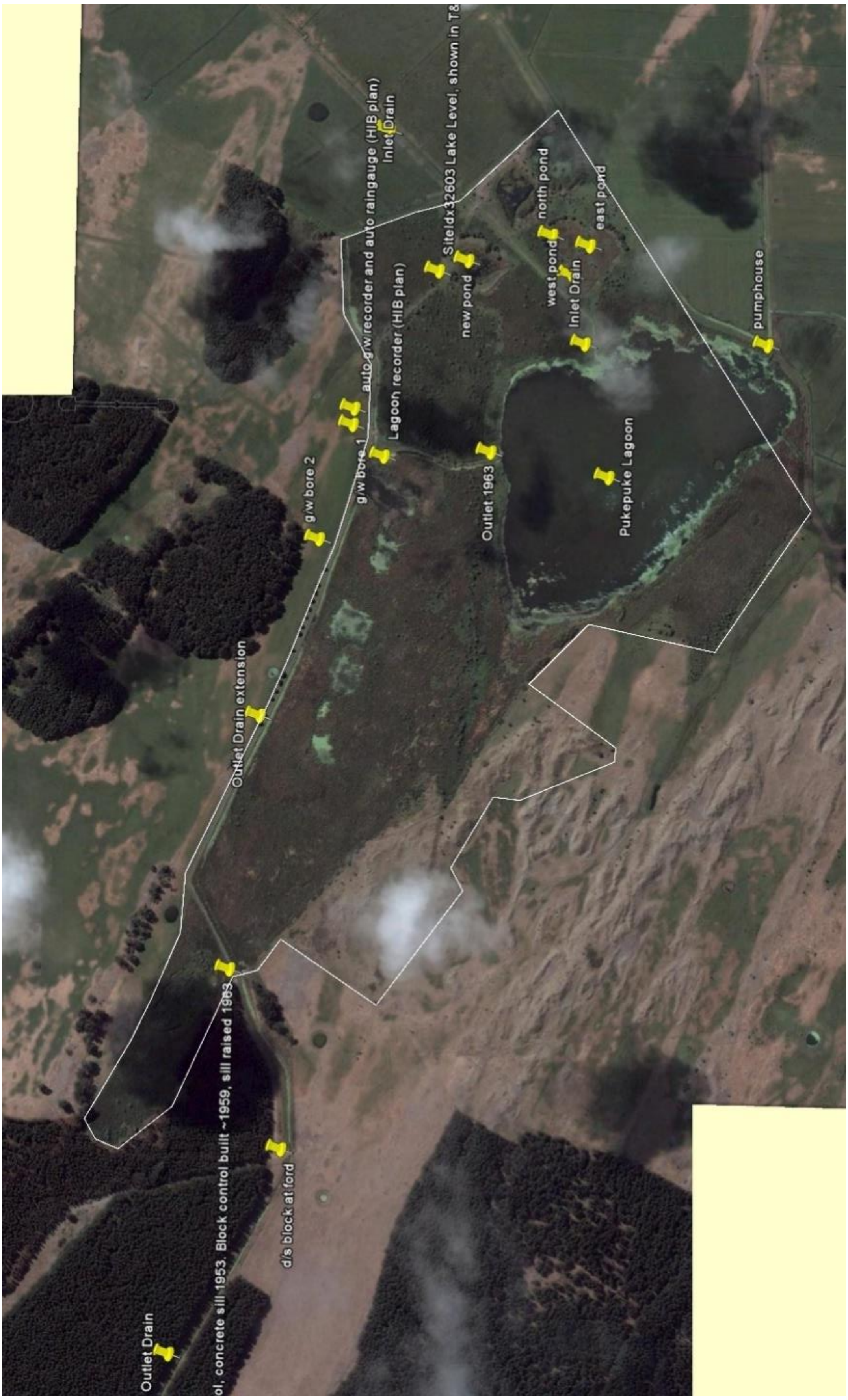

Figure 6 Key hydrological instrument locations from MWD Representative Basin monitoring from the late 1960s to the early 1980s, overlaying the 2010 Digital Globe satellite image. Prepared by Hydronet

Water levels in Pukepuke Lagoon ranged between 5.636 m and 6.777 m above MSL with a mean value of 6.255 m and standard deviation of 0.241 m. Actual stage (surface water level) and flow data are presented in Figure 7 (upper). The water level at the time of the LIDAR survey (6-5 January, 2016) from which the various contours shown in Figure 5 were derived, was 6.2 m above MSL which approximates the mean value.

Pukepuke surface water level is (manually) controlled by a “block structure” at the outlet drain weir for the purpose of minimising rapid change and maintain the fluctuation to about 0.1 m during the breeding season. Data presented in Figure 4 shows a seasonal range of about 1 m, reflecting high stages in winter due to high inflow and low stages in summer due to zero inflow and surface evaporation (Mark-Brown 1978). About once per decade (on average) the lake actually dries out.

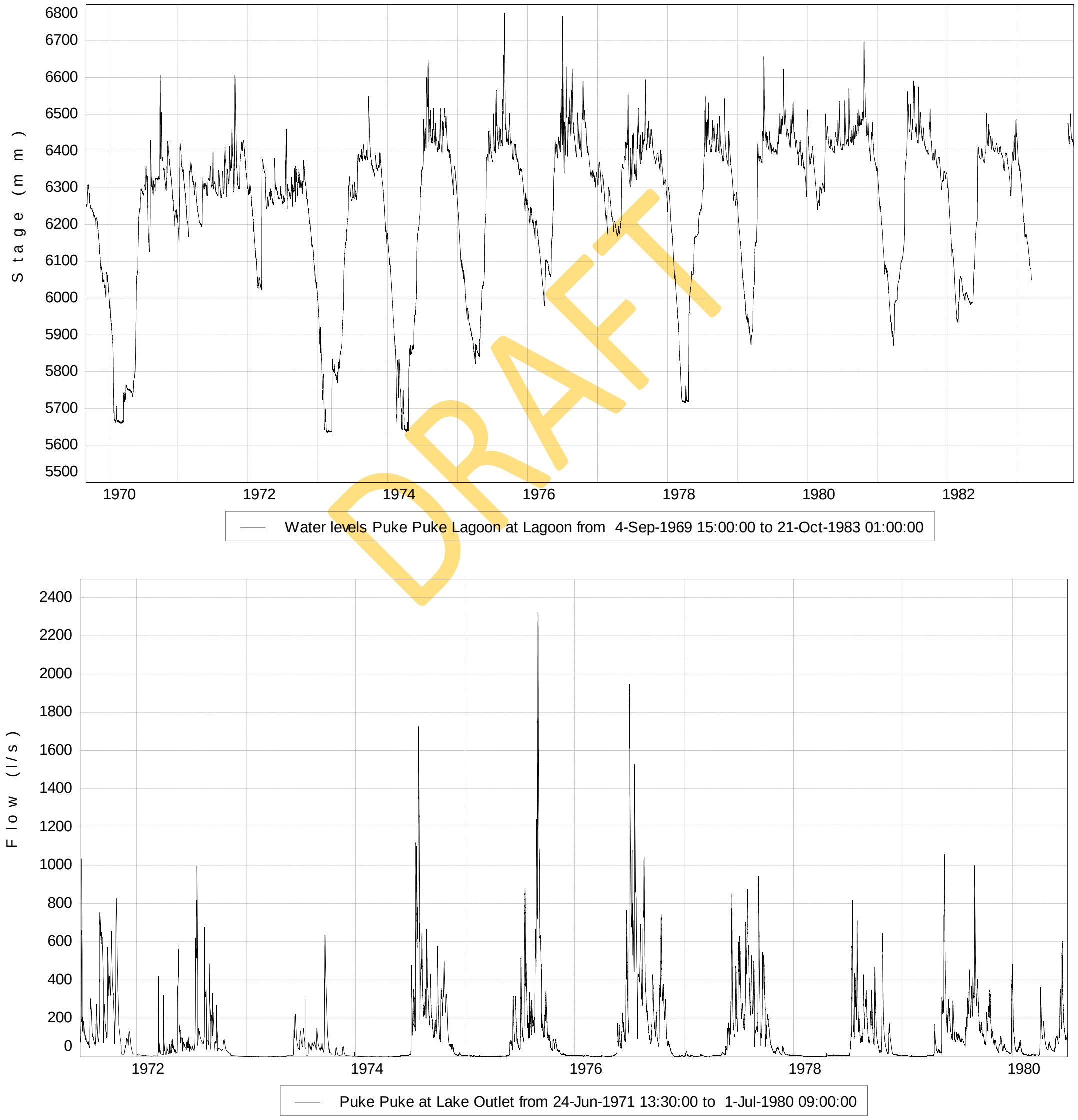

Figure 7 Surface water level (upper) and flow (lower) time-series graphs for Pukepuke Lagoon. Raw data were collected as part of the Representative Basin study by the Ministry of Works and Development between 1969 to 1983. Data were provided by NIWA and Horizons Regional Council and the graphs prepared by Hydronet.

The lagoon outflow data have been graphed in Figure 7 (lower). The mean flow was 110.6 litres/second and standard deviation 196.3 litres/second. The maximum value was 2,322 litres/second while the 1% exceedance value was 902 litres/second, i.e. the flow that is equalled or exceeded 1 % of the time. It is evident from this graph that for extended periods during the late summer in particular there was little or no flow leaving the lagoon. The flow-duration analysis showed the flow was less than 10 litres/second for 40% of the time.

The Jacobs (2017) hydrological assessment defined input and output contributions which make up the lake's water balance. The water balance modelling was calibrated using the Representative Basin study data (1969 to 1983) and found that 2.1 % of water entered the lake via direct rainfall interception, 9.1% by quickflow/surface runoff (via the drainage system) and 88.8% via baseflow. However, the baseflow necessarily combined direct local groundwater seepage and stream flow (interflow and groundwater), so the effect of the drainage system under non-quickflow conditions was not assessed. Outflow consisted of 1.8% evaporation, 13.6% leakage and 84.6% baseflow.

The extents to which Representative Basin data applies to the present hydrological regime given interim drainage development, and will apply with future given expected land use intensification and effects from projected climate change, will need to be the subject of further assessment.

2.2.3 Wetland

The lake and ponds are surrounded by approx. 50 ha of wetland and this area is defined by dark green (6.5 m elevation) contours in Figure 5. Raupo (Typha orientalis), grows up to 2 m high and occurs around the margin of the lake and within most of the remaining lagoon. Raupo plays a major role in naturally infilling lakes and wetlands in the Manawatu dune field. Aviss (1987) notes that while raupo is indicative of a fertile wetland associated with agricultural runoff, the water at Pukepuke is still clean enough and of high enough quality to attract the wide range of bird species present. Nonetheless, the Wildlife Service's aim was for "species diversity and not to allow a raupo-based monoculture". To that end, they had an ongoing programme of manual/mechanical cut back to maintain the lake's open waters (Turner, 1977; Fowles, 1982; Aviss, 1987). As noted earlier, some of the ponds were excavated and used for trialling selected herbicides in the 1970s, but the results have not been found.

An aquatic plant assessment by Edwards and Clayton (2002) included a scuba-based partial profile survey (the sampling transect is shown by the white dotted line in Figure 5) and the several main species of pond weeds are diagrammatically illustrated in Figure 8 . They also compared their results to an earlier survey carried out by Kelly (1978) and concluded that "there had been no significant change in vegetation status or condition over the past 25 years. They concluded that the relative isolation had helped protect the lake from common submerged nuisance weeds that are found at the more publicly accessible waterbodies in the region. Furthermore, the firm sandy substrate and shallow water help maintain a significant submerged vegetation presence as well as providing an ideal feeding ground for water fowl.

Edwards and Clayton (2002) dismissed Kelly's claim of possible eutrophication on the grounds of saline influence and Kelly's sampling from the water surface (c.f. diving) did not recognise a healthy, diverse vegetation. Edward and Clayton noted that vegetation composition and abundance could vary from year to year depending on seasonal weather characteristics – such variation having been recorded in a three year study during the 1970s.

The 1987 Pukepuke Reserve Wildlife Management Plan Appendices lists 180 aquatic and terrestrial plants species, 7 types of fish and 63 bird species.

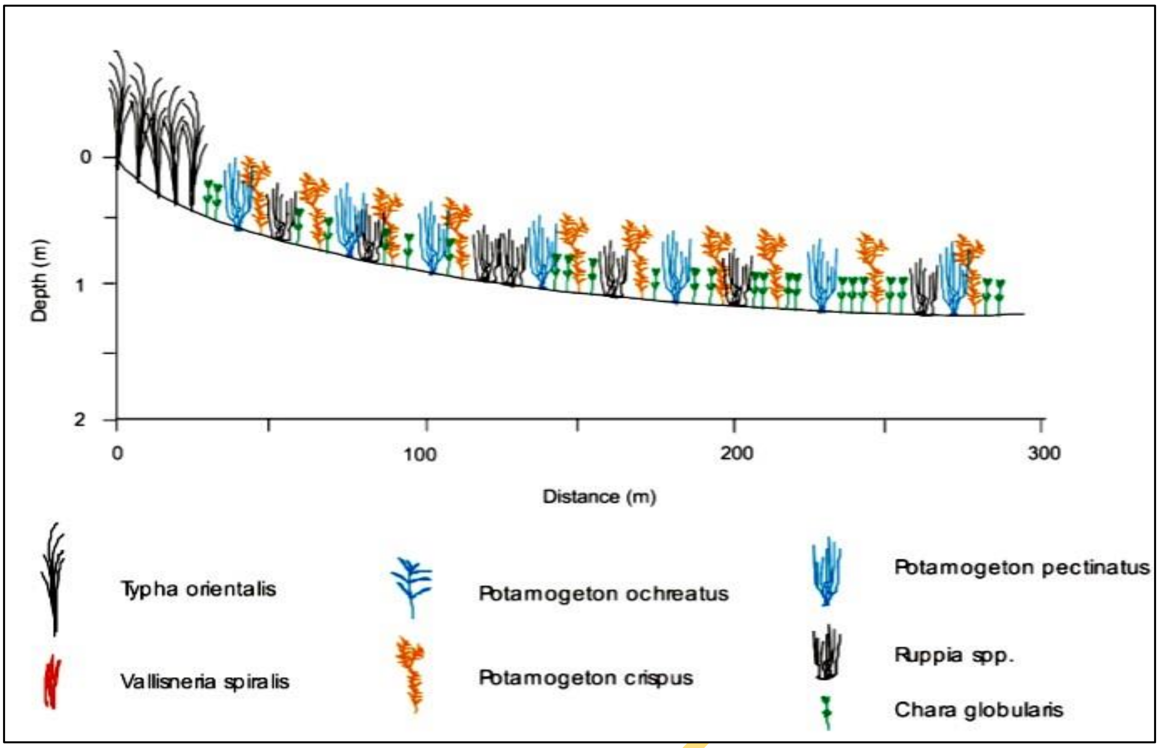

Figure 8 Stylised aquatic vegetation profile for Pukepuke Lake. Transect location is marked on Figure 5. Source Clayton and Edwards (2002)

2.2.4 Sand dunes

The Pukepuke Lagoon Conservation Area includes approx. 10 ha of stable (vegetated) sand dune along its central southwestern margin; these are evident in Figures 2 and are defined in Figure 5 by the 7.5 m (yellow) contour lines and the 10 m black contour lines. Dune elevation ranges up to 18.5 m above MSL giving a maximum height of about 12 m. While the most clearly defined (and highest) dunes are located in this central southwestern part of the Conservation Area, the entire water body/wetland margin along the southwestern and north eastern sides are defined by low dunes (sand drifts) which range between 0.5 to 1.5 m high. Some of these sand drifts are signalled by the brown (dry) areas adjacent to the wetland margin in Figure 5 (2011 aerial photo) and Figure 6 (2010 satellite image) both of which were taken under dry conditions. Such low relief dune forms would have formed rapidly; the author having measured migration rates in dunes near the Rangitikei Rivermouth exceeding 100m/yr with 36 m being recorded between sequential aerial photographs taken 44 days apart in September-October 2007. Existing vegetation can thus quickly become buried and this facilitates further wind erosion and dune instability. Sand dune types and dynamics are described further in Section 3.

3 LANDFORM CHANGE

3.1 HOLOCENE DUNE FIELD

To explain the geomorphology in the vicinity of Pukepuke Lagoon it is necessary to appreciate coastal evolution during the Holocene – the current warm period that began about 10,000 yrs ago.

The formation of Pukepuke Lagoon is closely associated with the development of the Manawatu dune field, which forms part of New Zealand's largest dune field which spans almost 200 km of coastline from Paekakariki to about Manutahi (some 15 km north of Patea) and extends up 18 km inland. The dune field started forming approximately 6500 years ago when the sea reached its present level. Prior to this, sea level had risen approximately 120 m in response to the melting of continental ice sheets that had commenced about 18,000 years ago following the last Ice Age maxima. At that time the shoreline was about 4 km further east than the present coastline (Figure 9) with further encroachment constrained by the Himatangi Anticline (see Figure 9).

The coast subsequently prograded westwards as sediment moved onshore across the shelf (a process which lasted several millennia) as well as sediment derived from cliff erosion and hinterland erosion from Whanganui and Taranaki to the west being transported as littoral drift to the Manawatu coast. While the average rate of shoreline progradation over the past 6000 to 7000 yrs is approximately 0.6 m/yr, the advance would almost certainly have been episodic.

An abundant sediment supply enables foredunes to develop along the shoreline and these dunes at times become unstable with blowouts and parabolic dunes occurring in sequence (Figure 10A) with the latter typically able to migrate inland at rates (measured on the Wanganui-Manawatu coast by the author) of 6 to 60 m/yr depending on dune height and ground cover. As noted in Section 2, the lower wind drift dunes have been measured migrating at over 100 m/yr. Migrating dunes can take on a range of forms (Figure 10B), with the largest (transgressive dunes) forming under high sediment supply and wind strength. All the illustrated dune forms can be observed in the Manawatu dune field as either stabilised or active features.

Cowie (1963) recognised that three phases of dune instability/migration had occurred in the dune field during the Holocene: termed the Foxton, Motuiti and Waitarere Phases which are spatially defined in Figure 9. The Foxton and Motuiti Phases were the most extensive: with transverse and parabolic dunes migrated far inland leaving in their wake wide sand plains and long dune ridges aligned parallel to the prevailing WNW winds. The Foxton Phase was likely initiated at the coast about 6500 years ago by the influx of sand from the shelf at the end of the period of sea-level rise, while the Motuiti Phase was initiated at the coast between 4500 and 3500 yrs ago as a result of sediment influx associated with several potential mechanisms including volcanism, tectonism or climatic aberrations. A particularly extensive sand plain developed behind the Motuiti phase dunes about 2000-3000 years ago as they migrated landward and the bare sand surfaces were deflated down to the elevation of damp sand just above the level of the seaward-sloping regional water-table.

A third episode of dune instability/migration, referred to here as the Early Waitarere Phase, commenced around the time of Maori settlement about 600 years ago (Muckersie and Shepherd, 1995). Man is extremely effective in disrupting vegetation by fire, grazing or foot/vehicle traffic and there is anthropological evidence of Maori initiating this episode of dune instability – possibly by fire to encourage the growth of bracken fern, a major source of starch in their diet (McKelvey, 1999). Evidence varies as to the stability status of dune field instability when Europeans arrived with some authors stating the Manawatu dune field was covered with grass and stable (O'Donnell, 1929;

Wendelken, 1974) with others that the dune field further north was unstable with extensive areas of bare sand (Wakefield, 1845, Field 1891).

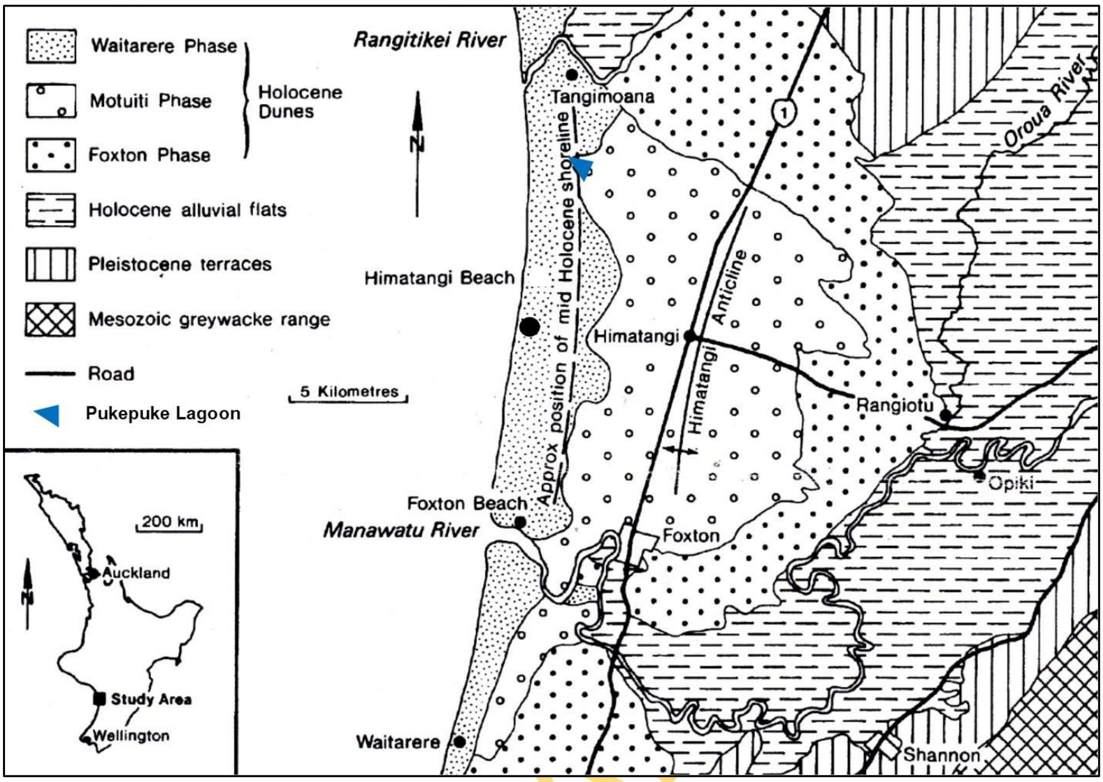

Figure 9 Manawatu dune-building phases based largely upon soil development from Cowie (1963) and other geological/geomorphological markers. Note that the Waitarere/Motuiti boundary between Himatangi and Tangimoana is shown in greater detail in Figure 1. After Shepherd et al. (1986); and Hesp (2001).

By comparison, there is very clear evidence of the dramatic effects European settler land use practices had on the dune field with burning to create pasture, grazing by cattle and also introduction of rabbit and deer. Within a few decades the entire regional dune field was reactivated and dunes migrating inland. Loss of pastoral land was estimated to be 40,000 ha (nationwide) in 1880 and over 120,000 ha in 1909 (Cockayne, 1909). This constitutes the fourth phase of dune instability/migration referred to here as the Late Waitarere Phase and required several decades of central government funded research, trials and conservations schemes administered by regional catchment authorities before “the sand problem” was fully contained in the 1980s.

Figure 11 illustrates the extent of dune instability between Himatangi and Tangimoana in the mid 20th century. It is noteworthy that closer to Tangimoana (right side of Figure 11) the extent of bare sand is less; this was because Tangimoana was selected as a sand conservation trial area between 1913 and 1930 during which 680 ha of marram grass were planted and 271 ha of radiata pine (McKelvey, 1999). The existence of the Tangimoana trial site indicates there was early instability in this area, instability quite possibly initiated/exacerbated by migration of the Rangitikei River mouth which would have at times eroded the dune field margin and compromised the vegetation cover – this being a common occurrence at inlets.

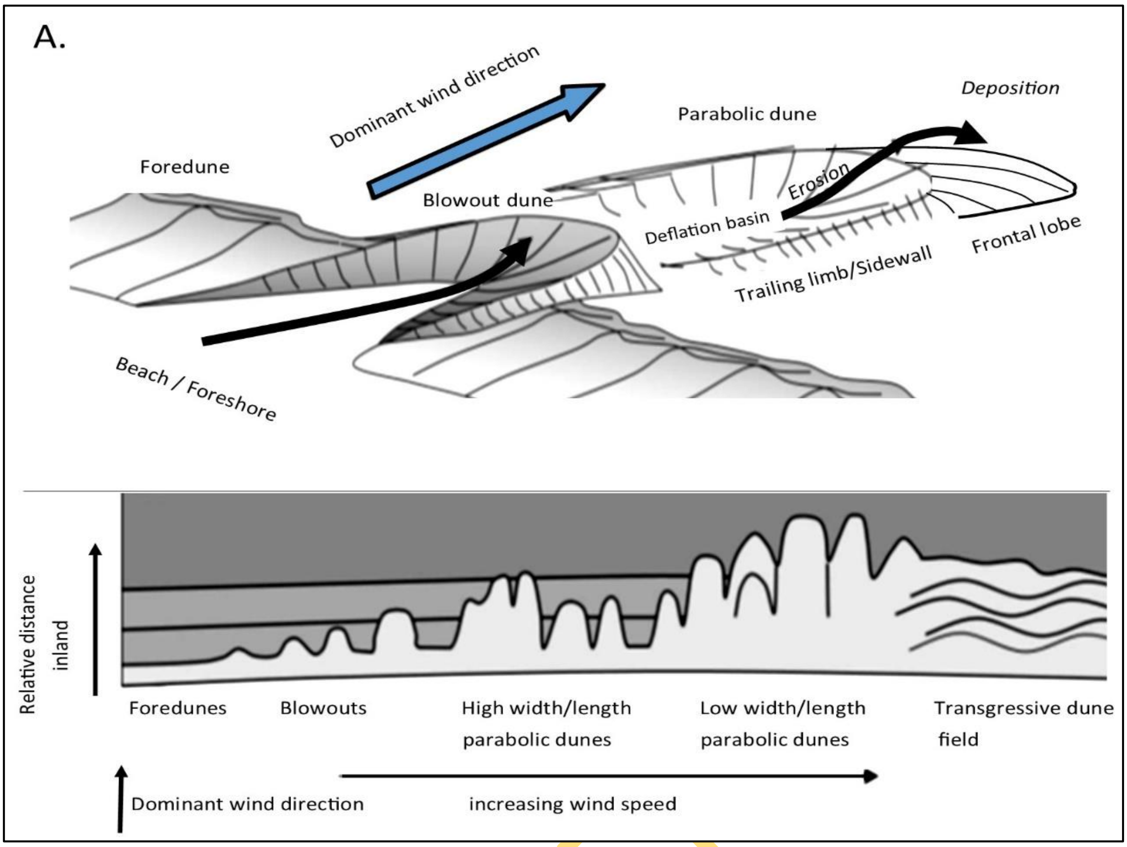

Figure 10 Coastal sand dune types, nomenclature and migration modes. Adapted from Bird (2000), and Sloss et al. (2012).

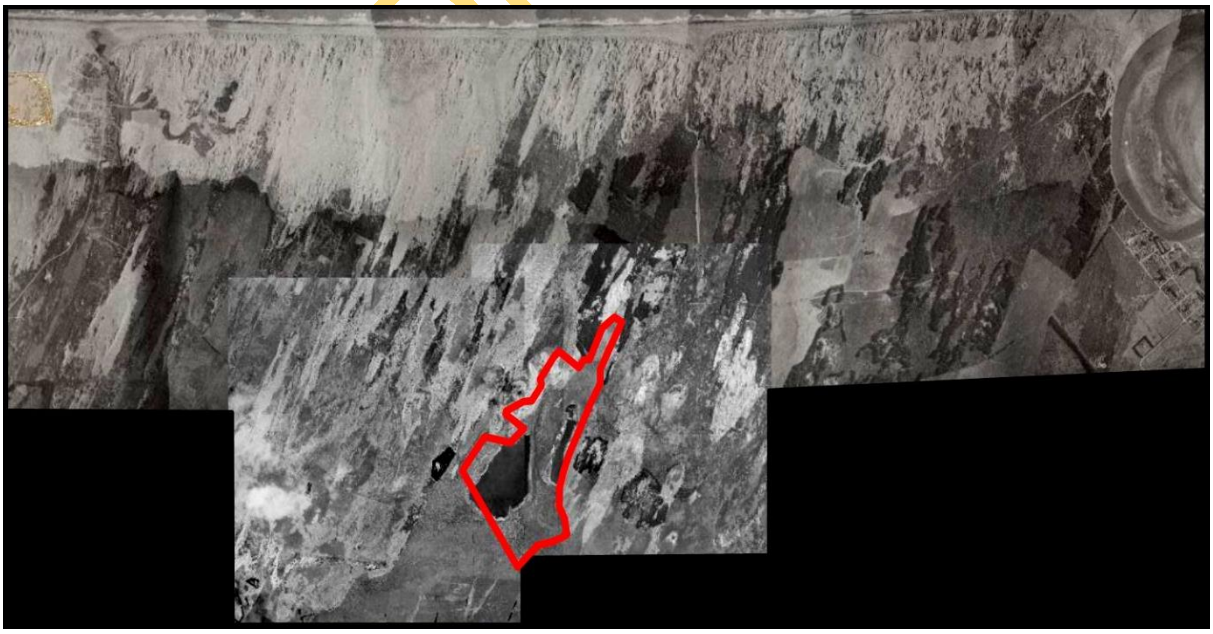

Figure 11 Illustration of Late Waiterere Phase unstable/migrating dunes between Himatangi on the left and Tangimoana on the right with Pukepuke Conservation Area marked in red. The aerial photo mosaic is part of a 1952 coastline series taken for the Department of Land and Survey for a sand dune study between the Otaki River and Wanganui. Note the lower two photos (upon which Pukepuke is marked, were taken in 1939 as the 1952 series did not extend this far inland.

The Waitarere Phase dunes migrated 3 to 4 km inland and impeded seaward drainage from the landward sand plain, which, in conjunction with rising water-tables associated with the prograding coastline, resulted in the development of a series of the shallow lakes and extensive wetlands (including Pukepuke) along the eastern (inland) margin (Figures 1 and 9).

3.2 HISTORICAL SHORELINE CHANGE

Our understanding of the Foxton, Motuiti and Early Waitarere Phases is based on a range of geological (primarily radio-carbon dating) and anthropological evidence (primarily sand covering human implements or remains). However, colonisation was accompanied by written description, maps and later photography of the landscape, and analysis of these records provides a more detailed understanding of the Late Waitarere Phase and formation of the Pukepuke Lagoon Conservation Area.

The first survey plans define the Native Reserve (Section 378) which was gazetted in 1869. All survey plans, aerial photographs and satellite images referred to in this study are listed in Appendix A and several key images are reproduced in Appendix B. Each image in Appendix B has the original 1869 Native Reserve boundary marked as well as the present Conservation Area boundary to assist the reader with spatial referencing. The Native Reserve was clearly much larger (158 ha) than the present conservation area (80 ha) with its centre being some 700 m to the northwest of the Conservation Area's centre

Shorelines defining the lagoon water bodies from 1872, 1908, 1929 and 2011 are overlaid upon the 1939 aerial photo in Figure 12. While there is little change evident between the 1872 and 1908, the 1929 shoreline has an entirely different shape. The 1929 lagoon water body closely resembled the current Conservation Area boundary, with the original (1872) water body area having been reduced from 130 ha to 51 ha (61%). A comparison of the 1929 shoreline with the 1939 shoreline in the underlying aerial photo shows substantial infill leaving a lake of just 17.3 ha and smaller arm along the northern to seaward of 3.8 ha, i.e. 21.1 ha in total making a reduction of 84% from the 1872 water body.

Lake shorelines between 1939 and 2015 are superimposed in Figure 13A and the corresponding surface areas are depicted in the accompanying time-series graph (Fig 13B). This set of 11 shorelines were derived from aerial photographs and more recent satellite images. These surface areas vary between a minimum of 10.9 ha in 1968 to a maximum of 18.2 ha in 2005. While surface area will vary somewhat depending on seasonal hydrological conditions (noise) at the time of image capture, systematic variation still appears evident with the surface area reducing through to the early 1970s, then increasing through to the 1990 and more recently decreasing to 15.2 ha in 2015. This pattern of change is consistent with the initial natural establishment and encroachment of raupo followed by the Wildlife Service's raupo control programme which increased the lake surface area. The more recent data points indicate raupo encroachment is again occurring.

In addition, linear regression analysis was carried out on data points from 1939 to 1969 (after which raupo management was definitely occurring), and the resulting model, represented by the red dashed line in Figure 13B, gives a rate of surface area decrease of 0.2 ha/yr. Extrapolating the regression line indicates that if the Wildlife Service control measures had not been implemented, then the lake's open water may have all but disappeared by now and a natural plant succession toward a semi-swamp forest, perhaps dominated by kahikatea and pukatea like the Omarupapaku Reserve near Foxton (Esler and Greenwood, 1968; McFadgen, 1972), may be well underway.

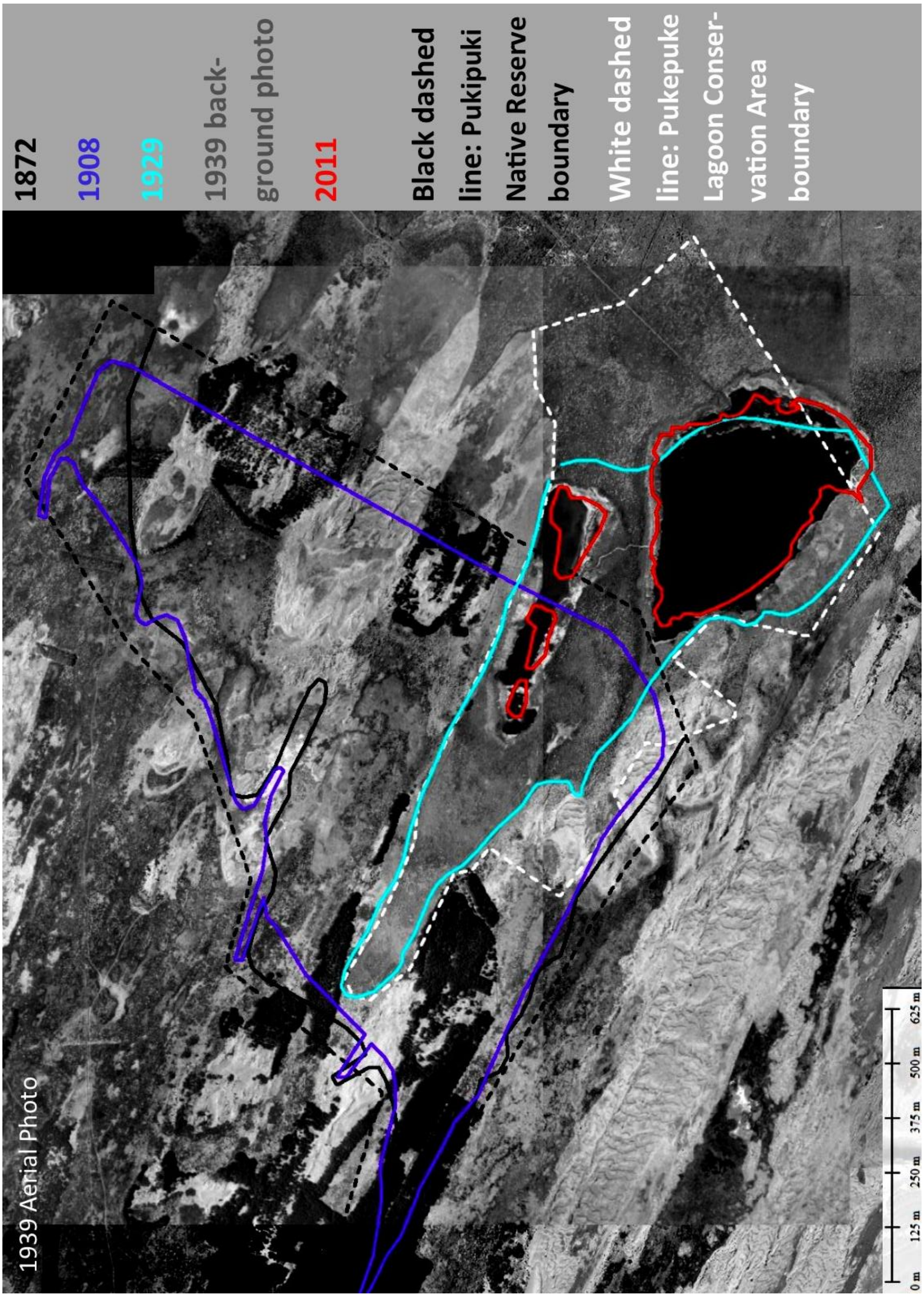

Figure 12 Pukepuke shorelines abstracted from the survey plans and aerial photographs shown in Appendix B. Black areas signal pine plantations or Pukepuke water surfaces, dark grey areas signal vegetation, light grey/white areas signal bare sand.

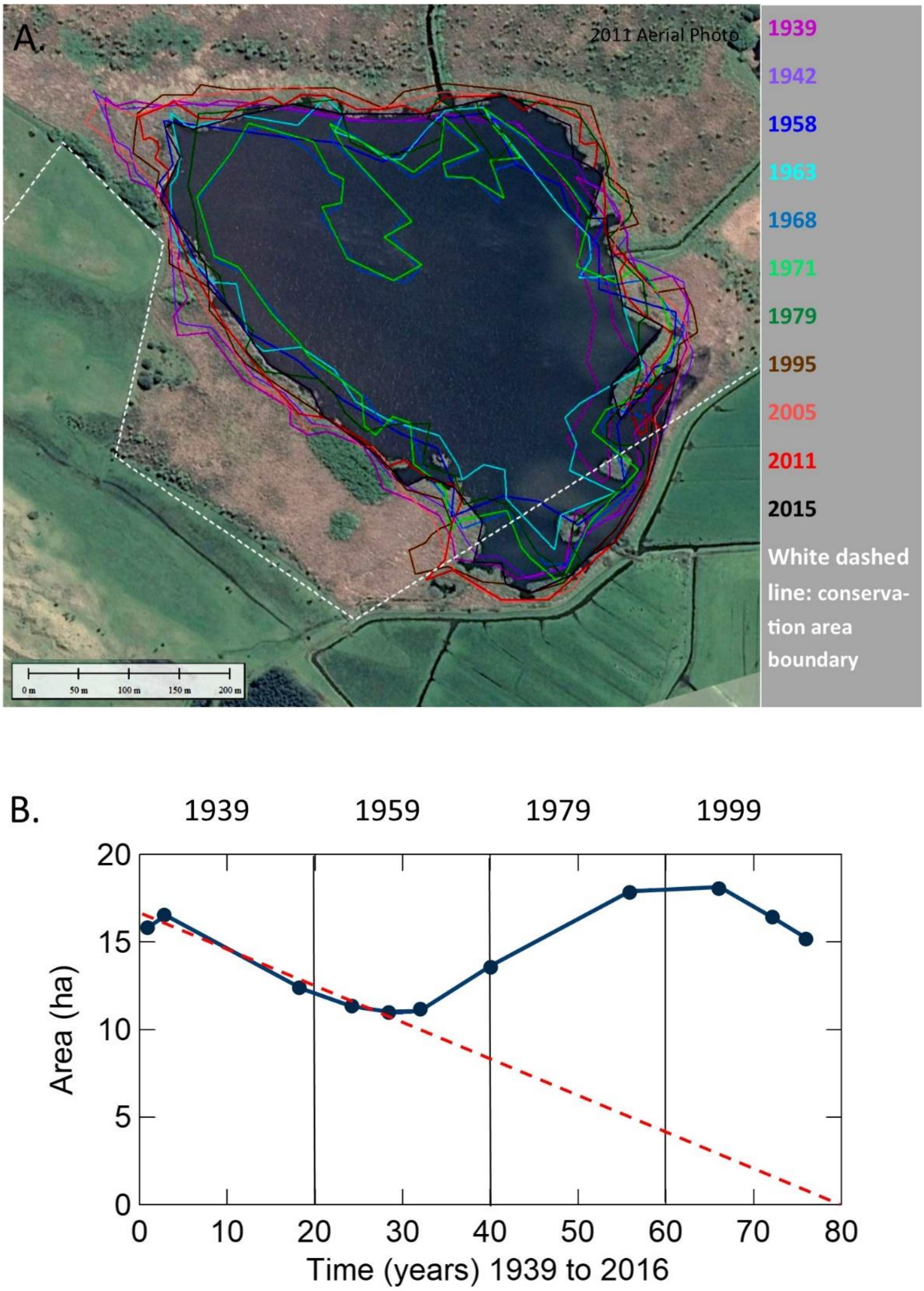

Figure 13 Water surface margin shorelines for Pukepuke lake (A) and corresponding area time-series (B). Dashed red line is the linear regression model for 1938 to 1968 data points extrapolated to the present.

3.3 HISTORICAL SAND DUNE CHANGE

Historical dune-front lines, as depicted or inferred from the key cadastral (survey) plans and as are visible on aerial photographs, have been abstracted and overlay the 1939 aerial photograph in Figure 14. The undulatory seaward line in the 1872 and 1908 plans, interspersed with seaward directed re-entrants (e.g. marked "a" in Figure 14) indicative of stream outlets, is consistent with a stable transverse dune front which defines the landwardmost advance of the Early Waitarere Phase of dune migration. However, as the Pukipuki and Kaikokopu Native Reserves appear to have been used for temporary/seasonal residence by local iwi (Wilson, 1959; Chris Shenton, pers comm) rather than permanent residence, it may be that the dunes were, nonetheless, somewhat unstable during the 1872-1908 period as was occurring elsewhere in the region (Cockayne 1909, O'Donnell, 1929).

From the underlying 1939 aerial photo in Figure 14, it is evident that forest planted on the 1929 dunes (marked "b"), possibly as part of the Tangimoana Trials mentioned earlier, has been overrun in places by mobile sand dunes ("c"). In addition, it is evident that by 1939 the dune front had advanced a further 600 m in places ("d") on the northern side of the lagoon and divided the water body ("e") into the present lake and a separate lesser water body along the line of the present outlet channel. While the interior of the dune field remained unstable for a further 20 to 40 years, only minor changes occurred to the dune front as is evidenced in Figure 14 by no additions after 1963.

3.4 DRAINAGE

The 1913 survey plan (Appendix B) gives an indication as to the extent of swamp fronting the Pukipuki Native Reserve/Pukepuke Conservation Area. The swamp at that time extended southward some 2.5 km and covered approx. 125 ha. However, by this time considerable drainage in the south (into Lake Kaikokopu) had already occurred as the earlier 1889 survey map show this swamp had been considerably larger (at least 330 ha).

Wilson (1959) witnessed and recorded the process of dune instability and the natural consequential changes to drainage as well as subsequent man-made changes to the drainage system in the early 20th century, i.e. during that period of demise for the Pukipuki Lagoon and formation of the Pukepuke Lagoon. While some of Major Wilson's descriptions are spatially and temporally vague, the account is nonetheless invaluable as it enables a reasonably comprehensive reconstruction when read in conjunction with the data presented in this report.

The Wilson family have farmed the dune and swamp land between Pukepuke and Himatangi since the late 19th century. Their property included much of that large area of swamp in the Pukepuke area depicted in the 1913 survey plan (Appendix B). To effectively drain this northern swamp area, the level of Lake Kaikokopu had to be lowered and this was achieved in 1909 by cutting through the extensive meanders between the lake and the sea. This resulted in lowering the surface by 8 feet which consequently reduced the lake surface area from approximately 130 ha in 1889 (survey plan), to 58 ha in 1921 (survey plan) and to about 16 ha at the present time (1:50,000 topographic plan). The scheme then involved excavating a main drain northward along their eastern boundary and into the Pukepuke Swamp ("b" in Figure 4 which is referred to as Conlan's drain) as well as excavating a diagonal drain joining this to Lake Kaikokopu ("a" in Figure 4 and referred to as the Hunia Diagonal Drain). The combined drain is referred to as the Kaikokopu North-South Drain in this report. Not only did the Kaikokopu North-South Drain provide an outlet for draining the Wilson's farmland, but it also enabled an outlet for adjoining properties along their eastern boundary. Consequently, the Manawatu

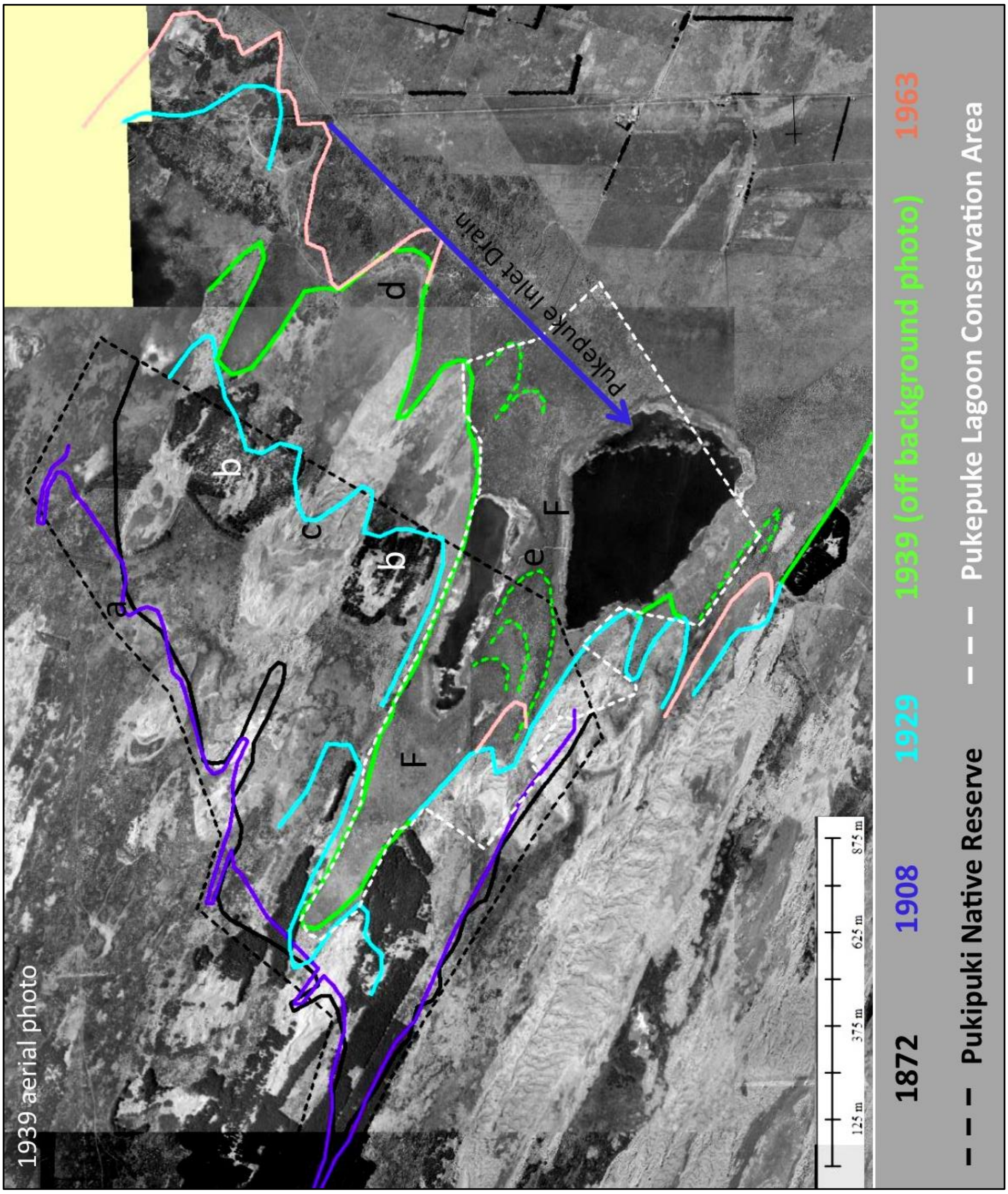

Figure 14 Dune migration as indicted by dune frontal locations between 1872 to 1963 derived from the survey plans and aerial photographs in Appendix B. Black areas are pine plantations or Pukepuke water surface, dark grey areas are vegetation, light grey/white areas are bare sand. The significance of locations marked “a” to “F” are explained in the text.

County Council became involved and later the Oroua Downs Drainage Board would administer a maintenance programme. The Kaikokopou North-South Drain appears to have been excavated shortly after lowering of the lake as it is marked on the 1913 survey plan (see insert in Appendix B). The drain may have extended further north beyond the coverage of this survey plan.

Major Wilson also describes how both the Pukipuki Creek, which drained the original Pukipuki Native Reserve Lagoon to the sea, and Boss Creek (Figure 1), which drained the adjacent Omanuka Lake catchment northward into the Rangitikei River, "would at times be blocked by drift sand in the summer until higher winter flows backed up and overtopped the dune obstructions". It appears that this drift sand was part of the Late Waiterere Phase dune instability/migration described above, and at that time was reshaping the Pukepuke Lagoon area.

The Wilson account goes on to describe how during one particular such episode "the flooded Boss Creek found an easier way by cutting through a sand drift and pouring south into our main drain, but this could not take such a volume of water and settlers in the northern end became waterlogged". To solve this acute matter…."A new course was excavated to join the (new) Pukepuke Lake with the original Pukipuki Creek to the sea". "And a new drain was then opened up to take the Boss Creek water into Pukipuki Lake instead of filling up the drain to Kaikokopu". The new diversion drain being the current Pukepuke Inlet Drain ("c" in Figure 4). Wilson's description explains the distinct intersection of drains b, c and d in Figure 4. The timing of the Boss Creek change and cutting of the Pukepuke drains; however, are not given. But we do know that the Pukepuke Inlet Drain is not shown on the 1913 survey plan and Wilson indicates that the Oroua Downs Drainage Board administered the expanded drainage system. With the Board apparently formed in 1918 this brackets this drainage work to the World War I period. It is noted that the Pukepuke Inlet Drain is marked in the 1929 survey plan (see insert in Appendix B).

It can be seen in Figure 14 that the Pukepuke Inlet Drain directed water into the recess between the southern and northern dune advances ("F"), this being the remaining lower lying area of the original Pukipuki Lagoon. The eastern (inland) boundary of the new Pukepuke Lake, however, was not well defined and merged into swamp. This boader would later be fixed by a bund and the area drained by incorporating a pumping station (marked in Figure 6) as farm development progressed.

It is of interest to note Major Wilson's comment… "several attempts were made to return Boss Creek water back into its old course to the Rangitikei River, but the course was blocked so well by drifts that it always scoured out our blocks and forced its way into Pukepuke instead". It is unclear when the additional main drain to the north ("d" in Figure 4) was constructed, possibly once it became evident that Boss Creek could not be returned to the Rangitikei River and maximising drainage efficiency into Pukepuke became desirable.

4 FUTURE CHANGE

4.1 INTRODUCTION

While the Pukepuke catchment will be subject to some change in the future associated with land use intensification and natural process forcing, the nature and impact is most unlikely to rival that of the past 100 to 150 years. However, potential climate change associated with industrial-driven global warming is a newly emerging factor and current projections/predictions will briefly be described. How the existing processes, along with possible climate changes, may affect the various lagoon controls and characteristics (dunes, lagoon infill and hydrology) in the future will then be discussed.

4.2 CLIMATE CHANGE

4.2.1 Introduction

The following resume is based primarily on MfE (2008, 2016), NIWA (2017) and a presentation by Dr Clive Howard-Williams (NIWA) to Horizons Regional Council on 15-2-2016 and reported in the Manawatu Standard: http://www.stuff.co.nz/manawatu-standard/news/76942609/niwa-forecasts-climate-change-effects-in-central-north-island

Climate change predictions for New Zealand are based on the most recent International Panel on Climate Change (IPCC) assessment report. For New Zealand, the Ministry for the Environment (MfE) and the National Institute of Water and Atmospheric Research (NIWA) consider four scenarios which align with those in the IPCC Fifth Assessment Report (2014). These pathways are known as Representative Concentration Pathways (RCPs) and are abbreviated as RCP2.6, RCP4.5, RCP6.0, and RCP8.5 (in order of increasing radiative forcing by greenhouse gases at the end of this century) such that:

- Low emissions mitigation scenario (RCP2.6) assumes global carbon dioxide emissions stop after 2080, after which some carbon dioxide is actually removed from the atmosphere;
- Two middle scenarios (RCP4.5 and RCP6.0) assume futures where global emissions stabilise at different levels, and
- A high emissions scenario (RCP8.5) assumes continuance of the present situation.

4.2.2 Temperature

For the Manawatu, the lower scenarios have temperature increases of 1deg C by 2040, while by 2090 that could increase by 1.75 deg C in some areas.

In the more extreme scenarios, the temperature rise by 2040 could be 1.25 deg C, and by 2090 that could be 3.25 deg C.

The extreme scenario showed that by 2090 low parts in the region would have 50 to 60 more days with temperatures over 25 deg C.

4.2.3 Rainfall

For the Manawatu, by 2040, the conservative estimate forecast rainfall to increase by 10 per cent, while more extreme forecasting had a 15 per cent increase. In 2090 that could be 15 per cent and 20 per cent increases respectively.

4.2.4 Wind and Storms

For the Manawatu coast, increases in (westerly) mean and extreme wind strength, increase in storm frequency and increase in El Nino-associated extreme events are predicted.

4.2.5 Sea level

The lower Representative Concentration Pathway predicts an average sea-level rise to 2060 of 0.26 m (0.18 to 0.35) while the upper pathway predicts 0.33 m (0.24 to 0.42). Increasing the prediction period to 2120 gives lower pathway values of 0.53 m (0.32 to 0.76) and upper pathway values of 1.03 m (0.72 to 1.38). Regional tectonic processes could modify these values by raising or lowering the land surface.

4.2.6 Waves

As waves are generated by wind, so a change in the wind regime could result in a change in the wave regime (including mean and extreme wave heights and approach directions). As wind speeds are predicted to increase, so too could wave heights. For the North Island west coast, MFE (2008) recommended a 10% increase to the extreme deep water wave climate be incorporated into coastal hazard modelling. Note that an increase in sea level may further contribute to higher wave conditions.

4.3 DUNE SYSTEM

The evidence presented in Section 3 indicated that the episode of dune advance impacting in the Pukepuke area had all but terminated by the early 1940s with morphological change thereafter being associated with natural infill by lake (organic) sediment and encroachment by raupo.

However, dune systems, are extremely easy to reactivate if the vegetation cover is compromised and there are several mechanisms which could occur in the future. In particular, over-grazing, plantation harvesting and vehicular traffic can all remove vegetation, while wave erosion can affect hundreds of metres, and even kilometres, of foredune in a single storm (Shand et al., 2006). Such devegetation can lead to blowout and parabolic dune development as described earlier and illustrated in Figures 10 and

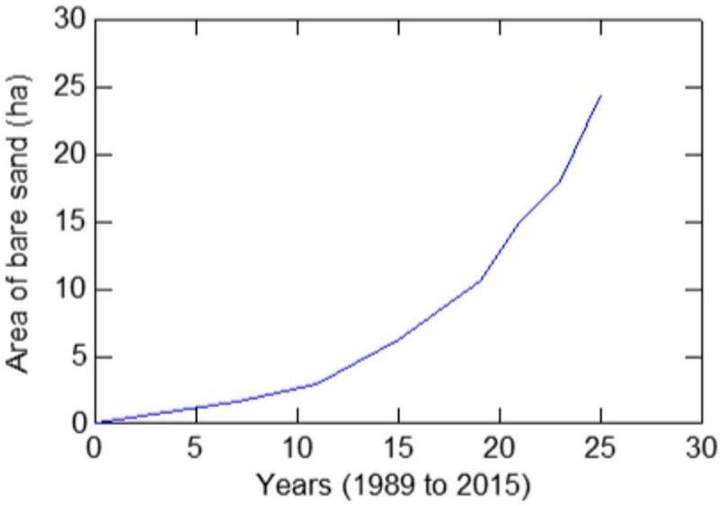

Figure 15 Increase in bare sand area landward of a 300 m long by 3 m high foredune erosion escarpment caused by storm waves erosion on 15 October 1989 at a site just north of the Wanganui Rivermouth.

11. Once wind erosion has a foothold within existing sand dunes, it can expand exponentially as illustrated in Figure 15; in this example from the nearby Wanganui coast, the foredune had been well vegetated and stable prior to storm wave erosion creating a 300 m long scarp (cliff) some 3 m high.

Climate-change can potentially effect foredune erosion by increased storm wave action, increase in sediment input to the coast (which buries vegetation) via enhanced hinterland erosion, and an increase in wind transport potential.

4.4 LAGOON PROCESSES

The graph in Figure 13B shows that had there been no raupo management by the Wildlife Service, then the entire open water surface area would now largely be covered by aquatic plants. However, since 1995 to 2005 when the surface area was about 18 ha, the cover appears to be lessening - down to 15.2 ha in 2015. Based on the rate of surface area loss of 0.2 ha/yr derived from the early years of natural raupo establishment/encroachment (1939 to 1968), open water could disappear in 70 to 80 years time if there were to be no further management. However, the centre of the lake is deeper than the margins so a non-linear rate may apply and an encroachment period of 100 years may be more realistic. In addition, the rate of 0.2 ha/yr may not necessarily apply in the future as the hydrological regime and other ecological controls may differ from those in the mid 20th century for when this rate was derived.

There have been very few studies of climate change impacts on biodiversity in New Zealand and those that have suggest that threats such as invasive pests and weeds, and habitat loss, are more serious risks in the short to medium term than climate change (NZCCC, 2014). However, in the longer term, increased lake temperature may increase the risk of invasive aquatic weeds. Warmer surface water could also lead to stratification and deoxygenation on the bottom with decomposition leading to habitat loss (too warm on the surface and not enough oxygen on the bottom) and fish mortality. However, increased winds could prevent stratification by driving mixing (Bell, pers comm).

4.5 HYDROLOGIAL REGIME

Our report has not investigated current trends and predicted future water demands in the Pukepuke catchment so we can only speculate that further drainage and irrigation will modify the hydrological regime. However, the Regional Council appears to recognise the potential for impacts associated with increasing land use intensification by their present coastal lakes project which focuses on future water availability and water quality (Jacobs, 2017).

While future climate change predictions for the Manawatu indicate some increase in rainfall can be expected, this could be offset by increases in temperature and wind along with an increase in salinity driven by sea-level rise.

5. SUMMARY

The original Pukiuki Lagoon had a surface area of 130 ha within the Native Reserve (section 378) of some 158 ha; this reserve being gazetted in 1869. Subsequent colonial land-use practices resulted in widespread dune instability which appears to have begun affecting the Reserve in the early 20th century. Migrating sand dunes pushed the lagoon water landward such that by the 1920s (or earlier) the Native Reserve was dry – the waters having been replaced by the the uniform sand surface (deflated down to a level just above the water table) that typically follows migrating dunes (Figure 10). The dune advance ceased in the 1930s with the hinterland drainage water concentrated in a low lying recess defined by the new dune-front ("F" in Figure 14); this would later become the Pukepuke Lagoon Conservation Area of some 80 ha, of which none of the present lake and only 30 ha of wetland overlaps the original lagoon. The present lagoon is therefore about 100 years old.

Along with the dune advance over the original lagoon, came settler drainage of the extensive swamp landward and to the south of Pukepuke. This drainage began in 1909 with the lowering of Lake Kaikokopu and was quickly followed by construction of the main drain running from the lake some 5 km into the Pukepuke Swamp. However, the dune advance blocked the Pukipuki Stream as well as the Boss Stream's Rangitikei River outlet, with their water flowing into, and overwhelming, the new Kaikokapu North-South Drain. The (present) Pukepuke Inlet drain was hastily cut along with a connector drain linking the new Pukepuke Lagoon with the original Pukipuki Stream and thus to the sea. Drainage is illustrated in Figure 4.

The current lagoon's catchment area of approximately 2300 ha consists of the upper Boss Stream catchment (including Lake Omanuka sub-catchment) and the northern part of the original lagoon catchment, but not the centre/southern part of the original catchment – this having been diverted by the Kaikokopu North-South Drain. The original catchment (excluding the Boss but including part of the now diverted catchment) could have had a catchment area of approx. 3500 ha. With its surface catchment reduced by over 1/3 (36%), some decrease in size of a new lagoon was inevitable. Catchments are also illustrated in Figure 4

The first available vertical aerial photographs (1939) show the main water body in about the same location and of similar size as the present water body (16 ha). However, analysis of surface areas using a series of aerial photos (11) shows the main lake size has changed considerably over this time with a minimum surface area in the late 1960/early 1970s of some 11 ha and maximum in the late 1990s/early 2000s of 18 ha (Figure 13). This behaviour resulted from the natural encroachment of raupo around the margins of the lagoon following its formation, subsequent manual/mechanical cutback by the Wildlife Service in 1970s and 1980s and apparent continuance of encroachment more recently.

The Wildlife Division of the Internal Affairs Department began managing the area in 1968 by establishing the Pukepuke Wildlife Reserve with objectives of managing, conserving, protecting and enhancing flora and fauna. Their approach was to discourage a raupo monoculture and encourage species diversity. Consequently, raupo control was a cornerstone of the Services' management programme.

Had the Wildlife Service intervention not occurred, our data analysis indicates that most of the water body would now be affected (covered) by aquatic plants. Furthermore, if raupo is left unchecked in the future, then the present approx. 16 ha of open water could be gone within 100 years. Ongoing swamp sedimentation/peat development would eventually dry the lagoon – this being the natural fate of every shallow dune lake in the area. However, if protection of the Conservation Area were to continue (c.f. pasture farming) then a natural plant succession would occur and a lowland semi-swamp forest, perhaps dominated by podocarps, could eventuate in the more distant future.

The Department of Conservation took over control of the Wildlife Reserve 1987 and established the Pukepuke Lagoon Conservation Area. The present project's management objective is that the lagoon be conserved to a healthy functioning state by 2030 and that a plan be developed to restore its natural heritage. Allowing the lagoon to continue its **natural progression** to a stable forest would seem to be consistent with this objective. In addition, adopting such a natural progression strategy could once again make the lagoon a focus of research – in this case "longitudinal" research.

One particularly positive consequence of both the past Wildlife Service and DOC conservation management regimes is that public, animal, and vehicle access has been limited and disturbance kept to a minimum. The last study of aquatic vegetation in 2002 noted that the lake is dominated by several native species and its sustained relative isolation has helped protect Pukepuke from common submerged nuisance weeds species associated with the more publicly accessible waterbodies in the region. Furthermore, the firm sandy substrate and shallow water help maintain reasonable water and plant growth conditions and habitat for wildlife.

Between the late 1960s and early 1980s, the Water and Soil Division of the Ministry of Works and Development (later to become part of NIWA) used the Pukepuke catchment for a detailed hydrological study as part of their Representative Basin programme. This resulted in establishing an automatic water-level recorder to monitor the lake level throughout this period along with establishing a network of manually read groundwater wells. The Representative Basin data have been used at times to describe basic catchment hydrology, but how well these 35 to 50 year old data apply to the catchment today and into the future is unknown.

As long as the dune field remains stabilise (vegetated), its size and location will not be affected by dune migration. However, this coast is particularly windy and thus vulnerable to vegetation disturbance and hence dune destabilization and downwind migration. Current and future land use practices as well as predicted climate change effects have causative potential. While a new dune phase of instability/migration is thus possible, potential loss to agriculture and forestry make it unlikely that such an episode would gain a foot hold once initiated, i.e. conservation practices would be invoked, at least in the foreseeable future.

6. PROJECT CONSIDERATIONS

In terms of how to proceed with the present Pukepuke Lagoon Natural Heritage Restoration Project, the present report raises several potentially relevant issues. These considerations are based on what DOC can realistically control, what fits with its objectives for Pukepuke, and assumed future budget constraints.

1) DOC's Pukepuke objective is based around "restoring natural heritage" and seems to fit with allowing the lagoon to naturally progress through lake sedimentation and plant succession to a forest state – a process that could take 100s of years to complete. This is the pre-colonial process that affected all sand country lakes following dune migration and lake/swamp formation.

   In addition, such a **natural progression approach** should be less expensive than the Wildlife Service's **containment approach** as considerable energy and resource is required to maintain (hold) an **evolving system** in a **fixed state**.

2) DOCs objective is also to have a "healthy" system. There are several tools to assist in this process.
   - (i) Adopt the optimum hydrological regime for a diverse ecology:
     DOC can control the lake input via a ring drain, and output via the downstream block controls.
   - (ii) Optimise water quality:
     Inflow could be diverted around a ring drain to exclude lake inflow during times of high contamination.
   - (iii) Control of identified non-desirable invasive pest plants and animals:
     An ongoing control programme of problem species could be required, in addition to access restriction/conditions.
   - (iv) Plant desirable species that may once have existed/predominated in such natural environments but are now lacking.

3. Several assessments would be required to adopt a **natural progression approach**.

   For example:

   - (i) Update the plant and animal register and assess the ecological state of the lagoon. Identify preferred and non-value species in a natural progression;
   - (ii) Identify the preferred hydrological regime for such a natural progression, in as much as the lake hydrology can be controlled to achieve this end. A review of hydrology from existing similar environments may be helpful;
   - (iii) Carry out a water quality assessment and identify optimum and best-to-avoid conditions for a natural progression regime. Correlate with the flow regime to identify potential exclusion (diversion) periods;
   - (iv) Identify potential impacts of the so defined "natural progression hydrology" on neighbouring agriculture and devise compromising solutions, e.g. construction/modification of ring drains;
   - (v) Identify cultural aspects relevant to the project, and
   - (vi) Identify planning and legal issues relevant to the project.

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CONSULTANT DISCLAIMER

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RDShand

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Senior Coastal Scientist

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APPENDIX A

Survey (cadastral) plans, vertical aerial photographs and satellite images used in this report

Date	Reference	Archive	Supplier
Survey Plans			
1865	ML 5247	LINZ	Quickmap
1872	**SO 10991 (RP 332)**	**LINZ**	**Quickmap**
1889	SO 16923	LINZ	Quickmap
1908	**ML 2039***	**LINZ**	**Quickmap**
1909	SO 15834*	LINZ	Quickmap
1913	**DP 11943**	**LINZ**	**Quickmap**
1921	DP 5396	LINZ	Quickmap
1929	SO 18838	LINZ	Quickmap
1929	**SO 18839***	**LINZ**	**Quickmap**
Vertical aerial photographs and satellite images			
1939	**SN 111**	**NZAM**	**OPUS**
1942	SN 181	NZAM	OPUS
1958	SN 2615	NZAM	Laurie Cairns Ltd
1963	**SN 3410**	**NZAM**	**Archives Central**
1968		NZAM	Laurie Cairns Ltd
1973		NZAM	Laurie Cairns Ltd
1979	**SN 5408**	**NZAM**	**Laurie Cairns Ltd**
1995	SN 12248A	NZAM	Laurie Cairns Ltd
2005#		Digital Globe	Google Earth Pro
2010#		Digital Globe	Google Earth Pro
2011	**SN 50921D**	**NZAM**	**LINZ**
2015#		Digital Globe	Google Earth Pro

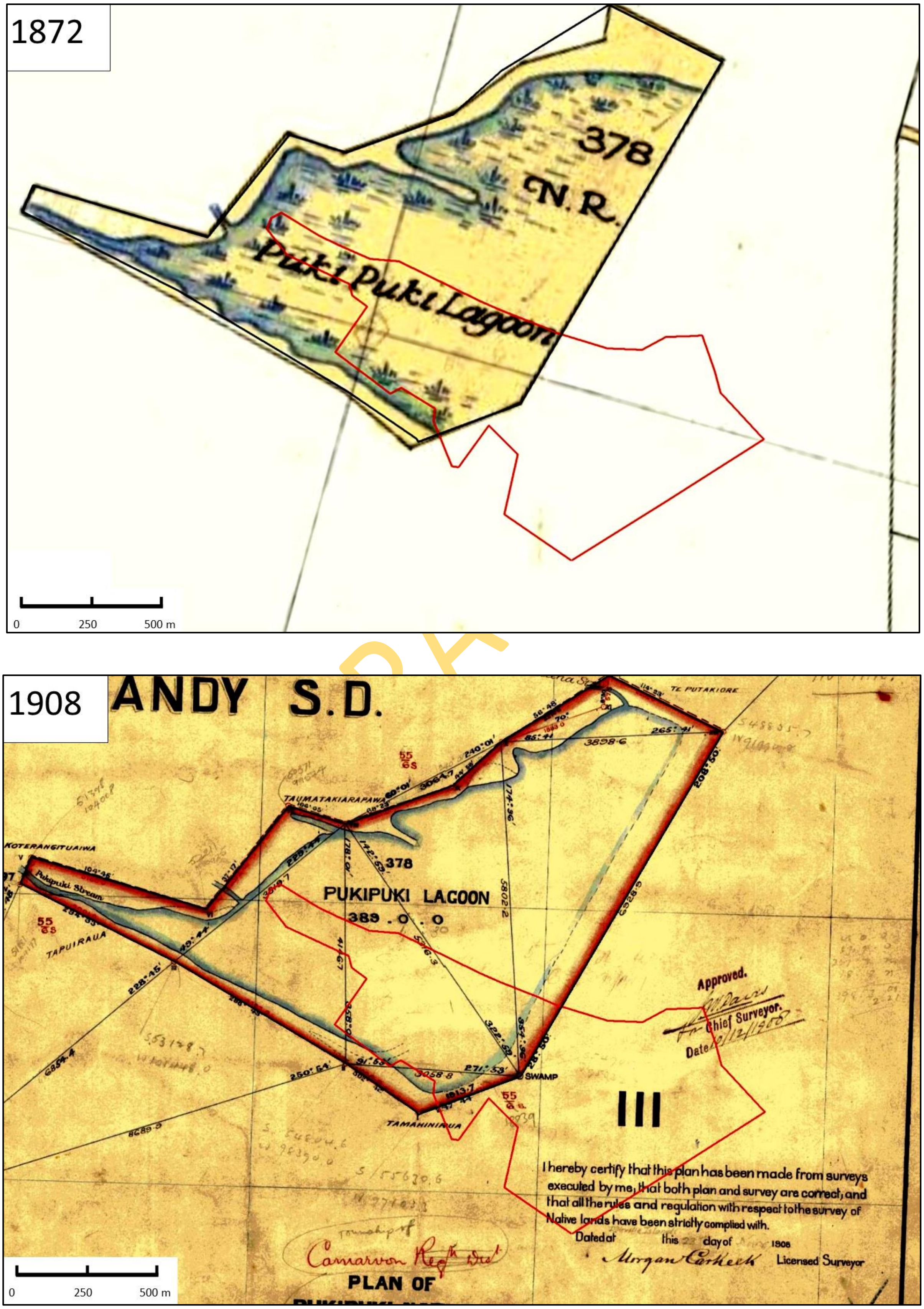
Bold references are reproduced in Appendix B

* Original Field and Traverse book pages (obtained from LINZ) inspected for additional detail

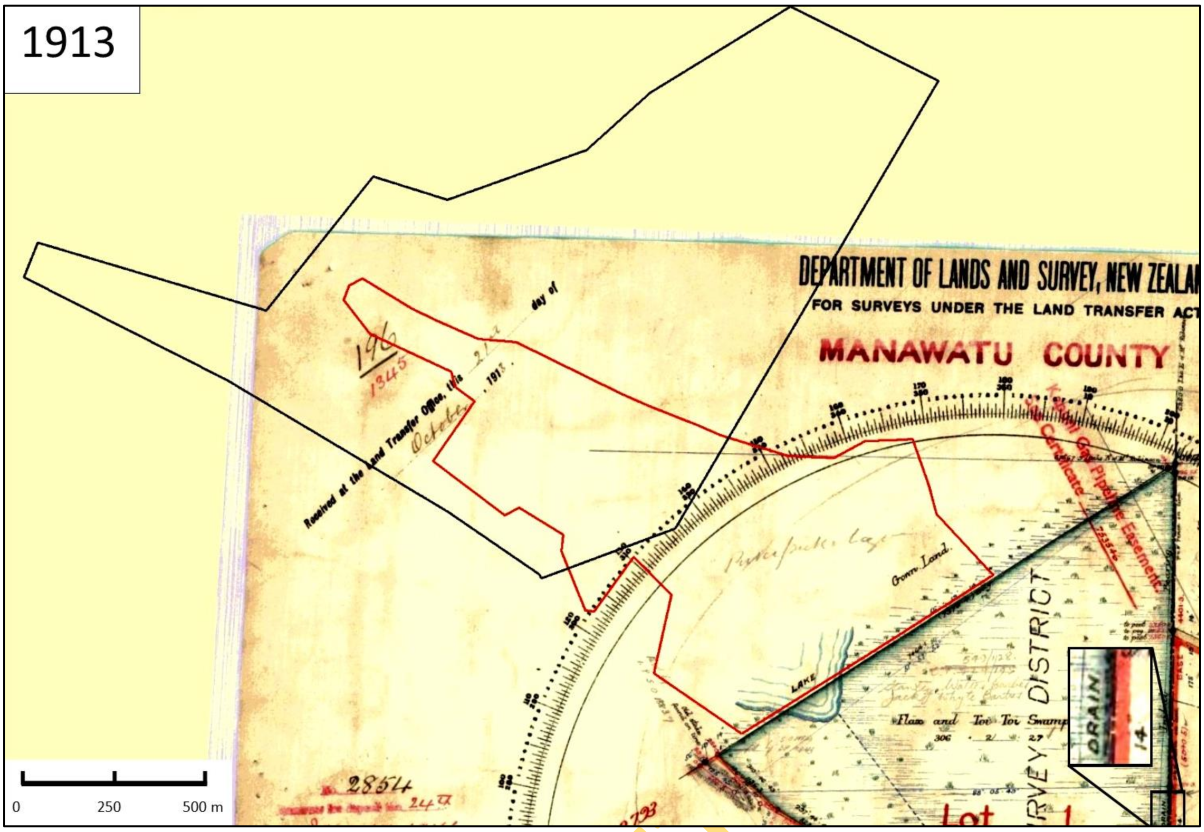
Satellite images

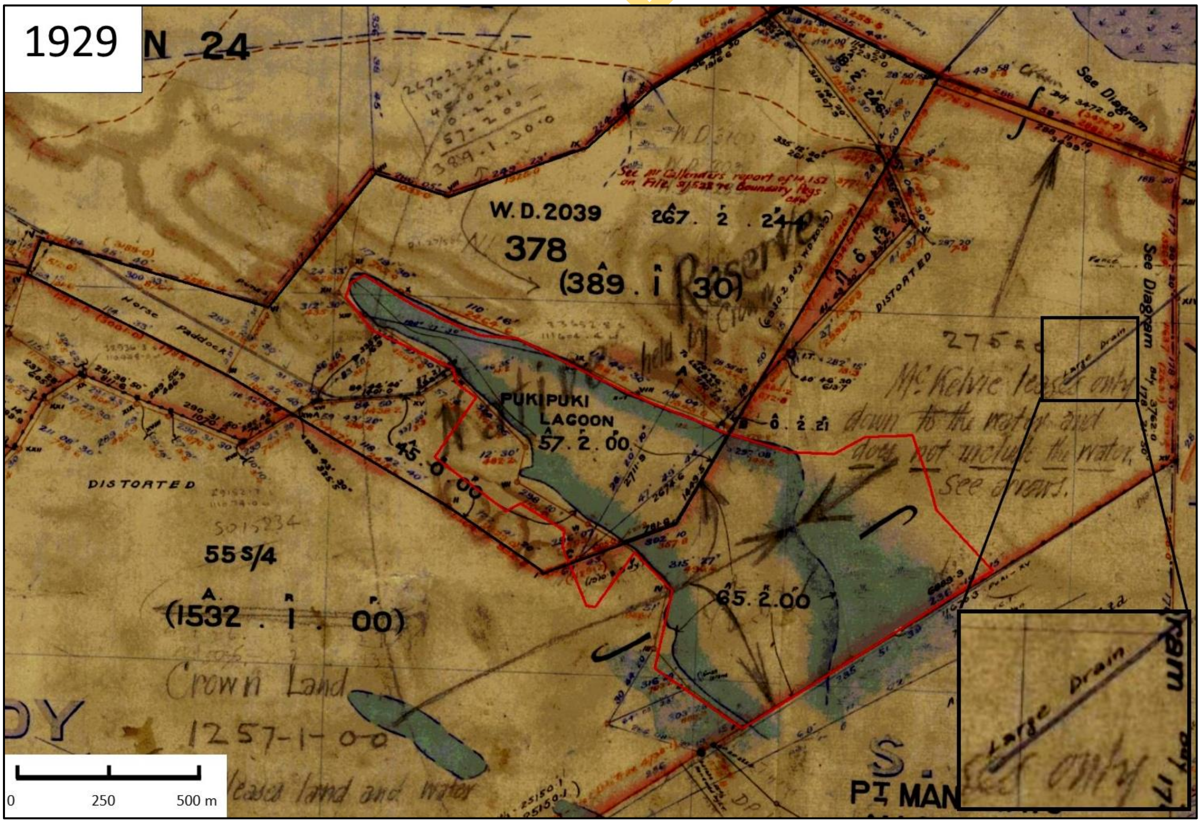
ML = Maori Land plan, SO = Survey Office plan, DP = Deposited plan, SN = serial number

APPENDIX B Key survey plans and aerial photographs used in this report

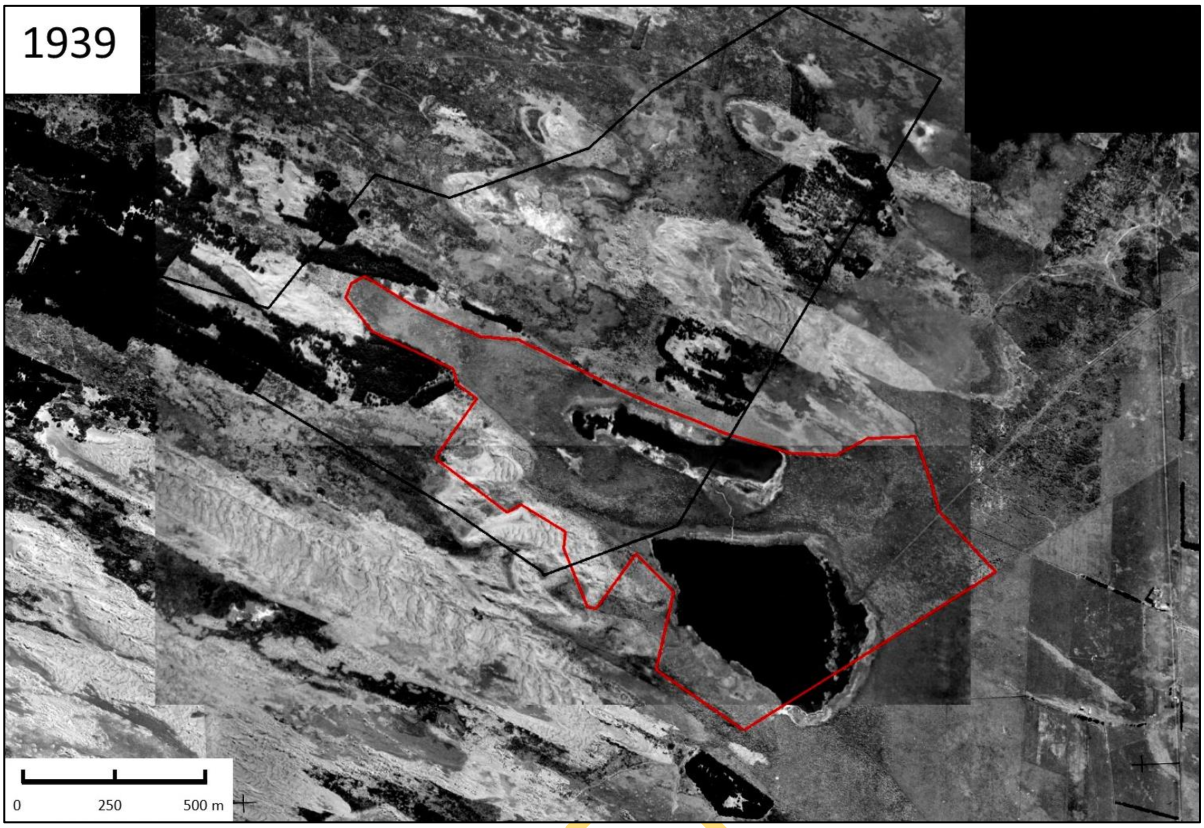


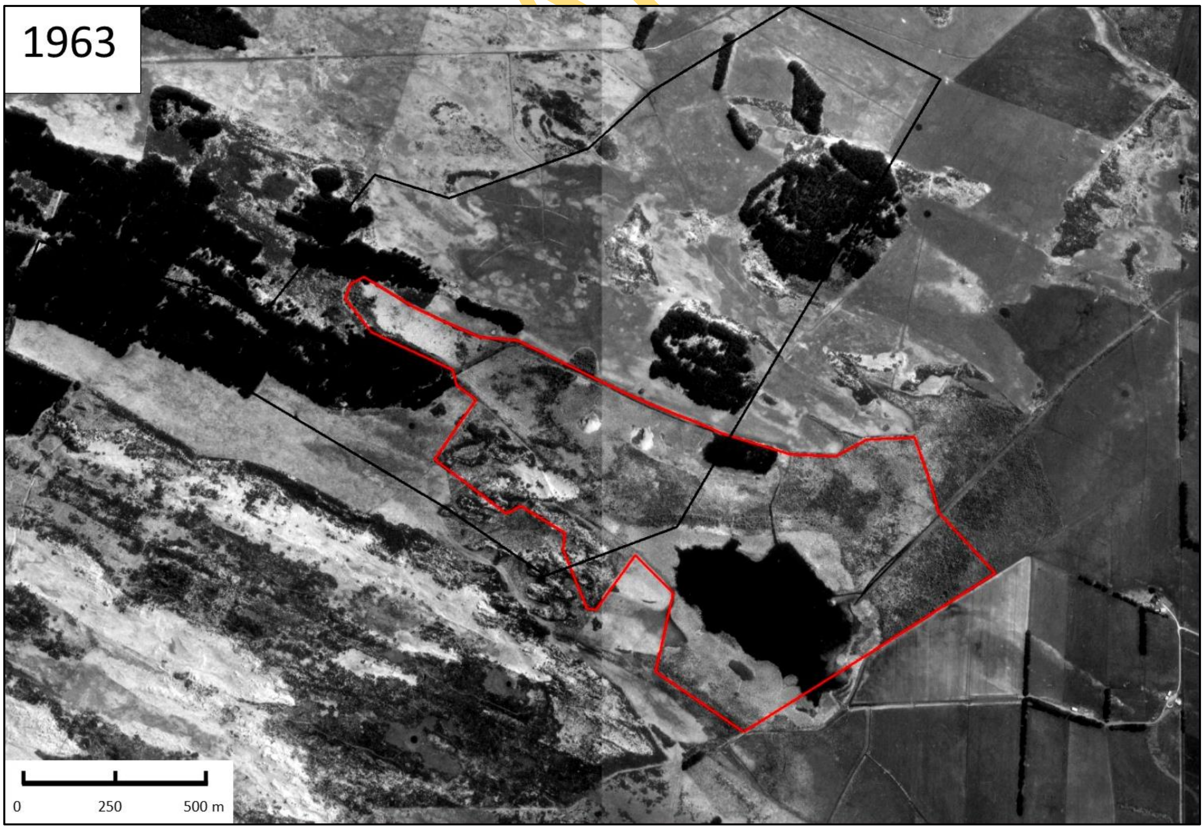
The **black boundary line** defines the original Pukipuki Native Reserve and the **red line** is the current Pukepuke Lagoon Conservation Area boundary.





The **black boundary line** defines the original Pukipuki Native Reserve and the **red line** is the current Pukepuke Lagoon Conservation Area boundary.





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