New Zealand Veterinary Journal

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/tnzv20

Health impacts of poor water quality on an endangered shorebird breeding programme in Aotearoa New Zealand

BD Gartrell, S Hunter, R Collen, M Jolly, K McInnes, A Richardson, C Reed, R Ward & A Pita

To cite this article: BD Gartrell, S Hunter, R Collen, M Jolly, K McInnes, A Richardson, C Reed, R Ward & A Pita (2024) Health impacts of poor water quality on an endangered shorebird breeding programme in Aotearoa New Zealand, New Zealand Veterinary Journal, 72:2, 103-111, DOI: 10.1080/00480169.2023.2263425

To link to this article: https://doi.org/10.1080/00480169.2023.2263425

NEW ZEALAND VETERINARY JOURNAL
2024, VOL. 72, NO. 2, 103–111
https://doi.org/10.1080/00480169.2023.2263425

Taylor & Francis
Taylor & Francis Group

CLINICAL STUDY

Health impacts of poor water quality on an endangered shorebird breeding programme in Aotearoa New Zealand

BD Gartrell [a], S Hunter[a], R Collen[b], M Jolly[a], K McInnes[c], A Richardson[d], C Reed[e], R Ward[f] and A Pita[g]

[a]Wildbase, Tāwharau Ora – School of Veterinary Science, Massey University, Palmerston North, New Zealand; [b]Department of Conservation, Invercargill, New Zealand; [c]Department of Conservation, Wellington, New Zealand; [d]The Isaac Conservation and Wildlife Trust, Harewood, Christchurch, New Zealand; [e]Pūkaha National Wildlife Centre, Mount Bruce, New Zealand; [f]The Cape Sanctuary, Cape Kidnappers, Hawkes Bay, New Zealand; [g]Molecular Epidemiology and Public Health Laboratory, Hopkirk Research Institute, Massey University, Palmerston North, New Zealand

ABSTRACT

Case history: Two clusters of mortality among endangered tūturuatu/tchūriwat'/shore plover (*Thinornis novaeseelandiae*) have occurred at captive breeding facilities around New Zealand in recent years. In the first, four chicks died at Pūkaha National Wildlife Centre (Mount Bruce, NZ) in February 2016, and in the second five adult birds at the Cape Sanctuary (Cape Kidnappers, NZ) died in 2022.

Clinical findings: In 2016, four chicks were noted to become weak, have increased vocalisations and closed eyes prior to death. The remaining chicks were treated for 5 days with amoxycillin/clavulanate orally twice daily. Water containers and brooders were cleaned and disinfected with chlorhexidine. No further mortality was seen.

In the 2022 cluster, three adult breeding birds died acutely and five others showed inappetence, weight loss and diarrhoea approximately 10 days after heavy rains flooded the local river. The five birds were treated with amoxycillin/clavulanate orally twice daily and oral fluids for 5 days. Two birds died and three survived. No breeding occurred in the aviaries in the following season.

Pathological findings: In 2016, the chicks showed pulmonary changes ranging from congestion and oedema to heterophilic inflammation consistent with septicaemia.

In 2022, the adult birds showed proliferation of bacteria in the distal small intestine associated with mucosal ulceration and heterophilic infiltration. Acid-fast staining of the caecal contents in one bird showed organisms consistent with *Cryptosporidium* spp.

Laboratory findings: Aerobic bacterial cultures of the lung and liver of two affected chicks carried out in 2016 showed heavy growth of *Plesiomonas shigelloides*. The same organism was cultured from water trays and holding tanks containing water boatmen (*Sigara arguta*) on which the chicks were fed.

In 2022, cultures from the livers of three dead birds each showed a mixed bacterial growth with differing dominant organisms (*Aeromonas sobria*, *Hafnia alvei*, *Citrobacter freundii* and an *Enterococcus* sp.). PCR and sequencing confirmed *Cryptosporidium parvum* in the caecum of one bird. Fresh faeces from 24 breeding birds from the captive breeding facilities were negative by PCR for *Cryptosporidium* spp.

The captive breeding facilities obtain water for the aviaries and aquatic invertebrates to feed to the chicks from local freshwater sources. Water quality testing at the Cape Sanctuary revealed concentrations of faecal indicator bacteria in excess of safe drinking water guidelines, with peaks following heavy rainfall.

Clinical relevance: Fluctuations in water quality associated with mammalian faecal bacteria can adversely affect bird health and impact on captive rearing of endangered wildlife.

Abbreviations: MPN: Most probable number

ARTICLE HISTORY
Received 12 June 2023
Accepted 11 September 2023
Published online 27 September 2023

KEYWORDS
Avian; cryptosporidiosis; endangered species; faecal bacteria; gastroenteritis

Introduction

The tūturuatu/tchūriwat'/shore plover (*Thinornis novaeseelandiae*) is a critically endangered shore bird endemic to New Zealand (Dowding and O'Connor 2013; Robertson *et al.* 2021). It was once widespread throughout coastal New Zealand but by the 1800s was restricted to the Chatham Islands due to the species' high susceptibility to avian and mammalian predation (Dowding and O'Connor 2013). At the population's lowest ebb there was one wild breeding population remaining on Rangatira Island and 21 birds on Western Reef off the coast of Chatham Island, since extirpated. Due to the very small population size and limited distribution of the species, a predator irruption

CONTACT BD Gartrell B.Gartrell@massey.ac.nz

on the Chatham Islands would put the species at serious risk of extinction, and considerable effort has been put into the establishment of insurance populations. Initial attempts to establish offshore island populations using wild bird translocations were unsuccessful, primarily due to dispersal (Aikman 1999; Dowding and O'Connor 2013). A captive breeding population, established in the 1980s using eggs from Rangatira Island, has had good breeding success. Over 500 captive-bred juveniles have since been released on predator-free islands around New Zealand to establish new populations (Dowding and O'Connor 2013; Dowding 2022). These populations can only exist on predator-free islands, and in recent years several well-established populations have been lost or severely reduced when rat (*Rattus* spp.) or stoat (*Mustela erminea*) incursions (usually only a single animal) have occurred, or as a result of avian predation, primarily by the karoro/southern black-backed gull (*Larus dominicanus*), ruru/morepork (*Ninox novaeseelandiae*) or kāhu/swamp harrier (*Circus approximans*) (Dowding 2022). Currently there are three captive breeding populations of tūturuatu; at the Isaac Conservation and Wildlife Trust in Christchurch, Pūkaha National Wildlife Centre at Mount Bruce near Masterton, and the Cape Sanctuary at Cape Kidnappers near Napier. The total population in 2023, including both wild and captive birds, is 280 adult birds.

The captive population of tūturuatu has a high incidence of avian poxvirus affecting young birds (Gartrell *et al.* 2002; Alley and Gartrell 2019) suspected to be due to a high degree of genetic bottlenecking resulting from the rapid species decline and the establishment of the captive population initially from only a few translocations. These two factors have resulted in low overall toll-like receptor gene diversity, and genetic differentiation of captive and wild tūturuatu (Magid *et al.* 2022). The captive breeding programme has had to adapt to manage this disease, with young birds being reared initially indoors, and then in mosquito proof aviaries.

The captive management of tūturuatu is similar across all three sites as outlined in a husbandry manual (Collen 2019), and the number of breeding pairs held at each facility changes between years in order to manage the breeding programme. Adult breeding pairs of tūturuatu are held in outdoor aviaries with freshwater streams diverted from natural water sources (Figure 1). Egg-laying can occur from October to January (Dowding 2022) with productive pairs producing up to three clutches of 2–3 eggs per year. To promote increased productivity, clutches of eggs are removed from parents at 15–25 days of incubation, which stimulates laying of replacement clutches. Clutches are then artificially incubated and hand-reared in indoor brooders (Figure 1) in clutch

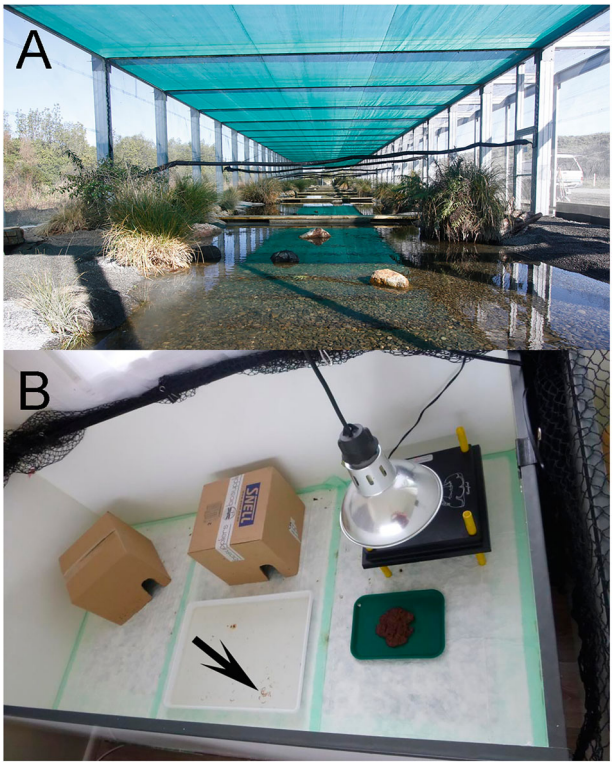

Figure 1. Photographs of facilities at Isaac Conservation and Wildlife Trust (Christchurch, NZ) which are typical of those for captive management of tūturuatu at all three facilities. A) aviaries with internal dividers lifted for cleaning, showing the flow of water and shingle substrate. B) Brooder set-up for the rearing of neonatal tūturuatu, showing heat lamp, brooding pad, shelter boxes, food tray and water tray with aquatic invertebrates (arrow).

groups, and are provided with supplemental heat, shelter, and food placed in trays with salt water to prevent pododermatitis. Chicks usually start feeding on live aquatic invertebrates collected from local freshwater streams within their first 1–2 days of life and gradually move on to an artificial diet of minced ox heart mixed 50:50 with an insectivore diet (Collen 2019).

All three captive breeding facilities for tūturuatu source water for the breeding aviaries from local freshwater streams or rivers. River water quality in New Zealand is affected by widespread diffuse pollution from developed land, particularly pastoral agriculture, with fine sediment causing reduced visual clarity, faecal microbial contamination, and nutrient enrichment (Davies-Colley 2013). River water quality depends strongly on flow state, and even rivers of "good" water quality are typically turbid and faecally polluted in stormflows. Grazing of livestock (on 40% of New Zealand's land area) mobilises all three major categories of diffuse pollutant, with the result that rivers draining pastoral catchments are moderately degraded (Davies-Colley 2013; Larned *et al.* 2016, 2020). Pathogens capable of causing gastroenteritis and other disease are also common. Phiri *et al.* (2020) showed that environmental drivers of microbe

abundance or presence/absence differed depending on whether the microbe was protozoan or bacterial. Protozoa were more prevalent in waterways with lower water quality, higher numbers of ruminants in the catchment area, and in September and December. Bacteria were more abundant with higher rainfall, saturated soils, and catchments with > 35% of the land in agriculture (Phiri *et al.* 2020).

Here we document two clusters of mortality in tūturuatu associated with water quality issues at two of these facilities, the first in chicks in 2016 and the second in adult breeding birds in 2022.

Cluster 1. Chicks at Pūkaha National Wildlife Centre

Case history and clinical findings

In the first cluster of mortality in February 2016, four chicks from two clutches being hand-reared at Pūkaha National Wildlife Centre were noted to become weak, with increased vocalisations and closed eyes. The birds showed a short period (48–72 hours) of lethargy, inappetence and weakness prior to death.

There had been no changes to the usual husbandry or to the substrate of rubber tubing and non-slip mats. Chicks from the two affected clutches were housed in separate brooders in the same room. Weather conditions in February 2016 were affected by El Niño patterns resulting in humid conditions across the North Island and an exceptionally warm month as recorded in nearby Masterton (mean maximum temperature 27.8°C), but with only 5 days of rain and a total of 16 mm of rainfall for the month (NIWA 2016).

One surviving bird from a clutch of three was transferred to Wildbase Hospital (Massey University, Palmerston North, NZ) where it was treated with 125 mg/kg amoxycillin/clavulanate (Clavulox palatable drops; Zoetis, Auckland, NZ) orally twice daily for 5 days. This bird ate well and continued to gain weight (14 g on admission to 16 g on discharge) and was discharged back to the breeding facility after 6 days of hospitalisation.

The water containers and brooders at Pūkaha National Wildlife Centre were cleaned and disinfected with chlorhexidine. Water boatmen (*Sigara arguta*) were flushed through three changes of bottled water before being fed out. No further mortality was seen.

Pathological findings

Post-mortem examination was carried out on four chicks. The chicks weighed ~6 grams and there were no obvious gross abnormalities. Histopathological examination of the first two birds to die showed moderate congestion in the lungs, with low-to-moderate numbers of parabronchi and adjacent air-capillaries containing proteinaceous fluid. In the intestine, sections contained either large amounts of bacteria and/or mineralised yolk material within lumina without an associated inflammatory response. In the remaining two birds, melaena was present in the intestinal contents. Histopathological examination showed moderate-to-marked pulmonary congestion and the pulmonary interstitium was moderately hypercellular due to the presence of increased numbers of heterophils and fewer mononuclear cells consistent with septicaemia. Within the heart of one bird, multiple small blood vessels contained short, rod-shaped Gram-negative bacteria. In these later deaths, the intestinal mucosa was generally too autolysed to critically interpret.

Microbiology

Samples of liver and lung from two birds were submitted to IDEXX Laboratories (Palmerston North, NZ) for aerobic bacterial culture. This showed heavy growths of *Plesiomonas shigelloides*. Environmental samples were collected from the water sources available to the chicks, namely the trays containing water boatmen in the chick brooders, and from the water in which the water boatmen were kept after they were collected from the local stream. Aerobic culture of these samples isolated the same organism.

Cluster 2. Adult birds at the Cape Sanctuary

Case history and clinical findings

In the second mortality cluster in 2022, three adult breeding birds at the Cape Sanctuary died acutely and five others showed inappetence, weight loss and diarrhoea approximately 10 days after heavy rains flooded the local river. Nine remaining birds were either removed from aviaries and placed into brooders (four birds) or left in the aviaries after cleaning and disinfection (five birds). All birds were treated with 125 mg/kg amoxycillin/clavulanate (Clavulox palatable drops; Zoetis) orally twice daily in mealworms (*Tenebrio molitor*).

The five birds that showed continuing signs of diarrhoea and fluffed plumage were transferred to Wildbase Hospital. On arrival the birds were low in body weight (mean 46.9 (min 42, max 53) g; species normal mean 61 g; Dowding 2022). Three of five birds showed matting of the vent with urates and faecal matter. The faeces were brown, soft and voluminous with a normal white urate component. Blood samples were taken from three birds on day 2 of hospitalisation for haematology (Table 1) and plasma biochemical analysis (Table 2). Two birds were mildly anaemic and borderline hypoproteinaemic. Two had

Table 1. Haematology results from adult tūturuatu (*Thinornis novaeseelandiae*) (n = 3) hospitalised with bacterial gastroenteritis following a flood event at Cape Sanctuary (Cape Kidnappers, NZ) in 2022.

	Reference ranges			Bird A		Bird B		Bird C
Analyte	CM[a]	SCD[b]	VI[c]	Day 2	Day 7	Day 2	Day 7	Day 2
PCV (%)	49.1	45–56	38–59	48	48	35[d]	46	34[d]
TP (g/L)	45	28–45	25–46	41	38	26[d]	42	30[d]
WBCC (x 10^9 cells/L)	3.8	3–10	4.3–20.2	14.8	7.6	4.8	7.8	7.5
Heterophils (x 10^9 cells/L)	1.468	1.5–8	4.2–9.5	9.8	5.17	1.6	5.5	2.5
Lymphocytes (x 10^9 cells/L)	1.514	0.6–4.5	2.8–7.6	4.3	2.1	2.8	1.56	4.8
Monocytes (x 10^9 cells/L)	0.175	0–0.1	0.02–1.0	0.7	0.2	0	0.5	0.15
Eosinophils (x 10^9 cells/L)	0.566	0–0.2	0–0.9	0	0.07	0	0	0
Basophils (x 10^9 cells/L)	0.132	0–0.1	0–0.8	0	0	0	0	0

[a]Reference ranges (means only) for the piping plover (*Charadrius melodus*; Ball 2003).
[b]Reference ranges for the canary (*Serinus canaria domestica*; Carpenter and Marion 2018).
[c]Reference ranges for the red-wattled lapwing (*Vanellus indicus*; Umar *et al.* 2016).
[d]Results considered clinically significant.
PCV = packed cell volume; TP = total plasma protein; WBCC = estimated total white blood cell count.

Table 2. Plasma biochemistry results from adult tūturuatu (*Thinornis novaeseelandiae*) (n = 3) hospitalised with bacterial gastroenteritis following a flood event at Cape Sanctuary (Cape Kidnappers, NZ) in 2022.

	Reference ranges					
Analyte	CM[a]	SCD[b]	VI[c]	Bird A	Bird B	Bird C
Aspartate aminotransferase (IU/L)	412	14–345	138–603	316	372	379
Bile acids (µmol/L)	ND	23–90	ND	< 35	< 35	< 35
Creatine kinase (IU/L)	ND	55–350	376–1623	1601[d]	1914[d]	641
Uric acid (µmol/L)	291	238–717	146–666	1315[d]	815[d]	451
Glucose (mmol/L)	19.9	11.38–24.14	6.66–16.37	19.7	21.2	25.8
Calcium (mmol/L)	2.74	1.37–3.37	1.32–3.22	2.3	2.11	2.37
Phosphate (mmol/L)	ND	0.94–1.58	0.79–2.42	2.02[d]	1.25	0.96
Potassium (mmol/L)	ND	2.2–4.5	ND	2.4[d]	3.7	2.1[d]
Sodium (mmol/L)	ND	135–165	ND	158	149	155

[a]Reference range (means only) for the piping plover (*Charadrius melodus*; Ball 2003).
[b]Reference range for the canary (*Serinus canaria domestica*; Carpenter and Marion 2018).
[c]Reference range for the red-wattled lapwing (*Vanellus indicus*; Umar *et al.* 2016).
[d]Results considered clinically significant.
ND = not done.

either moderate or marked hyperuricaemia and hypokalaemia while another bird showed hypokalaemia only.

The hospitalised birds were housed in individual pens, and treatment with 125 mg/kg amoxycillin/clavulanate orally twice daily was continued, with the addition of oral fluids using compound sodium lactate solution (Hartmanns; Baxter Healthcare, Auckland, NZ) at 50 mL/kg twice daily. The birds were fed their usual diet of beef mince mixed 50:50 with an insectivore diet (Insectivore Rearing Mix; Wombaroo) supplemented with meal worms. Four of five birds started gaining weight well on this treatment regime; however, one bird had persistently low weight and died after 10 days of hospitalisation. The remaining birds were treated for 16 days in total with antibiotics. Once this treatment had ceased, one bird died unexpectedly after 22 days of hospitalisation. The three surviving birds gained weight (mean 58 (min 57, max 60) g) and were discharged back to the captive rearing facility after 33 days of hospitalisation.

Following discharge, the birds remained well but no breeding activity was seen in the subsequent season. The breeding aviaries at the Cape Sanctuary suffered a further setback in February 2023 with severe flooding due to Cyclone Gabrielle and the drowning of four adult breeding birds including one of the previously hospitalised birds. At this time, the rapid removal of the nine surviving birds into brooders, and prophylactic treatment with amoxycillin/clavulanate was successful in preventing signs of illness despite the birds being exposed to concentrations of *Escherichia coli* (detected by the most probable number (MPN) method) up to 133,000 MPN/100 mL and enterococci up to 46,000 MPN/100 mL after Cyclone Gabrielle.

Pathological findings

Post-mortem examination was carried out on the five birds that died. Reddening of the lungs and mild hepatomegaly were evident on gross examination. On histological examination, all birds showed proliferation of large numbers of Gram-positive cocci and rod-shaped bacteria in the distal small intestine. This was associated with foci of mucosal ulceration and replacement with a thin layer of necrotic debris admixed with Gram-positive cocci and heterophilic infiltration of the subjacent lamina propria (Figure 2). Acid-fast staining of the caecal contents of one of the birds that died in hospital showed organisms consistent in morphology with *Cryptosporidium* spp.

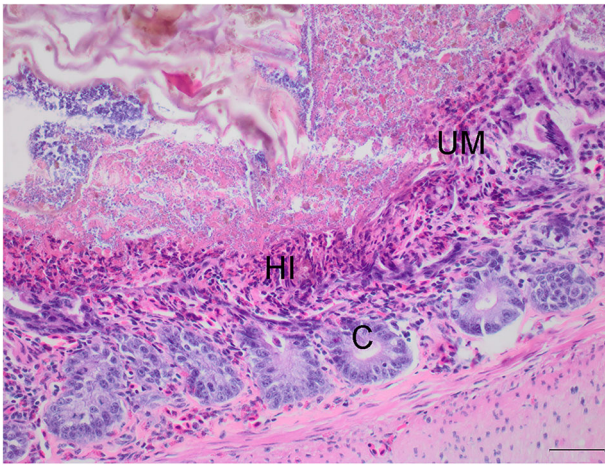

Figure 2. Histology of the distal small intestine of an adult tūturuatu showing the margin of a foci of mucosal ulceration (UM) and replacement with a thin layer of necrotic debris admixed with cocci and heterophilic infiltration (HI) of the subjacent lamina propria. The intestinal crypts (C) are unaffected (H&E; bar = 20 µm).

Laboratory findings

Samples from the liver of three dead birds were submitted to IDEXX Laboratories (Palmerston North, NZ) for aerobic bacterial culture. Each showed mixed growth with differing dominant organisms (*Aeromonas sobria*, *Hafnia alvei*, *Citrobacter freundii* and an *Enterococcus* sp.).

The caecal contents from the bird in which the *Cryptosporidium*-like organisms were observed was tested for *Cryptosporidium* spp. at the Hopkirk Research Institute (Massey University, Palmerston North, NZ). DNA was extracted using Quick-DNA Fecal/Soil Microbe Kits (Zymo Research, Irvine, CA, USA) following the manufacturer's instructions, after physical disruption of the oocyst using a beadbeater (Tissue Lyser II; Qiagen, Venlo, Netherlands) at 30 Hz for 5 minutes. DNA was subjected to PCR to amplify a fragment of the gp60 gene using a combination of external and internal primers (Glaberman *et al.* 2002; Waldron *et al.* 2011) specific for *Cryptosporidium* spp. Positive (human-derived *C. parvum*) and negative (nuclease-free water) controls were included in each PCR run. Amplicons were sequenced in both directions using Big Dye Terminator version 3.1 reagents and an ABI 3730XL automated DNA sequencer (Applied Biosystems, Foster City, CA, USA). Comparison of the resulting sequence with those in nucleotide databases using BLAST (http://www.ncbi.nlm.nih.gov/blast/) identified the organism as *C. parvum* (99.44% identity, accession number JQ362496).

Faecal samples were collected from 24 healthy captive breeding birds across all three captive breeding facilities and tested for *C. parvum* as described above. None of the faecal samples from the healthy birds were positive for *Cryptosporidium* spp.

At the Cape Sanctuary, water quality testing (Water Testing Hawkes Bay Laboratory, Hastings, NZ) was carried out at the pump inlet in the river and in the aviaries over a period of 69 days, commencing 3 days after the deaths of the adult breeding birds in 2022. The parameters measured included faecal indicator bacteria: *E.coli*; and *Enterococcus* spp. (Figure 3). Initially nitrates and nitrites were also measured (nitrate N 0.847 g/m^3 and nitrite N 0.0033 g/m^3), but this was not continued as the concentrations found were considered to be low in New Zealand freshwater systems (Ministry for the Environment 2020). The levels of faecal indicator bacteria in the river and aviaries were well in excess of safe drinking water guidelines (*E. coli* < 1 MPN/100 mL) and in the worst attribute

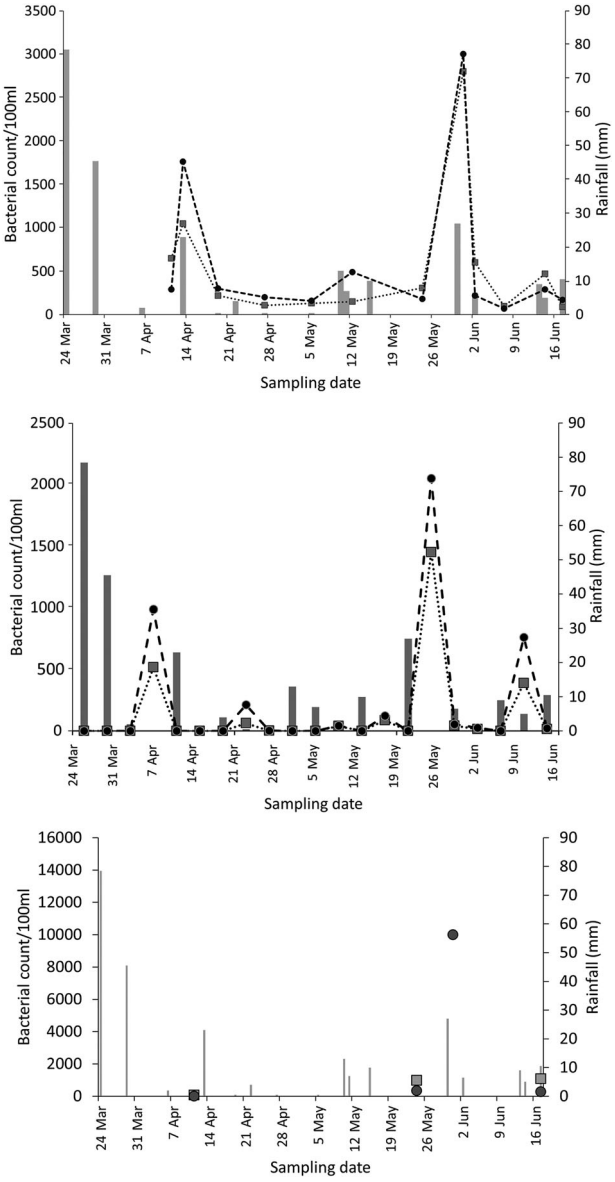

Figure 3. Composite graphs showing rainfall (in mm; grey bars) and bacterial counts (per 100 mL) of *Escherichia coli* (squares with dotted line) and *Enterococcus* spp. (circles with dashed line) in water sampled from the pump inlet from the river (top) from which freshwater for the facility was drawn, the open mesh aviary (middle), and the mosquito-proof aviaries (bottom) at the Cape Sanctuary (Cape Kidnappers, NZ) over 69 days commencing 3 days after the death of three adult tūturuatu.

band (E (red): 50% of samples > 540 MPN/100 mL) of the freshwater management guidelines (Ministry for the Environment 2020) during the period of monitoring, with noticeable peaks following heavy rainfall.

Additional key findings were that: after a large flood event, the concentrations of faecal indicator bacteria returned to ~100 cfu/mL after approximately 1 month; after a single night of heavy rain, concentrations of faecal indicator bacteria spiked quickly and returned to normal within 1 week; and after light rain overnight, concentrations of faecal indicator bacteria spiked but returned to normal after 2–3 days. Water flow in the breeding aviaries at the Cape Sanctuary is restricted to 6–8 hours per day in the mesh aviaries and 1–2 hours per day in the insect proof aviaries, and the remainder of the time the water sits still in shallow pools. Unexpectedly, the still water in the mesh aviaries had a much lower concentration of faecal indicator bacteria (after sitting for a while) than water at the pump inlet, while still water in the mosquito-proof aviaries had a higher concentration. We hypothesise that this reduction in microbial concentration in the mesh aviaries is due to solar disinfection (Gandhi and Prakash 2023), and that the netting in the mosquito-proof aviaries reduces ultraviolet light reaching the water.

Discussion

The pathogens involved in these two mortality clusters represent a diversity of organisms associated with poor water quality. *P. shigelloides*, the pathogen implicated in the chick mortality cluster, is a known global pathogen of freshwater fish (Janda *et al.* 2016; Fuentes-Valencia *et al.* 2022) but is also emerging as a cause of gastroenteritis and, rarely, septicaemic disease in people (Janda *et al.* 2016; Ekundayo *et al.* 2023). The main risk factors for infection in people is the ingestion of contaminated water or uncooked shellfish (Janda *et al.* 2016). The concentration of *P. shigelloides* in river water is highly associated with mammalian faecal contamination (Janda *et al.* 2016), and concentrations increase with rising water temperature (Janda *et al.* 2016; Ekundayo *et al.* 2023). This suggests that the tūturuatu chicks may have ingested the pathogen through contaminated water and water invertebrates, with the warm temperatures of the brooder environment potentially increasing bacterial multiplication in the feeding trays prior to ingestion.

For the adult mortality cluster, no single pathogen was isolated; instead, the range of bacterial species and the single case of *Cryptosporidium parvum* isolated from the affected tūturuatu are consistent with overwhelming exposure to water heavily contaminated with mammalian faeces, presumably from local livestock farms (Phiri *et al.* 2020, 2021). It is likely that the single case of cryptosporidiosis is an isolated spillover event possibly associated with co-infection with bacterial pathogens. This is supported by our wider survey of the breeding population of tūturuatu where no further *Cryptosporidium* spp. were detected.

Rather than focusing on specific pathogens, these two mortality clusters in the tūturuatu breeding programme highlight a wider problem with freshwater quality, with implications for both captive and free-living animals in New Zealand. In particular, the exposure of wild birds to mammalian faecal pathogens has implications for their health, but also for the carriage and wider dissemination of these pathogens (Smith *et al.* 2020), and the emergence and spread of antimicrobial resistance (Carroll *et al.* 2015; Ekundayo and Okoh 2020). We acknowledge that the measures of freshwater quality used in this study are rudimentary, and that more advanced tools such as genome sequencing (Devane *et al.* 2020), targeted microarrays (Dubinsky *et al.* 2016), and machine learning algorithms (Dubinsky *et al.* 2016; Ekundayo *et al.* 2023) can be used to explore sources of faecal indicator bacteria more accurately in freshwater systems. In relation to this study, the sources of the contamination are less important than mitigating its impacts. Further study is required to investigate these questions in the New Zealand context, so the remainder of this discussion will focus on the implications of using freshwater sources for the management of captive wildlife.

The provision of water that is clean and safe for drinking and bathing is a basic requirement of animal husbandry, especially for zoological species (Reiss and Woods 2011). In urban facilities, the use of a treated and monitored municipal water supply is a safe and effective method of ensuring water quality. However, for facilities that need to use local freshwater sources, this is much more problematic. Ideally, each zoological facility should regularly monitor freshwater quality for disease agents and contaminants, and treat as appropriate to meet standards suitable for equivalent livestock consumption (Reiss and Woods 2011). However, this is complicated with the management of shorebird and aquatic species, where water courses are necessary for birds to display a range of natural behaviours, including foraging and grooming (Collen 2019). It may also be inadvisable to set the threshold for water quality to be equivalent to mammalian livestock for a critically endangered bird species.

Monitoring of water quality is an expensive but vital tool for zoological facilities that source water from outside a municipal system. Regional councils and private laboratories offer a range of water quality testing, and the tūturuatu captive management group have instituted regular testing of faecal indicator bacteria in all facilities and less regular monitoring of nitrites, nitrates and heavy metals. Publicly available information on monitored freshwater rivers is available through the Land Air Water Aotearoa (LAWA)

collaboration, but this information is most useful for reporting long-term trends in water quality, rather than real-time fluctuations (LAWA 2023). As was demonstrated in the adult mortality cluster, having early access to water quality results can enable proactive management to protect animal health.

In practical terms, managing water quality in facilities that do not use a municipal water supply is often constrained by the facility's finances. Within the facilities, water quality can be improved by the use of interceptor-collector systems, such as sand traps to remove organic matter and particle filters (Merchán-Sanmartin *et al.* 2022). Ultraviolet filters are commercially available and are effective in reducing pathogen counts (Schiavano *et al.* 2018; de Boer *et al.* 2022). We consider chemical disinfection methods, such as chlorination, to be inappropriate for the captive management of tūturuatu due to the risks associated with the formation of disinfection by-products (Suarez *et al.* 2022; Sikder *et al.* 2023), but if the microbial contamination of the rivers cannot be reduced with other methods, then the use of chemical disinfection will need to be reviewed.

On the basis of the freshwater monitoring data, the following management guidelines were set in place for the Cape Sanctuary tūturuatu breeding facility. In the event of heavy rainfall, prior to the local river flooding, the intake of water for the aviaries is switched off and no new water is brought into the aviaries until the river has lowered to normal levels, river water colour has cleared, the pump and sump have been cleared and cleaned and debris/silt removed, and the water in the source river has been tested and faecal indicator bacteria concentrations have reduced to < 200 cfu/100 mL. In the event that contaminated floodwater/silt enters the aviary before the water intake is switched off, decisions on managing the situation will be in consultation with veterinary staff. Options include maintaining the birds in the aviary with/without medication (depending on the results of water testing); running contaminated water through the ponds to clear silt then leaving it to sit and solar-disinfect; bail out or salting the ponds and providing water bowls containing bottled water; or moving the birds into brooders if the contamination level is too high.

Water testing following smaller rainfall events (minor river rise, some water discolouration) indicates that stream clarity correlates well with concentrations of faecal indicator bacteria < 200 cfu/100 mL. Due to the high cost of repeated testing after every rainfall event, the facility has chosen to only test water quality after a larger flood events (brown water and water level raised by 0.5 m) and rely on clarity checks by trained staff for small rainfall events.

These protocols will only have a limited effect on mitigating freshwater contamination and, in the longer term, improving freshwater quality in the water courses that supply these aviaries is essential. Members of the tūturuatu captive management team have been working with landholders in the water catchment areas to support riparian planting of streams and fencing to exclude livestock (McKergow *et al.* 2016; Daigneault *et al.* 2017). However, our results indicate that heavy rainfall can overwhelm these barriers and result in the large-scale movement of mammalian faecal pollution into rivers and streams. It is important to note that heavy rainfall events are predicted to increase in frequency with climate change (Ministry for the Environment 2018). Widescale improvements in freshwater quality are likely to require the restoration of natural infrastructure such as reforestation and in particular the restoration of wetlands along water courses (Kurki-Fox *et al.* 2022). Without substantial improvement in freshwater quality, the viability of the tūturuatu breeding programme in its current locations will need to be reconsidered.

Acknowledgements

We acknowledge the work and support of the tūturuatu recovery team, tangata whenua, the Department of Conservation, and the staff at the three captive facilities; the Isaac Conservation and Wildlife Trust, Pūkaha National Wildlife Centre and the Cape Sanctuary.

Disclosure statement

No potential conflict of interest was reported by the authors.

ORCID

BD Gartrell http://orcid.org/0000-0002-8062-9313

References

Aikman H. Attempts to establish shore plover (*Thinornis novaeseelandiae*) on Motuora Island, Hauraki Gulf. *Notornis* 46, 195–205, 1999

Alley MR, Gartrell BD. Wildlife diseases in New Zealand: recent findings and future challenges. *New Zealand Veterinary Journal* 67, 1–11, 2019. https://doi.org/10.1080/00480169.2018.1520656

*__Ball RL.__ Charadriiformes (Gulls, Shorebirds). In: Fowler ME, Miller ER (eds). *Zoo and Wild Animal Medicine*. Fifth Edition. Pp 136–41. Elsevier, St Louis, MO, USA, 2003

*__Carpenter JW, Marion CJ.__ *Exotic Animal Formulary*. Fifth Edtn. Pp 167–375. Elsevier, St Louis, MO, USA, 2018

Carroll D, Wang J, Fanning S, McMahon BJ. Antimicrobial resistance in wildlife: implications for public health. *Zoonoses and Public Health* 62, 534–42, 2015. https://doi.org/10.1111/zph.12182

*__Collen R.__ *Shore plover (Thinornis novaeseelandiae) husbandry manual (Version 2.1)*. Department of Conservation, Wellington, NZ, 2019

Daigneault AJ, Eppink FV, Lee WG. A national riparian restoration programme in New Zealand: is it value for money? *Journal of Environmental Management* 187, 166–77, 2017. https://doi.org/10.1016/j.jenvman.2016.11.013

*Davies-Colley R. River water quality in New Zealand: an introduction and overview. In: Dymond JR (ed). *Ecosystem Services in New Zealand – Conditions and Trends*. Pp 432–47. Manaaki Whenua Press, Lincoln, NZ, 2013

de Boer S, González-Rodríguez J, Conde JJ, Moreira MT. Benchmarking tertiary water treatments for the removal of micropollutants and pathogens based on operational and sustainability criteria. *Journal of Water Process Engineering* 46, 102587, 2022. https://doi.org/10.1016/j.jwpe.2022.102587

Devane ML, Moriarty E, Weaver L, Cookson A, Gilpin B. Fecal indicator bacteria from environmental sources; strategies for identification to improve water quality monitoring. *Water Research* 185, 116204, 2020. https://doi.org/10.1016/j.watres.2020.116204

*Dowding JE. *Shore plover | tuturuatu*. https://nzbirdsonline.org.nz/species/shore-plover (accessed 29 August 2023). New Zealand Birds Online, Wellington, NZ, 2022.

Dowding JE, O'Connor SM. Reducing the risk of extinction of a globally threatened shorebird: translocations of the shore plover (*Thinornis novaeseelandiae*), 1990–2012. *Notornis* 60, 70–84, 2013

Dubinsky EA, Butkus SR, Andersen GL. Microbial source tracking in impaired watersheds using PhyloChip and machine-learning classification. *Water Research* 105, 56–64, 2016. https://doi.org/10.1016/j.watres.2016.08.035

Ekundayo TC, Okoh AI. Antimicrobial resistance in freshwater *Plesiomonas shigelloides* isolates: implications for environmental pollution and risk assessment. *Environmental Pollution* 257, 113493, 2020. https://doi.org/10.1016/j.envpol.2019.113493

Ekundayo TC, Ijabadeniyi OA, Igbinosa EO, Okoh AI. Using machine learning models to predict the effects of seasonal fluxes on *Plesiomonas shigelloides* population density. *Environmental Pollution* 317, 120734, 2023. https://doi.org/10.1016/j.envpol.2022.120734

Fuentes-Valencia MA, Osornio-Esquivel JL, Martínez Palacios CA, Contreras-Ávila JL, Barriga-Tovar E, la Mora GID, Arellano-Torres A, Baizabal-Aguirre VM, Bravo-Patiño A, Cajero-Juárez M, *et al.* Bacterial and parasite co-infection in Mexican golden trout (*Oncorhynchus chrysogaster*) by *Aeromonas bestiarum*, *Aeromonas sobria*, *Plesiomonas shigelloides* and *Ichthyobodo necator*. *BMC Veterinary Research* 18, 137, 2022. https://doi.org/10.1186/s12917-022-03208-5

Gandhi J, Prakash H. Photo-disinfection processes for bacterial inactivation and underlying principles for water constituents' impact: a review. *Chemical Engineering Journal Advances* 14, 100482, 2023. https://doi.org/10.1016/j.ceja.2023.100482

*Gartrell BD, Alley MR, Pauli J, Collen R, Barlow K. An outbreak of poxvirus infection in captive shore plovers. *Kokako* 9(2), 9–11, 2002

Glaberman S, Moore JE, Lowery CJ, Chalmers RM, Sulaiman I, Elwin K, Rooney PJ, Millar BC, Dooley JSG, Lal AA, et al. Three drinking-water-associated cryptosporidiosis outbreaks, Northern Ireland. *Emerging and Infectious Diseases* 8, 631–3, 2002. https://doi.org/10.3201/eid0806.010368

Janda JM, Abbott SL, McIver CJ. *Plesiomonas shigelloides* revisited. *Clinical Microbiology Reviews* 29, 349–74, 2016. https://doi.org/10.1128/CMR.00103-15

Kurki-Fox JJ, Doll BA, Line DE, Baldwin ME, Klondike TM, Fox AA. The flood reduction and water quality impacts of watershed-scale natural infrastructure implementation in North Carolina, USA. *Ecological Engineering* 181, 106696, 2022. https://doi.org/10.1016/j.ecoleng.2022.106696

Larned ST, Snelder T, Unwin MJ, McBride GB. Water quality in New Zealand rivers: current state and trends. *New Zealand Journal of Marine and Freshwater Research* 50, 389–417, 2016. https://doi.org/10.1080/00288330.2016.1150309

Larned ST, Moores J, Gadd J, Baillie B, Schallenberg M. Evidence for the effects of land use on freshwater ecosystems in New Zealand. *New Zealand Journal of Marine and Freshwater Research* 54, 551–91, 2020. https://doi.org/10.1080/00288330.2019.1695634

*LAWA. *LAWA: Land Air Water Aotearoa*. https://www.lawa.org.nz/about/ (accessed 29 August 2023). Land Air Water Aotearoa, Palmerston North, NZ, 2023

Magid M, Wold JR, Moraga R, Cubrinovska I, Houston DM, Gartrell BD, Steeves TE. Leveraging an existing whole-genome resequencing population data set to characterize toll-like receptor gene diversity in a threatened bird. *Molecular Ecology Resources* 22, 2810–25, 2022. https://doi.org/10.1111/1755-0998.13656

McKergow LA, Matheson FE, Quinn JM. Riparian management: a restoration tool for New Zealand streams. *Ecological Management and Restoration* 17, 218–27, 2016. https://doi.org/10.1111/emr.12232

Merchán-Sanmartin B, Carrión-Mero P, Morante-Carballo F, Briones-Bitar J, Gonzalez-Rugel A, Vera-Demera H. Design of the interceptor-collector and wastewater treatment system for pollution mitigation: a case study. *WIT Transactions on Ecology and the Environment* 259, 125–36, 2022. https://doi.org/10.2495/AWP220111

*Ministry for the Environment. *Climate Change Projections for New Zealand: Atmosphere Projections Based on Simulations from the IPCC Fifth Assessment*. 2nd Edition. Ministry for the Environment, Wellington, NZ, 2018

*Ministry for the Environment. *National Policy Statement for Freshwater Management 2020*. https://environment.govt.nz/publications/national-policy-statement-for-freshwater-management-2020/ (accessed 29 August 2023). Ministry for the Environment, Wellington, NZ, 2020

*NIWA. *Climate Summary for February 2016*. https://niwa.co.nz/climate/summaries/monthly/climate-summary-for-february-2016 (accessed 29 August 2023). National Institute of Water and Atmospheric Research, Wellington, NZ, 2016

Phiri BJ, Pita AB, Hayman DTS, Biggs PJ, Davis MT, Fayaz A, Canning AD, French NP, Death RG. Does land use affect pathogen presence in New Zealand drinking water supplies? *Water Research* 185, 116229, 2020. https://doi.org/10.1016/j.watres.2020.116229

Phiri BJ, Hayman DTS, Biggs PJ, French NP, Garcia-R JC. Microbial diversity in water and animal faeces: a metagenomic analysis to assess public health risk. *New Zealand Journal of Zoology* 48, 188–201, 2021. https://doi.org/10.1080/03014223.2020.1831556

*Reiss AE, Woods RW. *National Zoo Biosecurity Manual*. Zoo and Aquarium Association, Barton, ACT, Australia, 2011

*Robertson H, Baird K, Elliott G, Hitchmough R, McArthur N, Makan T, Miskelly C, O'Donnell C, Sagar P, Scofield R, *et al.* *Conservation Status of Birds in Aotearoa New Zealand, 2021*. Department of Conservation, Wellington, NZ, 2021

Schiavano GF, De Santi M, Sisti M, Amagliani G, Brandi G. Disinfection of *Mycobacterium avium* subspecies *hominissuis* in drinking tap water using ultraviolet germicidal irradiation. *Environmental Technology (United Kingdom)* 39, 3221–7, 2018. https://doi.org/10.1080/09593330.2017.1375028

Sikder R, Zhang T, Ye T. Predicting THM formation and revealing its contributors in drinking water treatment using machine learning. *ACS EST Water*, 3c00020, 2023. https://doi.org/10.1021/acsestwater.3c00020

Smith OM, Edworthy A, Taylor JM, Jones MS, Tormanen A, Kennedy CM, Fu Z, Latimer CE, Cornell KA, Michelotti LA, *et al.* Agricultural intensification heightens food safety risks posed by wild birds. *Journal of Applied Ecology* 57, 2246–57, 2020. https://doi.org/10.1111/1365-2664.13723

Suarez P, Alonso JL, Gómez G, Vidal G. Performance of sewage treatment technologies for the removal of *Cryptosporidium* sp. and *Giardia* sp.: toward water circularity. *Journal of Environmental Management* 324, 116320, 2022. https://doi.org/10.1016/j.jenvman.2022.116320

Umar S, Aqil K, Qayyum R, Younus M, Qamar-un-Nisa, Ali S, Shah MA, Irfan M, Usman M, Ali A, *et al.* Haematology and blood chemistry references values for clinically healthy red-wattled lapwing (*Vanellus indicus*). *European Journal of Wildlife Research* 62, 797–803, 2016. https://doi.org/10.1007/s10344-016-1052-7

Waldron LS, Ferrari BC, Cheung-Kwok-Sang C, Beggs PJ, Stephens N, Power ML. Molecular epidemiology and spatial distribution of a waterborne cryptosporidiosis outbreak in Australia. *Applied and Environmental Microbiology* 77, 7766–71, 2011. https://doi.org/10.1128/AEM.00616-11

*Non-peer-reviewed