

1 *Invasion Note*

2 **Swimming capabilities of stoats and the threat to inshore**  
3 **sanctuaries**

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18 Running head: Swimming capabilities of stoats

19

20 **ABSTRACT**

21 Stoats (*Mustela erminea*) are small carnivorous mammals which were introduced into New Zealand  
22 in the late 19<sup>th</sup> century, and have now become widespread invasive pests. Stoats have long been  
23 known to be capable of swimming to islands 1-1.5 km offshore. Islands further out have usually  
24 been assumed to be safe from invasion, therefore routine stoat monitoring on them has been  
25 considered un-necessary. Recent incursions, including a stoat found on Rangitoto Island (3 km  
26 offshore) in 2010, and another which was deduced to have reached Kapiti (5 km offshore) in 2009,  
27 along with distribution modelling and genetic studies, strongly support the proposition that stoats  
28 can swim much further than 1.5 km. Acceptance of this hypothesis depends on estimating the  
29 probability that such small animals could indeed swim so far unaided. This paper reports the results  
30 of a project designed to assist this debate by recording the paddling action, speed and minimal  
31 endurance of nine stoats observed (once each) swimming against an endless current in a flume at  
32 the Aquatic Research Centre, University of Waikato. Four of the five males and two of the four  
33 females could hold a position for at least five minutes against the maximum current available,  
34 averaging  $1.36 \pm 0.336$  km/h. In steady swimming against a current of c. 1 km/hr, they all used a  
35 rapid quadripedal paddling action (averaging 250 strokes/min, stronger with the spread forepaws).  
36 Four of the nine swam strongly for >1 h, including one female who covered 1.8 km in nearly 2 h non-  
37 stop. Results from such artificial conditions cannot be conclusive, but support suggestions that wild  
38 stoats could indeed swim much further than 1.5 km, hence we conclude that the “risk zone” for  
39 stoat reinvasions of inshore islands has been seriously under-estimated.

40

41 **Keywords:** Stoat; *Mustela erminea*; island sanctuaries; invasion risk; swimming.

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43  
44 **INTRODUCTION**

45 Stoats (*Mustela erminea*) are small, energetic mustelid carnivores native to the northern Holarctic  
46 (King and Powell 2007). Their excellent ability to disperse long distances in challenging conditions  
47 was amply demonstrated by their rapid recolonisation of the boreal region in early postglacial times,  
48 including many offshore islands (Fleming and Cook 2002; Martinkova et al. 2007). On land, marked  
49 individual stoats have been recorded dispersing >20 km within a few weeks of independence (King  
50 and McMillan 1982), and swimming across fast rivers without hesitation (Murphy and Dowding  
51 1995). In lakes and in the sea, unmarked stoats have been seen swimming at considerable distances  
52 from land (Veale 2013).

53 Nowhere are these capabilities more significant than near the c. 250 offshore islands of New  
54 Zealand which are protected faunal reserves. The most valuable of these are the ones that shelter  
55 various combinations of threatened species of native fauna unable to co-exist with alien predators  
56 on the main islands, especially rats and stoats (King 2005; Veale et al. 2012b). At least 100 islands  
57 around the New Zealand coast have been cleared of at least 180 populations of 14 species of  
58 invasive mammals, and national conservation strategy relies heavily on increasingly ambitious  
59 eradications (McMurtrie et al. 2011) and restoration of islands (Townes et al. 1997; Townes et al. 2013).  
60 More than 70 species of terrestrial vertebrates are recovering or likely to recover as a result of these  
61 eradications (Townes et al. 2013), but the problem of detecting early reinvasions remains acute  
62 (Elliott et al. 2010). Permanent eradication of an established population open to reinvasion from  
63 neighbouring uncontrolled areas with the same “eradication unit” (Abdelkrim et al. 2005) is  
64 impossible.

65 Around 1900, stoats reached Resolution Island (0.6 km off the South Island’s Fiordland coast),  
66 ruining Richard Henry’s attempt to protect flightless birds from predation (Hill and Hill 1987). Maud  
67 Island, in the Marlborough Sounds, located only about 900 m from the nearest coast of the northern  
68 South Island, has been invaded by female stoats three times since 1982. All were pregnant, as 99%  
69 of all females always are (King and Moody 1982; King and Powell 2007), and the second female  
70 produced two generations of offspring by sibling mating, as illustrated by Crouchley (1994).

71 Islands further than 1.5 km offshore have usually been assumed to be safe from stoat invasion  
72 (Colbourne 2005; Miller et al. 1994) unless linked to the mainland by stepping-stone islands. For  
73 example, Chalky Island is 2.5 km from the Fiordland mainland but accessible via three intermediate  
74 islands, as mapped by Elliott et al (2010). Stoats occupied Chalky Island, and visited the linking  
75 islands, until a successful eradication programme in 1999 targetted all islands in the chain. However,  
76 a more recent survey recorded at least 84 cases of unassisted visits of stoats to islands up to about  
77 3.0 km offshore (Veale et al. 2012b)

78 A successful multispecies eradication programme cleared stoats and all other exotic mammals from  
79 Rangitoto Island, 3 km offshore in the Hauraki Gulf (Figure 1), by the end of 2009, and surveillance  
80 continued into 2011. In 2010, a year after the main eradication, a single male stoat reappeared,  
81 confirmed by genetic analyses to be a reinvader from the mainland, not a survivor (Veale et al.  
82 2012a). Could such a small land animal (weight 200-400 g, with legs hardly 60 mm long and no  
83 special adaptations for life in water) really swim that far? If so, how many other inshore islands of

84 the New Zealand archipelago supporting threatened species are more vulnerable to invasion than  
85 has been assumed?

86 This question became urgent after a female stoat reached Kapiti Island, 5 km off the west coast of  
87 the North Island, site of decades of expensive restoration and reintroductions of sensitive native  
88 species (Figure 1). This stoat probably arrived in 2009, and survived long enough to found a new  
89 population by sibling matings (Prada et al. 2013), which cost more than NZ\$600,000 to eradicate  
90 (Department of Conservation, unpublished). Like the Rangitoto stoat, it also came from the  
91 mainland. Suggestions that it swam there unaided have caused great debate among conservation  
92 authorities.

93 In January 2013 we aimed to assist this debate by defining the *minimum* swimming abilities of ten  
94 captive stoats in a flume at the Aquatic Research Centre, University of Waikato, Hamilton. We  
95 planned to observe their foot structure and swimming action, estimate their speed and endurance  
96 against a continuous current, and predict a theoretical maximum swimming distance.

## 97 **METHODS**

98 The flume was 10 m long and 0.5 m wide, with transparent Perspex sides. It circulated fresh water at  
99 21-22°C as an endless stream. We defined a swimming chamber 1.6 m long and 25 cm deep by  
100 blocking off a section of the flume with unclimbable barriers, solid above water level, mesh below.  
101 Heavy Perspex lids on top prevented animals from jumping out. We assumed that a stoat which  
102 could maintain a constant position against the current at a given speed could swim forward at that  
103 speed in still water.

104 We used fresh water not salt, since stoats swim to islands in lakes as well as in the sea, and  
105 swimming tests in fresh water should give conservative results because it is slightly more demanding  
106 to swim in fresh rather than in the more buoyant salt water. We set up a video camera on a tripod,  
107 with the entire swimming chamber in view, to record the position and activities of each animal in the  
108 chamber from start to finish of each trial. We also used hand-held cameras to focus close-up on  
109 swimming action from above and from the side, and underwater cameras to record paw action from  
110 underneath.

111 We used a flow meter to measure the speed of the current maintained by the motor running at  
112 speeds of 10, 20, 30, 40 and 50 Hz (50 Hz was the maximum it was permitted to run for more than a  
113 few minutes). The barriers defining the swimming chamber caused turbulence, especially at the  
114 upstream end of the chamber and to a lesser extent along the sides. Current speeds were therefore  
115 measured at three positions across the flow (front, centre and back), three positions along it (left,  
116 centre, right), and at two depths (just below the surface, where the stoat's body floated, and 50 mm  
117 below the surface, at paddling depth), total 18 readings at five speeds. A simple linear regression  
118 showed greater variation at the higher speeds, to a maximum of 0.55 m/sec (1.98 km/h) in the  
119 immediate front (upstream) centre of the chamber. The average speed of the current across the 18  
120 positions at the 5 motor speeds ranged from 0.04 to 0.36 m/sec (Figure 2), equivalent to 1.14, 0.43,  
121 0.68, 0.97 and 1.3 km/h.

122 Live stoats and weasels cannot be handled humanely except under anaesthetic (King and Powell  
123 2007). The six males and four females available had all been habituated to captivity for at least a  
124 year, but still could not be handled directly. We considered it important to avoid the additional

125 stress of anaesthesia before the trials, so we designed a special system of portable nest boxes and  
126 transfer tubes with sliding doors. When we were ready to begin a test and the animal was safely  
127 inside its familiar nest box, we could open the door of its home cage and close the sliding door to  
128 shut it in the nest box. It was carried to the Aquatic Centre in its own nest box, and there moved  
129 briefly via the transfer tube into the flume. Before starting to work with stoats, we tested all our  
130 equipment and procedures with tame Norway rats.

131 While each stoat was fresh, we increased the speed of the current in stages, maintaining it for only  
132 so long as the animal showed it could maintain its position within the chamber without being swept  
133 against the back wall, and then moving to the next stage. We expressed the result in km/hr,  
134 corrected for variation in the current speed at the exact position where the stoat chose to swim. At  
135 the maximum current speed any given animal could swim against, every individual concentrated on  
136 swimming steadily in the front centre of the chamber close to the upstream mesh, and we recorded  
137 its performance there over not more than 5 minutes.

138 For observation of minimum endurance times, the flume speed was reduced to 0.28 m/sec or less (c.  
139 1 km/h), as appropriate for each individual. At these slower current speeds, animals were able to  
140 explore the chamber, so we recorded and timed their every change in position, and estimated their  
141 swimming speed and distance covered relative to the speed of the current at that position. From the  
142 video records we tabulated the number of seconds each stoat spent swimming at each current  
143 speed, again corrected for position, and hence the distance swum at each speed. The total distance  
144 any individual swam was found by adding the list of positions and distances recorded throughout its  
145 trial. To minimise stress, we tested each animal only once.

146 All tests were done under the minimum illumination required by the cameras. Filming in dark  
147 conditions under IR was not necessary because stoats are equally active in both diurnal and  
148 nocturnal light.

149 We filmed the swimming action of the stoats, their maximum short-term speed, and the total time  
150 each individual spent actively swimming before showing signs of serious distress. Stoats were  
151 retrieved when the head began to sink, or the body was shivering violently, or the paddling action  
152 was too weak to prevent the body being washed against the downstream barrier.

153 Exhausted animals were retrieved with a net, and dried off in a nest box filled with fresh absorbent  
154 bedding. They were immediately taken to a vet and anaesthetised, pre-mortem blood glucose levels  
155 determined, and then euthanased. We never let the animals drown, so do not know how close to  
156 total exhaustion any of them were.

## 157 **RESULTS**

158 Three of the males swam strongly for more than an hour, and one of the females for nearly two  
159 hours (Table 1); two males and one female swam for more than half an hour. Two females gave up  
160 quickly (in 11 and 22 minutes) for reasons unknown.

161 All stoats used a rapid quadrupedal paddling action (stronger with the forelegs), with spreading of  
162 the paws. At first, the head and shoulders were held well up out of the water, with the rest of the  
163 body and tail parallel to and just below the surface. At that stage the strong shoulder action driving  
164 the high paddling rate was very clear from above, as described in a vivid eye witness account of a

165 stoat in the wild quoted by King & Moors (1979). The tail was often bushed out, a classic sign of  
166 anxiety. As the stoat tired, the body became less buoyant, the shoulders lower (Figure 3), and the  
167 paddling action shallower.

168 Four of the five males and two of the four females could hold a steady position for at least for 5 min  
169 against the maximum available current, averaging 1.3 km/h (Table 1). When they strayed into the  
170 front centre of the chamber, where the flow was channelled through the mesh barrier, they had to  
171 swim faster, up to 1.98 km/h. The fifth male and the other two females reached at least 1.2 km/h.

172 During steady endurance swimming, we estimated the average number of paw strokes per minute  
173 from the video records, which provided 1-8 observations (1 per stoat) per speed setting. Fore-leg  
174 strokes averaged about 220-300/minute at all current speeds (Table 2), and were much longer and  
175 deeper than those of the hind legs (Figures 3 and 4).

176 The underwater video records showed that the swimming action included paw spreading during  
177 power strokes (Figure 4), especially of the front paws, followed by folding of the interdigital webbing  
178 during the recovery stroke, as in all specialist swimming animals. On land, only the pads touch the  
179 ground, so the interdigital webbing is not visible on the hard surface of a standard tracking plate  
180 (Ratz 1997), but it is quite clear in footprints recorded on soft mud (Lawrence and Brown 1967).

181 Two stoats found effective ways to minimise their effort. M5 was able to float almost motionless for  
182 up to 5 minutes, then he resumed paddling as strongly as ever, often in response to movement by  
183 observers outside the flume. F1 found the one place in the swimming chamber best sheltered from  
184 the current and spent most of her time there (Figure 3).

185 When in the flume, all stoats had no choice but to swim at the speed set by the current, but they did  
186 have the choice as to how long they were willing to continue swimming. Effort and endurance are  
187 inversely correlated, so if our choice of current speeds between 0.19 and 0.28 m/sec for estimating  
188 endurance was too fast, the animals would have been obliged by exhaustion to stop swimming in  
189 the flume earlier than they would have done in the wild. At slower speeds, many animals wasted  
190 energy trying to jump out.

191 We chose not to take pre-swim blood samples from our stoats, which would have added extra stress  
192 affecting their performance, so do not know the normal glucose levels for stoats that have not been  
193 swimming. The norm for the ferret *Mustela furo* is 5.61 mmol/L, range 3.37-7.44 mmol/L (Lewington  
194 2007). The only stoat we had that was placed in the water but then retrieved after only 4 minutes  
195 (M6, which we suspected was sick) was confirmed by the vet to be suffering from a respiratory  
196 disease. He had a blood glucose level of 5.2 mmol/L. No stoats were available for sampling that had  
197 not been part of these experiments.

198 One female was removed from the water after 11 minutes, when she panicked and struggled to stay  
199 afloat for no obvious reasons. The high level of blood glucose recorded for her is consistent with a  
200 short-term hyperglycaemic flight response. All seven stoats which swam for at least half an hour  
201 recorded very low blood glucose levels (Figure 5), consistent with hypoglycaemia induced by intense  
202 exercise, which onsets most rapidly in animals exposed to cold conditions (Young and Castellani  
203 2001). By the time the stoats were anaesthetised for blood sampling, they had recovered sufficient  
204 energy to move about in the nest box, and some were still capable of being quite aggressive.

205 Theoretical modeling from these data might be a tempting prospect, but too much additional  
206 information on local tides, currents and weather conditions would be needed to make useful  
207 predictions concerning the potential distance a stoat could cover. A current list of inshore islands of  
208 conservation value that should be monitored for stoat incursions is provided by Veale et al (2012b).

## 209 **DISCUSSION**

210 These measurements show only the *minimum* swimming speed and endurance times attainable by  
211 captive stoats, deprived of natural exercise for a year, and tested under duress. A fit and active wild  
212 stoat free to choose its own time, motivation and swimming speed might swim much further,  
213 especially given the added buoyancy of salt water. Individuals such as M5 that have the ability to  
214 rest while floating, or are assisted by strong currents, floating debris or stepping-stone islands, could  
215 considerably extend their range.

216 Females, all already fertilised, present a special risk to any offshore islands they can reach. They are  
217 much smaller than males but, at least from these data, are not necessarily inferior to males in  
218 swimming speed or endurance – in fact, the only stoat of our nine to swim steadily for almost two  
219 hours was a female. The nearest comparable but unconfirmed record in the literature reported a  
220 stoat swimming about 3.5 km in Lake Waikaremoana in about 45 mins (Veale 2013). We suspect that  
221 this statement was incorrect in its estimate of either the time or the distance covered.

222 The quadipedal paddling action of stoats, stronger with the front paws, was similar to that of the  
223 American mink *Neovision vison* (Williams 1983), but different from that of ferrets (Fish and  
224 Baudinette 2008), which paddle only with the forefeet, and different from that of Norway rats,  
225 which paddle only with the hind feet.

226 The average maximum swimming speed of 0.36 m/sec (1.3 km/h), briefly to 0.55 m/sec (1.98 km/h)  
227 recorded by six of our nine stoats was probably an underestimate imposed by the limitations of our  
228 equipment. Ferrets can swim at speeds of up to about 0.44 m/sec (Fish and Baudinette 2008), and  
229 mink nearly twice as fast (0.70 m/sec) (Williams 1983). Most stoats stayed on the surface all the time,  
230 but M1 deliberately ducked under several times to search for underwater escape routes.

231 Glucose levels were measured just before death but between 20 and 30 minutes after swimming  
232 ended, so could have been affected by early post-exercise processes. We were required by our  
233 Animal Ethics permit to take the time to deliver the animals to a vet for euthanasia, rather than do  
234 that on the spot.

235 Despite remarkable individual variation among the test animals, we conclude that it is feasible to  
236 assume at least some wild stoats would be capable of swimming to Rangitoto. Updated genetic  
237 analyses of the 2010 stoat incursion to Rangitoto indicate that this stoat originated from south-east  
238 Auckland (A. Veale unpublished). If it launched near the mouth of the Tamaki River at ebb tide, it  
239 would have had the help of a current setting toward Rangitoto at 0.3 m/sec (Oldham et al. 2004),  
240 and a stepping stone on Browns Island (Figure 1). Given the help of a serendipitous floating log  
241 pushed by a current towards an island, greater distances are possible. On 8 August 2012, a fishing  
242 party observed a possum on a floating log near Kapiti Island  
243 ( <http://www.youtube.com/watch?v=gldwNUveldA>). Possums cannot swim, but stoats could not

244 only easily take advantage of such help, but also they can choose to rest when necessary by floating  
245 unassisted.

246 These data are not conclusive in themselves, but, in conjunction with the known records of stoats  
247 visiting islands collated by Veale's team, and their consequent modelling work (Veale et al. 2012b),  
248 they imply that: (1) all islands of the New Zealand archipelago <3-5 km offshore should be treated as  
249 at risk of invasion by stoats, (2) the "safe" zone for important conservation islands inshore has been  
250 drastically underestimated, and (3) the assumption that such islands do not need the continued  
251 surveillance provided by expensive and permanently maintained traplines is a false economy.

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254 arranging for their transport to Hamilton; to Dudley Bell and Conrad Pilditch for the use of the flume  
255 and other equipment under their control in the Aquatic Research Centre; and to Martin Gore and Ian  
256 Moon for making the special nest-boxes and live animal transfer equipment to our design. The work  
257 was done under protocol 866 approved by the Animal Ethics Committee of the University of Waikato.  
258 A member of the AEC (Bruce Patty) attended most of the trials. The animals were euthanased by  
259 vets at the Newstead Veterinary Practice, Hamilton. Funding was provided by the University of  
260 Waikato Research Trust Contestible Fund, managed by Carol Robinson. A. Veale participated in this  
261 project by permission of the University of Auckland and Prof M Clout.

## 262 **TABLES**

263 Table 1. Details of the nine experimental animals. The tenth, M6, was introduced to the water but  
264 not tested because it was suffering from a respiratory infection.

265 Table 2. Number of front paw strokes per minute exerted by stoats swimming against an endless  
266 current. Mean speed of current (m/sec) estimated from flow meter readings taken at 18 positions in  
267 the chamber. Most stroke counts measured during the endurance phase of the trials, usually at 0.28  
268 m/sec (1 km/hr).

## 269 **FIGURE CAPTIONS**

270 Figure 1. Maps showing recent long-distance stoat incursions to islands, the locations of the stoats  
271 captured, and the distances to the mainland and to stepping-stone islands.

272 Figure 2. Range of current speeds available in the flume.

273 Figure 3. F1 holding position by swimming against a current of 0.28 m/sec (1.01 km/h). Water enters  
274 from right through a barrier. Vertical marks at 20 cm intervals. This individual quickly found the slight  
275 shelter effect provided by the frame of the mesh barrier, and spent most time there.

276 Figure 4. Swimming action, including the spreading of the paws during the power stroke.

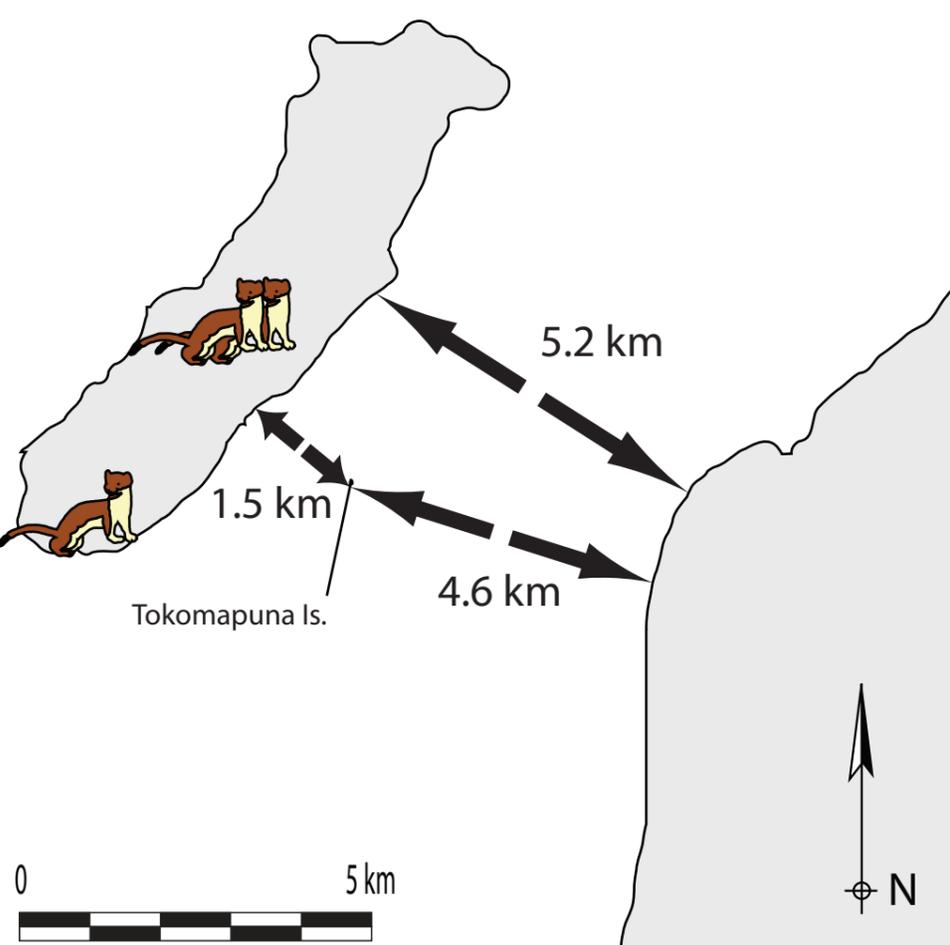
277 Figure 5. Blood glucose levels for 10 stoats, measured by a vet within 30 minutes of leaving the  
278 water.

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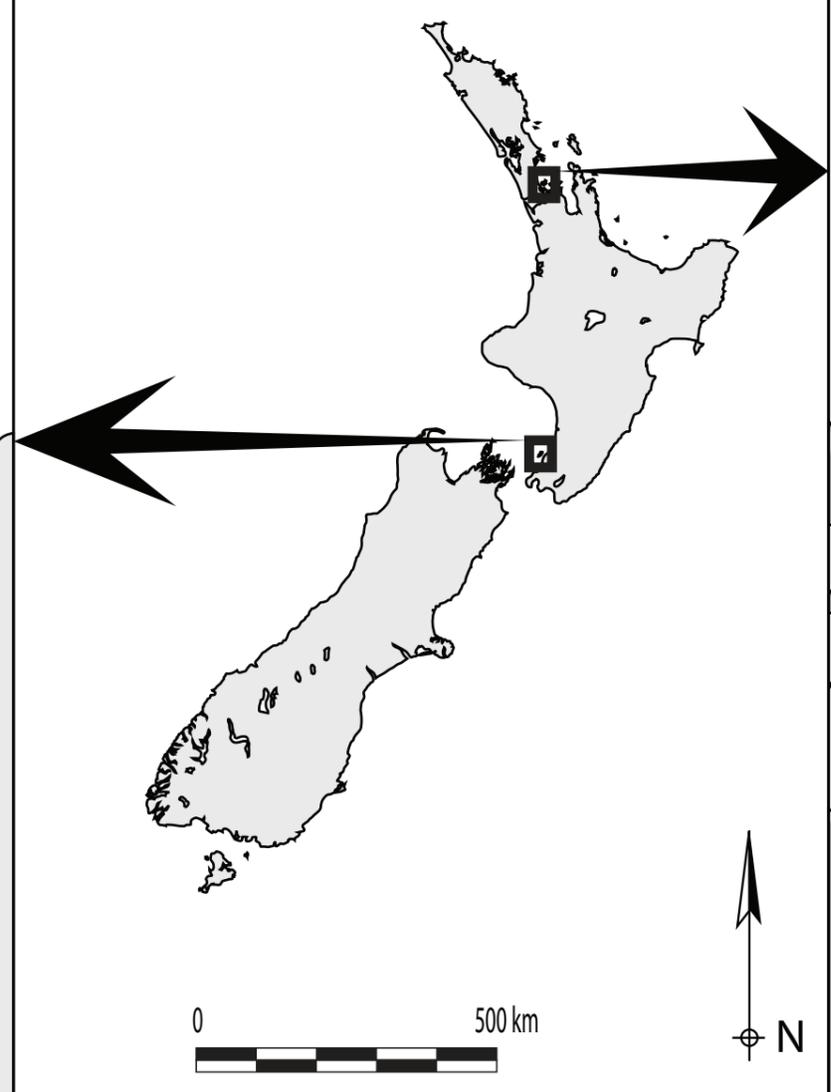
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# Kapiti Island



# New Zealand



# Rangitoto Island

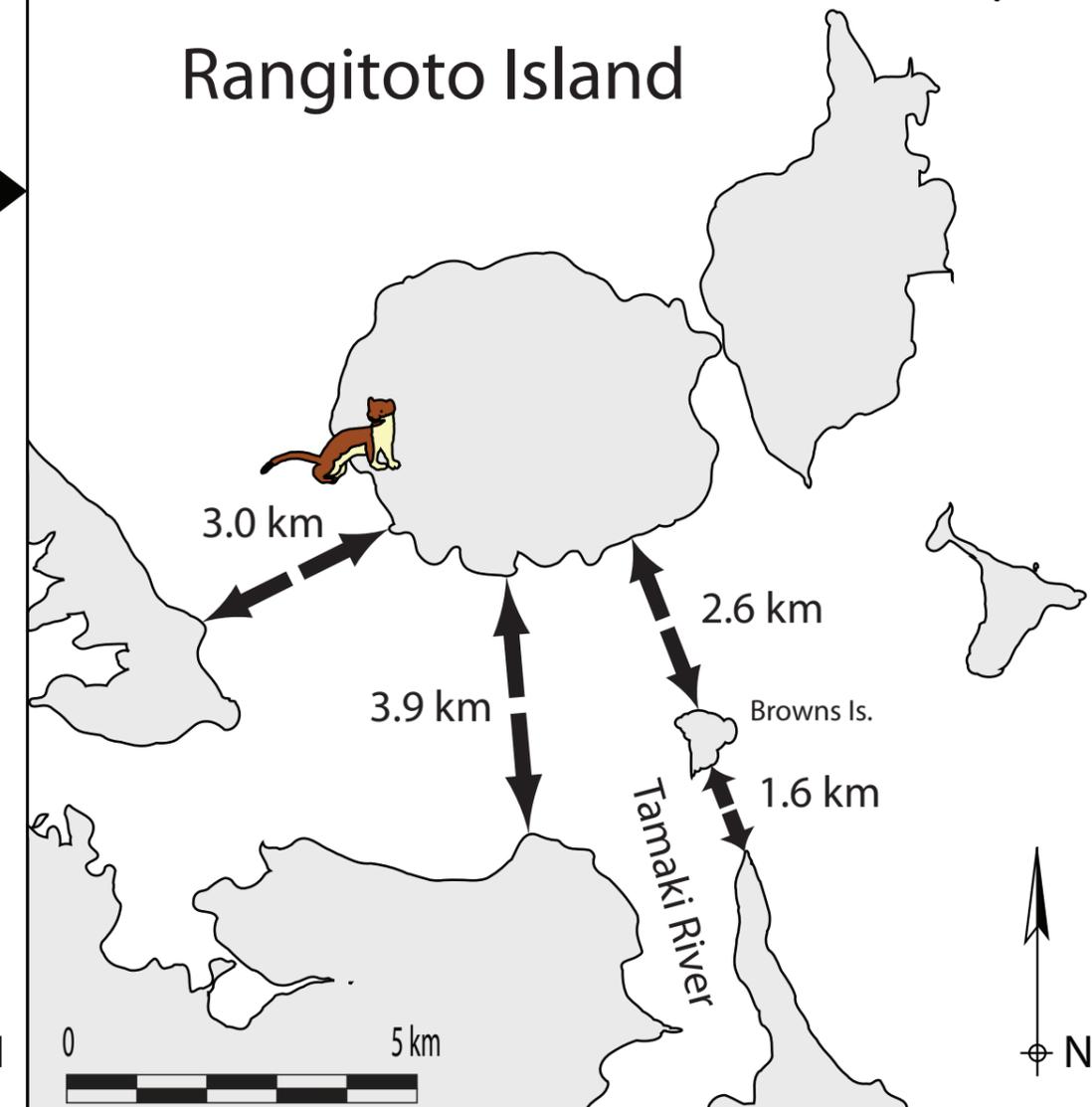


Figure 2. Range of current speeds available in the flume.

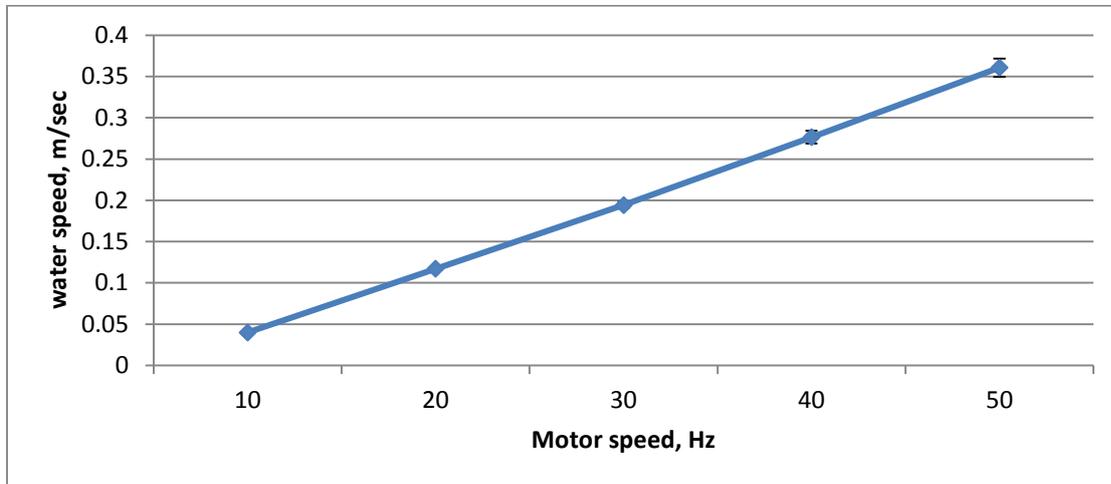


Figure 3. F1 holding position by swimming against a current of 0.28 m/sec (1.01 km/h). Water enters from right through a barrier. Vertical marks at 20 cm intervals. This individual quickly found the slight shelter effect provided by the frame of the mesh barrier, and spent most time there.



Figure 4. Swimming action, including the spreading of the paws during the power stroke

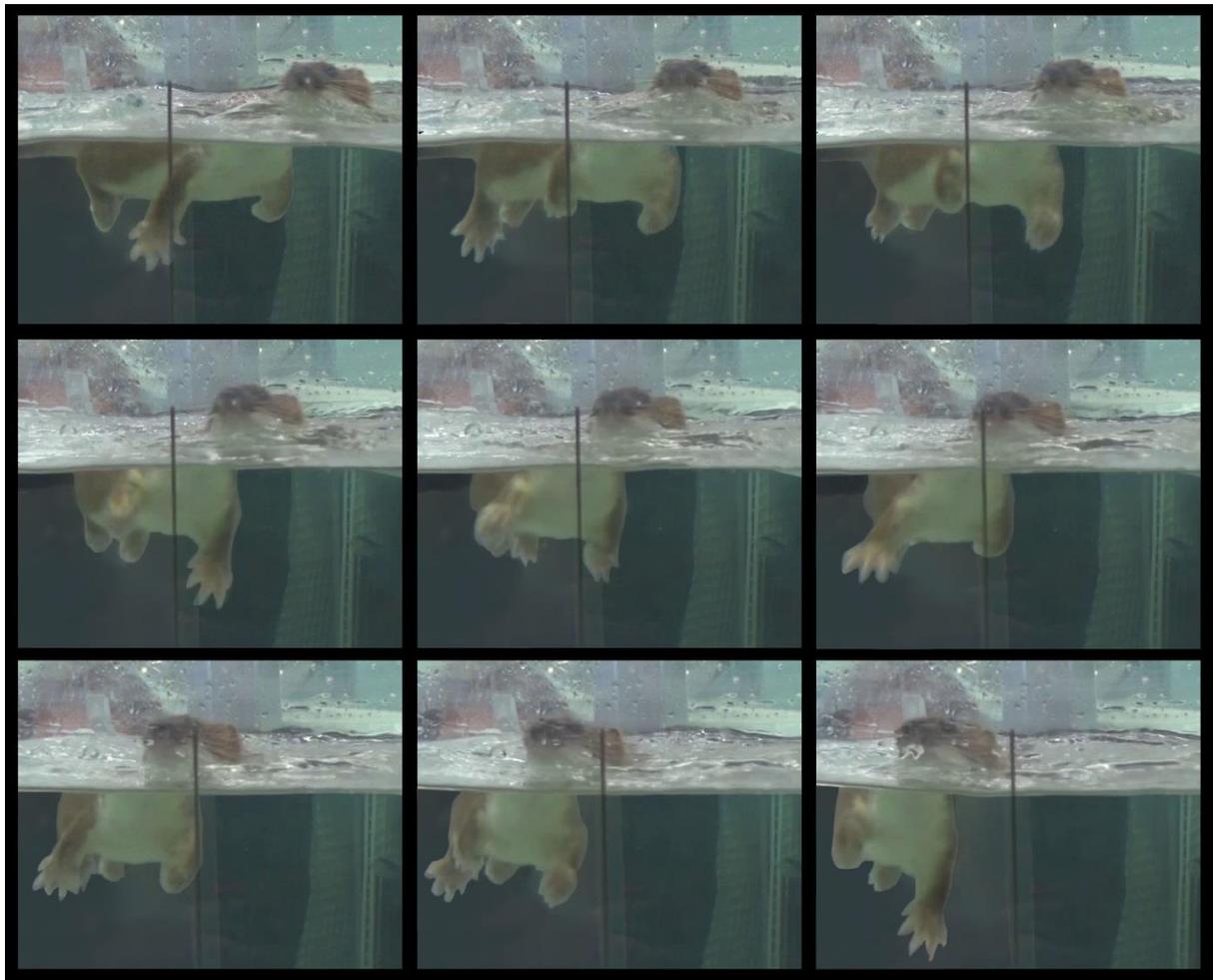


Figure 5. Blood glucose levels, measured by a vet within 30 minutes of leaving the water.

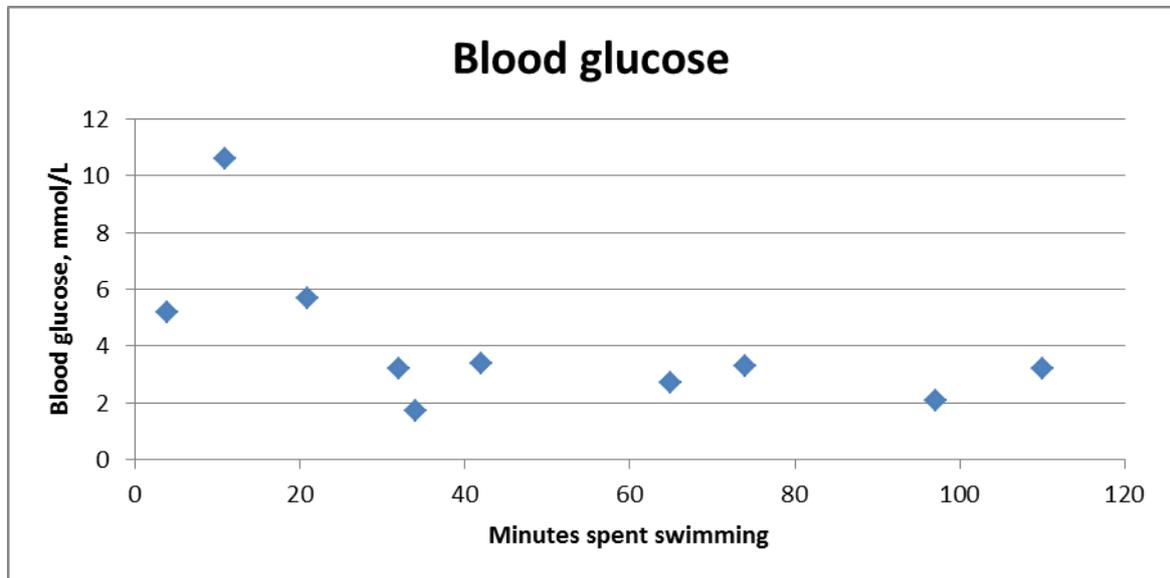


Table 2. Number of front paw strokes per minute exerted by stoats swimming against an endless current. Mean speed of current (m/sec) estimated from flow meter readings taken at 18 positions in the chamber. Most stroke counts measured during the endurance phase of the trials, usually at 0.28 m/sec (1 km/hr).

<b>Motor (Hz)</b>	<b>20</b>	<b>30</b>	<b>35</b>	<b>38</b>	<b>40</b>	<b>45</b>	<b>49</b>	<b>50</b>
<b>Current (m/sec)</b>	<b>0.12</b>	<b>0.19</b>	<b>0.23</b>	<b>0.26</b>	<b>0.28</b>	<b>0.32</b>	<b>0.35</b>	<b>0.36</b>
F1				308	294			
F2					175			
F3	262		260		252	252	239	
F4	258	256			272	268	266	
M1					265			
M3			148		180			
M4		261	270		285	312	306	
M5	238				268	285	285	288
M6	220							
n observations	4	2	3	1	8	4	4	1
Mean	244.5	258.5	226	308	248.9	279.3	274	288
SD	19.42	3.54	67.73		45.84	25.66	28.48	

Table 1. Details of the nine experimental animals. The tenth, M6, was introduced to the water but not tested because it was suffering from a respiratory infection.

Stoat ID	Body weight, g	Max swim speed, km/h (m/sec)	Time spent swimming, mins	Total distance swum, km	Blood glucose level, mmol/L
M1	327	1.30 (0.36)	64.9	1.08	2.7
M2	384	1.22 (0.34)	42.0	0.61	3.4
M3	376	1.30 (0.36)	33.8	0.60	1.7
M4	381	1.30 (0.36)	97.1	1.30	2.1
M5	346	1.30 (0.36)	74.1	0.71	3.3
M6*	356	-	04	-	5.2
F1	253	1.26 (0.35)	108.8	1.79	3.2
F2	201	1.30 (0.36)	10.8	0.18	10.6
F3	224	1.30 (0.36)	21.6	0.33	5.7
F4	198	1.22 (0.34)	32.8	0.36	3.2