Auckland Regional Council
TE RAUHĪTANGA TAIAO

Mahurangi Estuary Numerical Modelling

Stormwater Overflow Events

June TR 2009/059

Auckland Regional Council
Technical Report No.059 June 2009
ISSN 1179-0504 (Print)
ISSN 1179-0512 (Online)
ISBN 978-1-877528-71-2

This report is part of a series of reports that were commissioned during the period 1993-1999 that were used to support the establishment of the Mahurangi Action Plan. They are being made available following a review of technical information.

Reviewed by:

Name: Amy Taylor

Position: Project Leader Land

Organisation: ARC

Date: 1/06/09

Approved for ARC Publication by:

Name: Grant Barnes

Position: Group Manager Monitoring & Research

Organisation: ARC

Date: 1/06/09

Recommended Citation:

Oldman, J. W. (1997). Mahurangi Estuary Numerical Modelling: Stormwater overflow events. Prepared by NIWA for Auckland Regional Council. Auckland Regional Council Technical Publication 2009/059.

Mahurangi Estuary Numerical Modelling: Stormwater Overflow Events

Oldman J. W.

Prepared for

Auckland Regional Council

NIWA Client Report: ARC70216/3
April 1997

National Institute of Water & Atmospheric Research Ltd
PO Box 11-115, Hamilton
New Zealand
Tel: 07 856 7026
Fax: 07 856 0151

CONTENTS

Reviewed by:

R.G.Bell

Approved for release by:

J.C.Rutherford

Executive Summary

NIWA has been commissioned by the Auckland Regional Council to develop numerical models of the Mahurangi Estuary to enable the ARC to manage the Mahurangi and its environs in a sustainable manner. This report gives details of modelling the dispersion of storm overflow discharges from the existing Warkworth sewerage system. Results are presented for storm overflow events lasting ½, 1, 2 and 4 hours at a mean daily flow of 35 cumecs in the Mahurangi River and a spring tidal range of 3 m. In addition, the four hour storm overflow is modelled for river flows of 5 and 140 cumecs.

The data presented shows there is potential for relatively high faecal coliform concentrations to be present within the Mahurangi Estuary following an overflow event at Warkworth. For an effluent concentration of 10^6 FC/100 mL predicted concentrations in the main channel of the upper estuary are up to 24,000 FC/100 mL but these reduce as freshwater inflows increase and the time period for the overflow decreases. Within the estuary itself concentrations on the inter-tidal areas are predicted to be as high as 4,000 FC/100 mL. These are worst-case predictions which ignore solar-induced inactivation of faecal indicator bacteria.

Within the main channel the central core of the plume is diluted relatively quickly. This is corroborated by field data for areas close to the Warkworth Town Basin (i.e. Hamiltons Landing and north). Consequently, in the upper-estuary, predicted peak faecal coliform concentrations occur within the first tidal cycle following an overflow event and there is a rapid drop-off in predicted faecal coliform concentrations on successive tidal cycles. Within the inter-tidal areas the model predicts a slower drop in faecal coliform concentrations. For sites close to the estuary entrance (i.e. Huawai Bay, Pukapuka Inlet) peak predicted faecal coliform concentrations are up to 400 FC/100 mL and linger from 4 to 7 tidal cycles after the overflow.

1.0 INTRODUCTION

NIWA has been commissioned by the Auckland Regional Council to develop numerical models of the Mahurangi Estuary to enable the ARC to manage the Mahurangi and its environs in a sustainable manner. Earlier reports give details of the development of the estuary models and their application to catchment land use and sewage treatment works discharge scenarios (Oldman and Black, 1997, Oldman et al. 1998, Oldman, 1998). This report gives details of modelling the dispersion of faecal coliforms resulting from storm-overflow discharges from the existing Warkworth sewerage system.

2.0 BACKGROUND AND METHODS

During rainfall events of greater than 25 mm/day there is a risk of storm overflows entering the Mahurangi Estuary via the Town Basin. Discussions between Rodney District Council and the ARC have determined that an overflow with peak flows of 50 litres per minute and peak faecal coliform (FC) concentrations of 10^6 FC/100 mL could be expected. This report presents model results for storm overflow events lasting ½, 1, 2 and 4 hours at a mean daily flow of 35 cumecs in the Mahurangi River at the College Site and a spring tidal range of 3 m. Swales et al (1997) stated that such a flood event has a return period of 1 in 2.2 years. For the four-hour overflow event additional runs were completed for mean daily river flows of 5 and 140 cumecs (1 in 1 year and 1 in 10 year return period respectively). It has been assumed that there is no inactivation of faecal coliforms due to solar radiation, so decreases in concentration are entirely due to physical dilution and mixing processes. This means that the selected scenarios will represent worst-case conditions in terms of FC concentrations within the estuary.

The numerical model package used was the combined hydrodynamic (3DD) and transport/dispersion (POL3DD) models developed by Black (1995, 1996). Results from the calibrated 3DD/POL3DD models (Oldman and Black, 1997) are presented in two ways. Firstly, time series of concentrations at oyster farm sites and selected main channel sites (Figure 1a,b) and secondly spatial maps of FC concentration for the whole harbour, covering a period of 100 hours (8 tidal cycles) following the overflow event.

3.0 RESULTS

All storm overflow simulations were started at 3 hours prior to spring high water (Figure 2) so that the plume excursion is minimised during the discharge. This effectively adds to a worst case scenario whereby maximum effluent concentrations would occur in the Town Basin during the discharge. On the outgoing tide (model time > 3 hours) horizontal and vertical mixing of the plume result in a reduction in peak effluent concentrations as the plume moves down the estuary. On the following tides the plume moves up and down the estuary with peak effluent concentrations reducing on each tidal cycle and the extent of the plume increasing. The effluent from the storm overflows is released into the model in the variable thickness layer (k=1) (Oldman and Black, 1997). Away from the source the thickness of this layer decreases as effluent diffuses into the underlying layers (k=2,3 ...). To enable estuary wide comparisons of effluent concentrations to be made we present the predicted FC concentrations within the fixed k=2 layer of the model.

3.1 Half hour overflow event : Mahurangi River flow at 35 cumecs

Figure 3 shows the time series plots of the FC concentrations, generated solely by a half-hour storm overflow, for the areas within the oyster farms (shown in Figure 1b). For the Cowans Bay oyster farm peak concentrations occur within the 1st tidal cycle following the overflow event while for others the arrival of the peak concentrations ranges from the 1st through to the 8th tidal cycle (> 90 hours). On arrival of the peak concentrations there is a relatively slow decay in concentrations. This is due to the lower tidal velocities (and hence mixing) that occurs on the inter-tidal areas, which means remnants from the flanks of the main plume are left behind and pushed up the side arms on the following flood tide. The following table gives the peak faecal coliform concentrations (at any time during the model simulation) for each of the oyster farms.

Table 1. Peak faecal coliform concentrations within the specified oyster farm sites following the half hour storm overflow event with a 35 cumec river inflow.

Oyster farm site	Tidal cycle of peak concentration	Peak faecal coliform concentration (FC/100 mL)
Cowans Bay	1	330
Dyers Creek (North)	2	390
Dyers Creek (South)	2	85
Browns Bay	5	135
Te Kapa Inlet	8	25
Pukapuka Inlet	8	45
Huawai Bay	8	15

Figure 4 shows the time series plots of the FC concentrations generated by the overflow event for the sites within the main channel. Nearer Warkworth, peak concentrations occur on the first tidal cycle following the overflow event. For sites further down the estuary the arrival of the peak concentration occur some 5 tidal cycles or 62 hours following the storm-overflow event (or later for sites nearer the mouth). After the peak concentration has been reached there is a more rapid fall off in concentrations due to the strong tidally driven mixing compared to the side arms. Peak values reached at each of the main channel sites (at any time during the model simulation) are listed in Table 2.

Table 2. Peak faecal coliform concentrations within the main channel following the half hour storm overflow event with a 35 cumec river inflow.

Main channel site	Tidal cycle of peak concentration	Peak faecal coliform concentration (FC/100 mL)
Town Basin	1	2780
Cement works	1	1885
Duck Creek	1	1275
Dawsons Creek	1	1510
Cowans Bay	1	805
Dyers Creek	2	795
Grants Island	2	610
Scotts Landing	5	100

Maps of hourly FC concentrations throughout the first two tidal cycles and subsequent high and low waters are given in Figure 5. One hour after the start of the overflow (2 hours prior to high water : Figure 5a : top) the plume can be seen emerging from the Mahurangi River in the vicinity of Duck Creek. Peak concentrations within the plume are of the order of 2000 FC/100 mL. One hour later (Figure 5a bottom) the plume has moved to opposite Duck Creek with peak concentrations of the order of 900 FC/100 mL. At high water (Figure 5b : top) the core of the plume is just to the north of Vialls Landing and has concentrations of the order of 900 FC/100 mL. One hour after high water (Figure 5b : bottom) the plume has emerged from the Mahurangi River and exhibits peak concentrations of the order of 900 FC/100 mL. During the initial part of the falling tide (Figure 5c) tidal flows carry the plume down the estuary towards Hepburn Creek. Peak concentrations range from 500 down to 200 FC/100 ml. As peak tidal flows occur the plume is rapidly transported beyond Hamiltons Landing and on to Cowans Bay (Figure 5d). Peak concentrations have dropped to around 200 FC/100 mL. Approaching low water the plume reaches as far downstream as Grants Island with peak concentrations of around 150 FC/100 mL (Figure 5e). On the incoming tide (Figure 5f) the plume is pushed back up the estuary towards Cowans Bay. Peak concentrations remain around 150 FC/100 mL. Figure 5g shows the plume progressing further up the estuary with peak concentrations in the vicinity of Hepburn Creek of the order of 150 FC/100 mL. By the second high water following the overflow event peak concentrations of the order of 150 FC/100 mL are present on the inter-tidal areas between Vialls Landing and Hepburn Creek. Plots are given for the second tidal cycle and then for the next 6 successive high and low waters.

3.2 One hour overflow event : Mahurangi River flow at 35 cumecs

Figure 6 shows the time series plots of the FC concentrations, generated solely by a 1 hour storm overflow, for the areas within the oyster farms (shown in Figure 1b). Table 3 gives the peak faecal coliform concentrations (at any time during the model simulation) for each of the oyster farms.

Table 3. Peak faecal coliform concentrations within the specified oyster farm sites following the one hour storm overflow event with a 35 cumec river inflow.

Oyster farm site	Tidal cycle of peak concentration	Peak faecal coliform concentration (FC/100 mL)
Cowans Bay	2	735
Dyers Creek (North)	2	860
Dyers Creek (South)	3	200
Browns Bay	6	280
Te Kapa Inlet	8	55
Pukapuka Inlet	8	45
Huawai Bay	8	40

Figure 7 shows the time series plots of the FC concentrations for the sites within the main channel following the 1-hour storm overflow event. Peak values reached at each of the main channel sites (at any time during the model simulation) are listed in Table 4.

Table 4. Peak faecal coliform concentrations within the main channel following the one hour storm overflow event with a 35 cumec river inflow.

Main channel site	Tidal cycle of peak concentration	Peak faecal coliform concentration (FC/100 mL)
Town Basin	1	11180
Cement works	1	4065
Duck Creek	1	3105
Dawsons Creek	1	3515
Cowans Bay	1	2000
Dyers Creek	2	1770
Grants Island	2	1475
Scotts Landing	8	215

Maps of hourly FC concentrations throughout the first two tidal cycles and subsequent high and low waters are given in Figure 8 for a one-hour overflow. One hour after the start of the overflow (2 hours prior to high water : Figure 8a top) the plume can be seen emerging from the Mahurangi River in the vicinity of Duck Creek. Peak concentrations within the plume of the order of 6500 FC/100 mL. One hour later (Figure 8a bottom) the plume has moved seawards, opposite Duck Creek, with peak concentrations of the order of 2000 FC/100 mL. At high water (Figure 8b : top) the core of the plume is just to the north of Vialls Landing and has concentrations of the order of 1800 FC/100 mL. One hour after high water (Figure 8b : bottom) the plume has emerged from the Mahurangi River and exhibits peak concentrations of the order of 1800 FC/100 mL. During the initial part of the falling tide (Figure 8c) tidal flows carry the plume down the estuary towards Hepburn Creek. Peak concentrations range from 1100 down to 500 FC/100 ml. During peak ebb tidal flows, the plume is rapidly transported beyond Hamiltons Landing and on to Cowans Bay (Figure 8d). Peak concentrations drop to around 400 FC/100 mL. Approaching low water the plume reaches as far downstream as Grants Island with peak concentrations of around 300 FC/100 mL (Figure 8e). On the incoming tide (Figure 8f) the plume is pushed back up the estuary towards Cowans Bay. Peak concentrations remain around 300 FC/100 mL. Figure 8g shows the plume progressing further up the estuary with peak concentrations in the vicinity of Hepburn Creek of the order of 300 FC/100 mL. By the second high water following the overflow event peak concentrations of the order of 300 FC/100 mL are present on the inter-tidal areas between Vialls Landing and Hepburn Creek. Plots are given for the second tidal cycle and then for the next 6 successive high and low waters.

3.3 Two hour overflow event : Mahurangi River flow at 35 cumecs

Figure 9 shows the time series plots of the FC concentrations, generated solely by a 2 hour storm overflow, for the areas within the oyster farms (shown in Figure 1b). Table 5 gives the peak faecal coliform concentrations (at any time during the model simulation) for each of the oyster farms.

Table 5. Peak faecal coliform concentrations within the specified oyster farm sites following the two hour storm overflow event with a 35 cumec river inflow.

Oyster farm site	Tidal cycle of peak concentration	Peak faecal coliform concentration (FC/100 mL)
Cowans Bay	2	1445
Dyers Creek (North)	2	1685
Dyers Creek (South)	2	400
Browns Bay	5	565
Te Kapa Inlet	8	125
Pukapuka Inlet	8	140
Huawai Bay	8	60

Figure 10 shows the time series plots of the FC concentrations for the sites within the main channel following the 2-hour storm overflow event. Peak values reached at each of the main channel sites (at any time during the model simulation) are listed in Table 6.

Table 6. Peak faecal coliform concentrations within the main channel following the two hour storm overflow event with a 35 cumec river inflow.

Main channel site	Tidal cycle of peak concentration	Peak faecal coliform concentration (FC/100 mL)
Town Basin	1	15555
Cement works	1	8670
Duck Creek	1	5900
Dawsons Creek	1	8230
Cowans Bay	1	3310
Dyers Creek	2	3940
Grants Island	2	3110
Scotts Landing	5	370

Maps of hourly FC concentrations throughout the first two tidal cycles and subsequent high and low waters are given in Figure 11 for a two-hour overflow. One hour after the start of the overflow (2 hours prior to high water : Figure 11a top) the plume can be seen emerging from the Mahurangi River in the vicinity of Duck Creek. Peak concentrations within the plume of the order of 9000 FC/100 mL. One hour later (Figure 11a bottom) the plume has moved to opposite Duck Creek with peak concentrations of the order of 5500 FC/100 mL. At high water (Figure 11b top) the core of the plume is just to the north of Vialls Landing and has concentrations of the order of 5000 FC/100 mL. One hour after high water (Figure 11b bottom) the plumes has emerged from the Mahurangi River and exhibits peak concentrations of the order of 5000 FC/100 mL. During the initial part of the falling tide (Figure 11c) tidal flows carry the plume down the estuary towards Hepburn Creek. Peak concentrations range from 2000 down to 1000 FC/100 ml. As peak tidal flows occur the plume is rapidly transported beyond Hamiltons Landing and on to Cowans Bay (Figure 11d). Peak concentrations have dropped to around 750 FC/100 mL. Approaching low water the plume reaches as far downstream as Grants Island with peak concentrations of around 750 FC/100 mL (Figure 11e). On the incoming tide (Figure 11f) the plume is pushed back up the estuary towards Cowans Bay. Peak concentrations remain around 750 FC/100 mL. Figure 11g shows the plume progressing further up the estuary with peak concentrations in the vicinity of Hepburn Creek of the order of 650 FC/100 mL. By the second high water following the overflow event peak concentrations of the order of 600 FC/100 mL are present on the inter-tidal areas between Vialls Landing and Hepburn Creek. Plots are given for the second tidal cycle and then for the next 6 successive high and low waters.

3.4 Four hour overflow event : Mahurangi River flow at 35 cumecs

Figure 12 shows the time series plots of the FC concentrations, generated solely by a four hour storm overflow, for the areas within the oyster farms (shown in Figure 1b). Table 7 gives the peak faecal coliform concentrations (at any time during the model simulation) for each of the oyster farms.

Table 7. Peak faecal coliform concentrations within the specified oyster farm sites following the four hour storm overflow event with a 35 cumec river inflow.

Oyster farm site	Tidal cycle of peak concentration	Peak faecal coliform concentration (FC/100 mL)
Cowans Bay	2	3140
Dyers Creek (North)	2	3550
Dyers Creek (South)	2	990
Browns Bay	5	1225
Te Kapa Inlet	8	275
Pukapuka Inlet	6	340
Huawai Bay	8	125

Figure 13 shows the time series plots of the FC concentrations for the sites within the main channel following the overflow event. Peak values reached at each of the main channel sites (at any time during the model simulation) are listed in Table 8.

Table 8. Peak faecal coliform concentrations within the main channel following the four hour storm overflow event with a 35 cumec river inflow.

Main channel site	Tidal cycle of peak concentration	Peak faecal coliform concentration (FC/100 mL)
Town Basin	1	16040 *
Cement works	1	18320
Duck Creek	1	15460
Dawsons Creek	1	21755
Cowans Bay	1	6410
Dyers Creek	2	6465
Grants Island	2	5600
Scotts Landing	5	750

* Here the influence of the variable thickness (k=1) surface layer can be seen. Close to the source there is a 20 cm layer of pure effluent (i.e. 10^6 FC/100 mL) which, when added to the next k=2 layer (presented here is this Table), would give higher effluent concentrations closer to the source.

Maps of hourly FC concentrations throughout the first two tidal cycles and subsequent high and low waters are given in Figure 14 for a four-hour overflow. One hour after the start of the overflow (2 hours prior to high water : Figure 14a top) the plume can be seen emerging from the Mahurangi River in the vicinity of Duck Creek. Peak concentrations within the plume of the order of 8000 FC/100 mL. One hour later

(Figure 14a bottom) the plume has moved to opposite Duck Creek with peak concentrations of the order of 7000 FC/100 mL. At high water (Figure 14b top) the core of the plume is just to the north of Vialls Landing and has concentrations of the order of 6500 FC/100 mL. One hour after high water (Figure 14b bottom) the plumes has emerged from the Mahurangi River and exhibits peak concentrations of the order of 6000 FC/100 mL. During the initial part of the falling tide (Figure 14c) tidal flows carry the plume down the estuary towards Hepburn Creek. Peak concentrations range from 4500 down to 2000 FC/100 ml. As peak ebb tidal flows occur the plume is rapidly transported beyond Hamiltons Landing and on to Cowans Bay (Figure 14d). Peak concentrations have dropped to around 2000 FC/100 mL. Approaching low water the plume reaches as far downstream as Grants Island with peak concentrations of around 1800 FC/100 mL (Figure 14e). On the incoming tide (Figure 14f) the plume is pushed back up the estuary towards Cowans Bay. Peak concentrations remain around 1500 FC/100 mL. Figure 14g shows the plume progressing further up the estuary with peak concentrations in the vicinity of Hepburn Creek of the order of 1500 FC/100 mL. By the second high water following the overflow event peak concentrations of the order of 1500 FC/100 mL are present on the inter-tidal areas between Vialls Landing and Hepburn Creek (Fig. 14h). Plots are given for the second tidal cycle and then for the next 6 successive high and low waters.

3.5 Four hour overflow event : Mahurangi River flow at 140 cumecs

Figure 15 shows the time series plots of the FC concentrations, generated solely by a high river flow and the four hour storm overflow, for the areas within the oyster farms (shown in Figure 1b). Table 9 gives the peak faecal coliform concentrations (at any time during the model simulation) for each of the oyster farms.

Table 9. Peak faecal coliform concentrations within the specified oyster farm sites for the four hour storm overflow event with a 140 cumec river inflow.

Oyster farm site	Tidal cycle of peak concentration	Peak faecal coliform concentration (FC/100 mL)
Cowans Bay	2	3380
Dyers Creek (North)	2	4350
Dyers Creek (South)	2	1465
Browns Bay	3	1845
Te Kapa Inlet	8	1040
Pukapuka Inlet	5	450
Huawai Bay	6	515

Figure 16 shows the time series plots of the FC concentrations for the sites within the main channel following the overflow event. Peak values reached at each of the main channel sites (at any time during the model simulation) are listed in Table 10.

Table 10. Peak faecal coliform concentrations within the main channel for the half hour overflow event with a 140 cumec river inflow.

Main channel site	Tidal cycle of peak concentration	Peak faecal coliform concentration (FC/100 mL)
Town Basin	1	5990 *
Cement works	1	16680
Duck Creek	1	9680
Dawsons Creek	1	4250
Cowans Bay	1	1950
Dyers Creek	1	7980
Grants Island	1	6160
Scotts Landing	2	1060

* Here the influence of the variable thickness (k=1) surface layer can be seen. Close to the source there is a 20 cm layer of pure effluent (i.e. 10^6 FC/100 mL) which, when added to the next k=2 layer (presented here is this Table), would give higher effluent concentrations closer to the source.

Maps of hourly FC concentrations throughout the first two tidal cycles and subsequent high and low waters are given in Figure 17. One hour after the start of the overflow (2 hours prior to high water : Figure 17a top) the plume has reached Vialls Landing. Peak concentrations within the plume of the order of 6000 FC/100 mL. One hour later (Figure 17a bottom) the plume has moved to the south of Vialls Landing and has peak concentrations of the order of 3500 FC/100 mL. At high water (Figure 17b top) the core of the plume is just to the north of Hepburn Creek and has concentrations of the order of 3500 FC/100 mL. One hour after high water (Figure 17b bottom) the plumes has reached the south of Hepburn Creek Inlet and exhibits peak concentrations of the order of 3500 FC/100 mL. During the initial part of the falling tide (Figure 17c) tidal flows carry the plume is rapidly moved down the estuary towards Cowans Bay. Peak concentrations range from 1100-800 FC/100 ml. As peak tidal flows occur the plume is rapidly transported beyond Grants Island (Figure 17d). Peak concentrations have dropped to around 900 FC/100 mL. Approaching low water the plume reaches as far downstream as Scotts Landing with peak concentrations of around 500 FC/100 mL (Figure 17e). On the incoming tide (Figure 17f) the plume is dispersed and covers a wide area from just south of Grants Island through to Cowans Bay. Peak concentrations remain around 350 FC/100 mL. Figure 17g shows the plume at progressing further up the estuary towards Hamilton Landing with relatively even concentrations of the order of 300 FC/100 mL. By the second high water following the overflow event (Figure 17h) peak concentrations of the order of 300 FC/100 mL are present over large areas of the estuary from Grants Island through to Hamiltons Landing. Plots are given for the second tidal cycle and then for the next 6 successive high and low waters.

3.6 Four hour overflow event : Mahurangi River flow at 5 cumecs

Figure 18 shows the time series plots of the FC concentrations for the areas within the oyster farms (shown in Figure 1) following the four-hour overflow event associated with a smaller river flow. Table 11 gives the peak faecal coliform concentrations (at any time during the model simulation) for each of the oyster farms.

Table 11. Peak faecal coliform concentrations within the specified oyster farm sites for the half hour overflow event with a 5 cumec river inflow.

Oyster farm site	Tidal cycle of peak concentration	Peak faecal coliform concentration (FC/100 mL)
Cowans Bay	5	1540
Dyers Creek (North)	7	740
Dyers Creek (South)	5	330
Browns Bay	8	165
Te Kapa Inlet	8	10
Pukapuka Inlet	8	10
Huawai Bay	-	0

Figure 19 shows the time series plots of the FC concentrations for the sites within the main channel following the overflow event. Peak values reached at each of the main channel sites (at any time during the model simulation) are listed in Table 12.

Table 12. Peak faecal coliform concentrations within the main channel for the half hour overflow event with a 5 cumec river inflow.

Main channel site	Tidal cycle of peak concentration	Peak faecal coliform concentration (FC/100 mL)
Town Basin	1	24515
Cement works	2	22900
Duck Creek	4	9080
Dawsons Creek	3	9150
Cowans Bay	3	2730
Dyers Creek	7	3295
Grants Island	7	1455
Scotts Landing	5	140

Maps of hourly FC concentrations throughout the first two tidal cycles and subsequent high and low waters are given in Figure 20. One hour after the start of the overflow (2 hours prior to high water : Figure 20a top) the plume can be seen emerging from the Mahurangi River in the vicinity of Duck Creek. Peak concentrations within the plume of the order of 12000 FC/100 mL. One hour later (Figure 20a bottom) the plume has moved to opposite Duck Creek with peak concentrations of the order of 11000 FC/100 mL. At high water (Figure 20b top) the core of the plume is just to the north of Vialls Landing and has concentrations of the order of 10000 FC/100 mL. One hour after high water (Figure 20b bottom) the plumes has emerged from the Mahurangi River and exhibits peak concentrations of the order of 10000 FC/100 mL. During the initial part of the falling tide (Figure 20c) tidal flows carry the plume down the estuary towards Hepburn Creek. Peak concentrations range from 4000 down to 3000 FC/100 ml. As peak tidal flows occur the plume is rapidly transported beyond Hamiltons Landing and on to Cowans Bay (Figure 20d). Peak concentrations have dropped to around 3000 FC/100 mL. Approaching low water the plume reaches as far downstream as Grants Island with peak concentrations of around 3000 FC/100 mL (Figure 20e). On the incoming tide (Figure 20f) the plume is pushed back up the estuary towards Cowans Bay. Peak concentrations remain around 3000 FC/100 mL. Figure 20g shows the plume at progressing further up the estuary with peak concentrations in the vicinity of Hepburn Creek of the order of 3000 FC/100 mL. By the second high water following the overflow event peak concentrations of the order of 3000 FC/100 mL are present on the inter-tidal areas between Vialls Landing and Hepburn Creek. Plots are given for the second tidal cycle and then for the next 6 successive high and low waters.

4.0 DISCUSSION

Data presented in this report gives details of modelled storm-overflow events from the Warkworth STW system. The data presented shows there is potential for relatively high FC concentrations to be present within the Mahurangi Estuary following any overflow event at Warkworth. Not only the length of the overflow event but also the river flows present at the time of the overflow determine the extent and concentrations of the resulting plume.

Figures 21a-b show the time series of predicted FC concentrations within the main channel at Dawsons Creek and Grants Island for each of the overflow events modelled. It can be seen that an increase in duration of the storm overflow (Fig. 21a) increases FC concentrations within the main channel throughout the estuary. The timing of the arrival of the peak in concentration is directly related to river flow (Fig. 21b) with higher river flows producing a peak in concentrations more rapidly than lower flows. Lower river flows result in a more persistent plume throughout the estuary following the slower arrival of the peak concentration.

Based on the most likely 35 cumec river flow scenario, the central core of the plume in the main channel is diluted relatively quickly resulting in a rapid drop off in FC concentrations on successive tidal cycles (e.g. Figure 4). Within the inter-tidal areas (and therefore oyster farms) this fall off in FC concentrations following the peak is more gradual (e.g. Figure 3).

Predictions for areas nearer the entrance (i.e. Huawai Bay, Pukapuka Inlet) show that peak FC concentrations, albeit smaller than up-estuary sites, occur at anything from 4 to 8 tidal cycles after the overflow. Over this length of time it is likely that some degree of FC inactivation would have occurred. For example, even assuming a midday winter FC die-off T_{90} value of 100 hours, concentrations near the entrance after 7 tidal cycles would be reduced to down around 15% of those presented.

5.0 REFERENCES

Black, K.P. (1995). "The numerical hydrodynamic model 3DD and support software", Occasional Report No. 19, Department of Earth Sciences, University of Waikato, New Zealand. 53 pp.

Black, K.P. (1996). "Lagrangian dispersal and sediment transport model POL3DD", Occasional Report No. 21, Department of Earth Sciences, University of Waikato, New Zealand. 69 pp.

Oldman, J.W. and Black, K.P. (1997). "Mahurangi Estuary numerical modelling", NIWA Consultancy Report ARC60208/1.

Oldman, J.W. (1998). "Numerical modelling of Warkworth sewage discharge to Mahurangi Estuary", NIWA Consultancy Report ARC70216/1.

Oldman, J.W.; Stroud, M.J.; Cummings, V.J; Cooper, A.B. (1998). "Land use scenario modelling", NIWA Consultancy Report ARC70216/2.

Swales, A.; Hume, T.M.; Oldman, J.W.; Green, M.O. (1997). "Mahurangi Estuary : Sedimentation History and Recent Human Impacts", NIWA Client Report ARC60210.

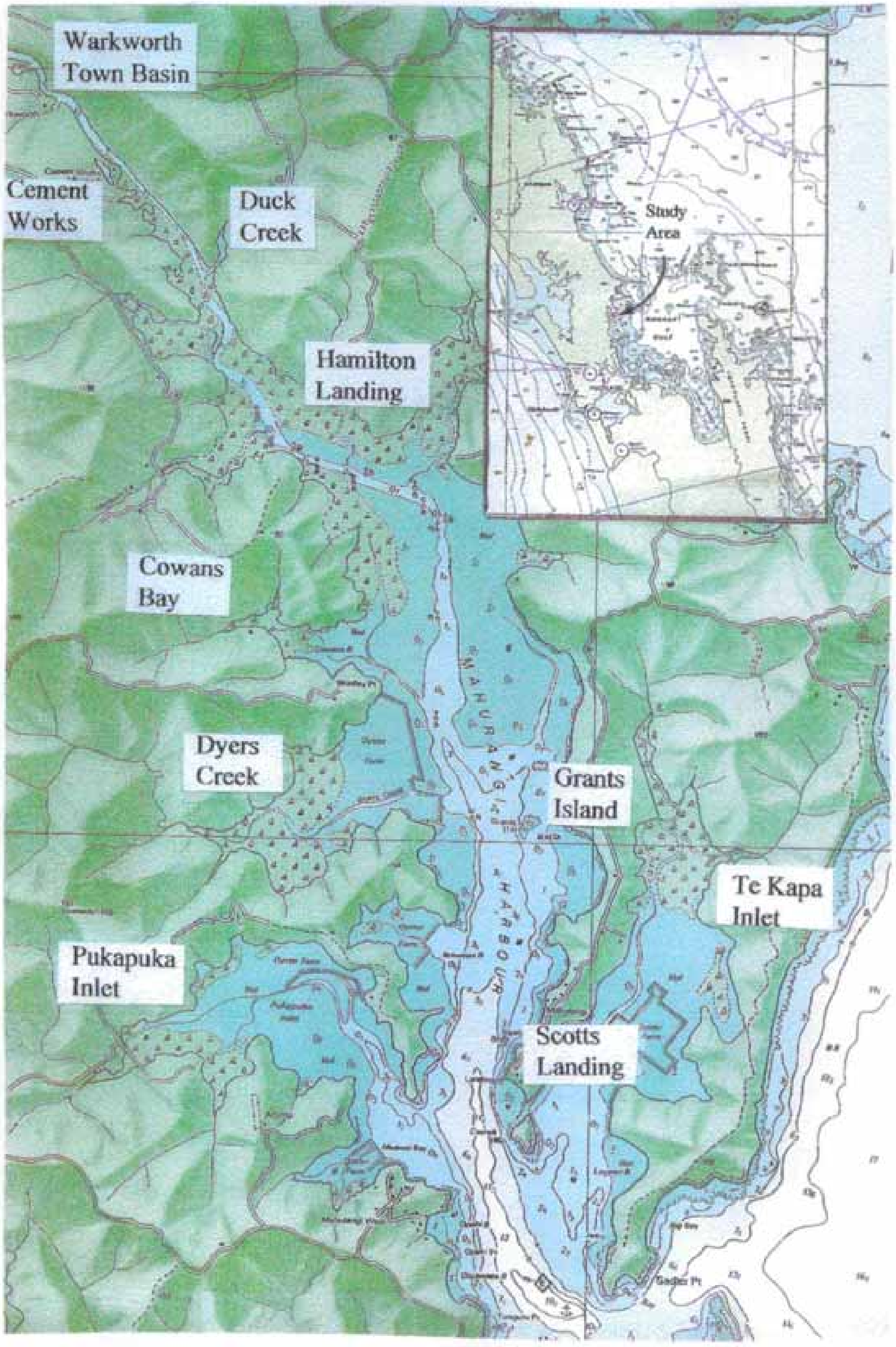


Figure 1. Location map for the Mahurangi Estuary : from hydrographic chart NZ5321 (with permission from the Royal New Zealand Navy).

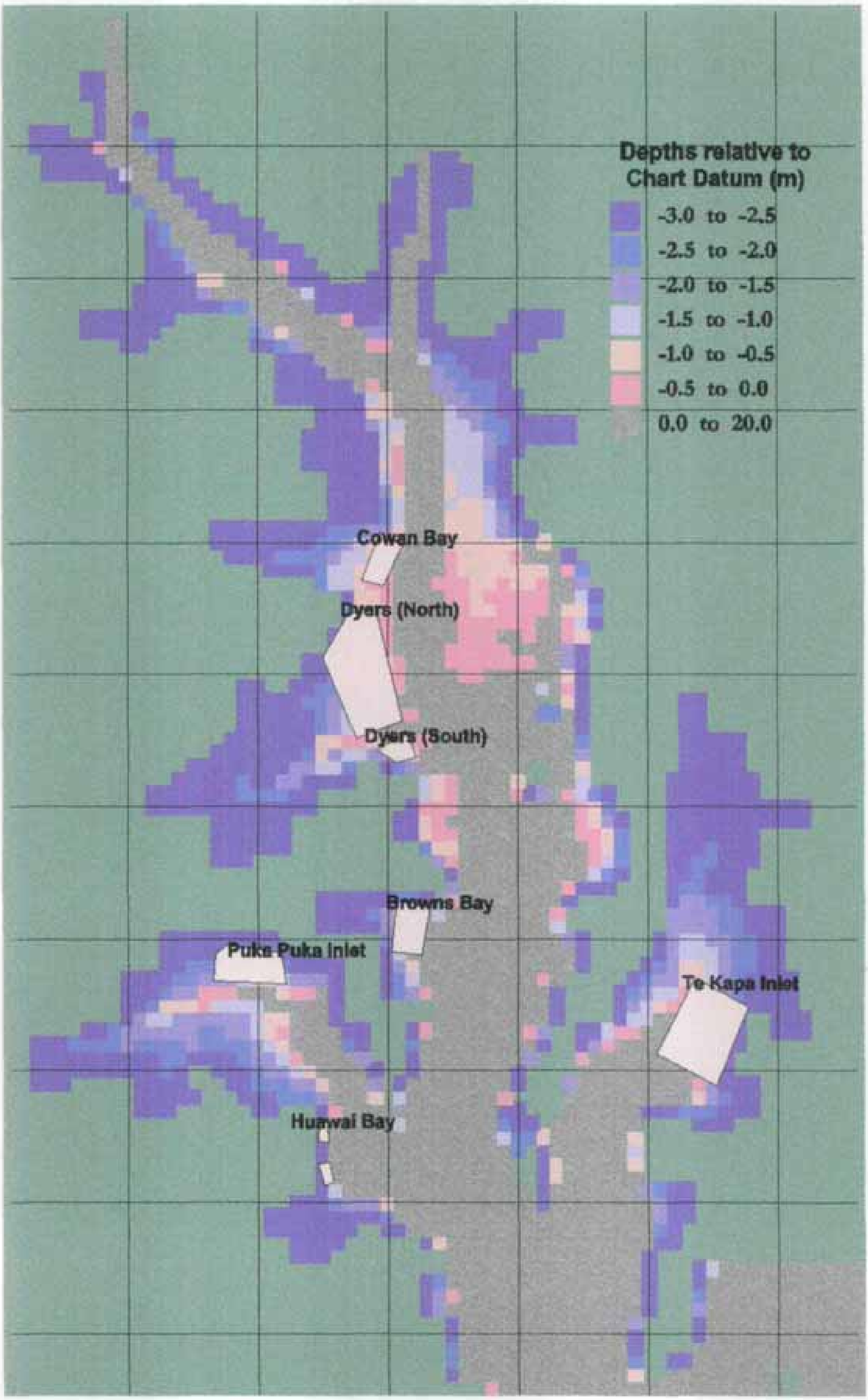


Figure 1b. Location of oyster farms within the Mahurangi Estuary.

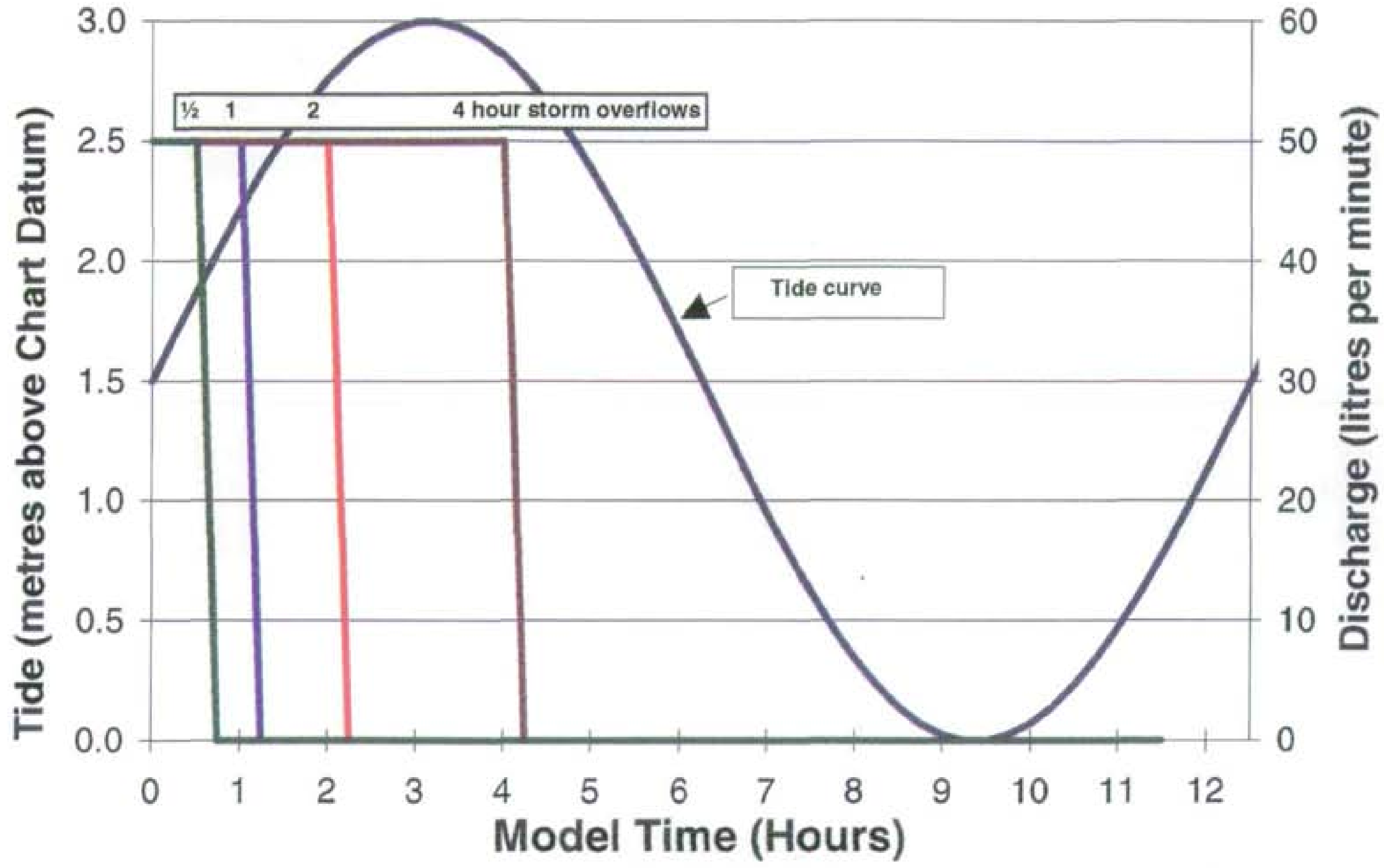


Figure 2. Storm overflow discharge and tidal curves used for study.

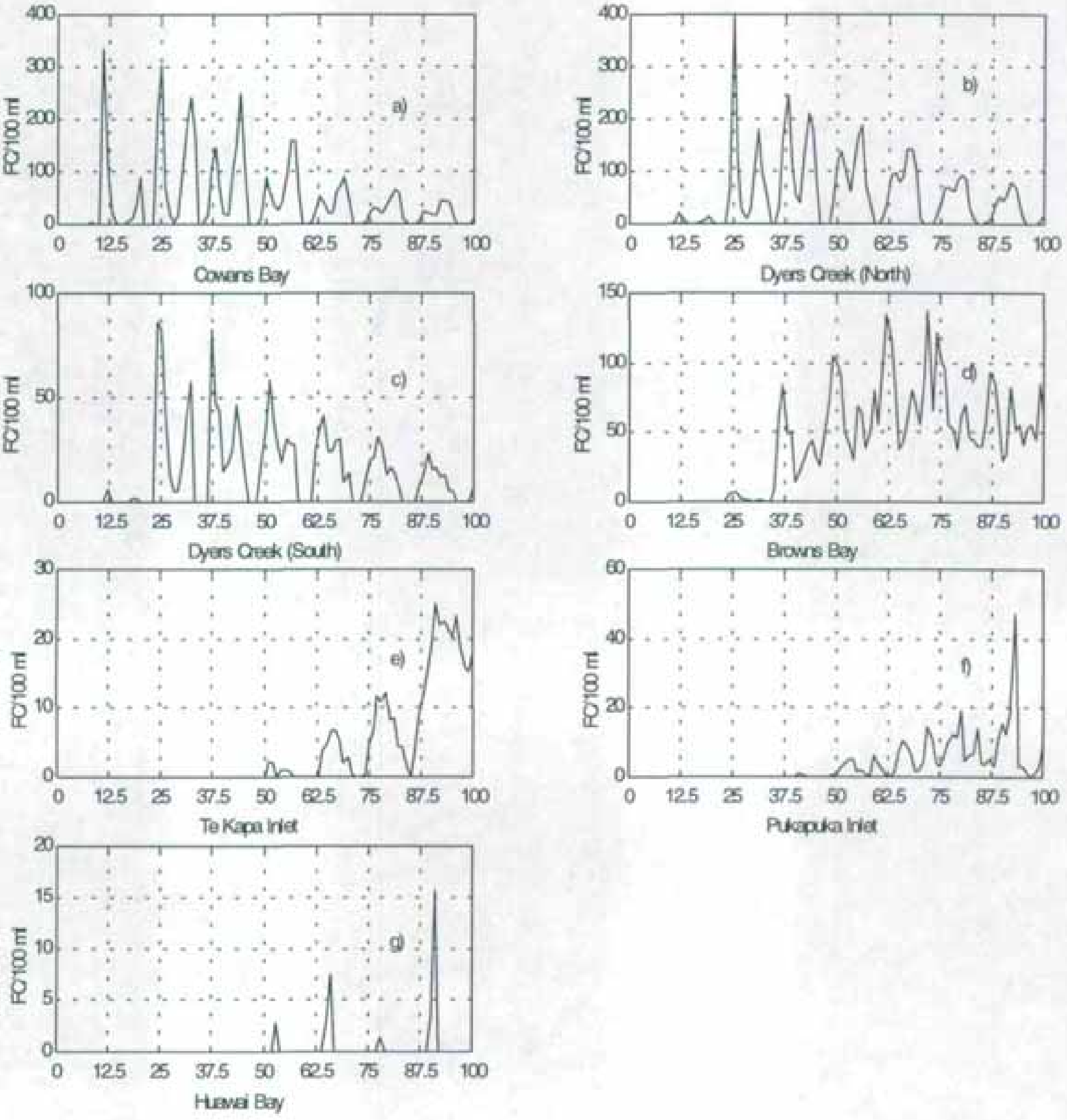


Figure 3. Predicted Faecal Coliform concentrations within the oyster farms for a half hour overflow event with 35 cumec freshwater inflows. (Horizontal axis is time in elapsed hours from the model start. Note: each tidal cycle = 12.5 hours).

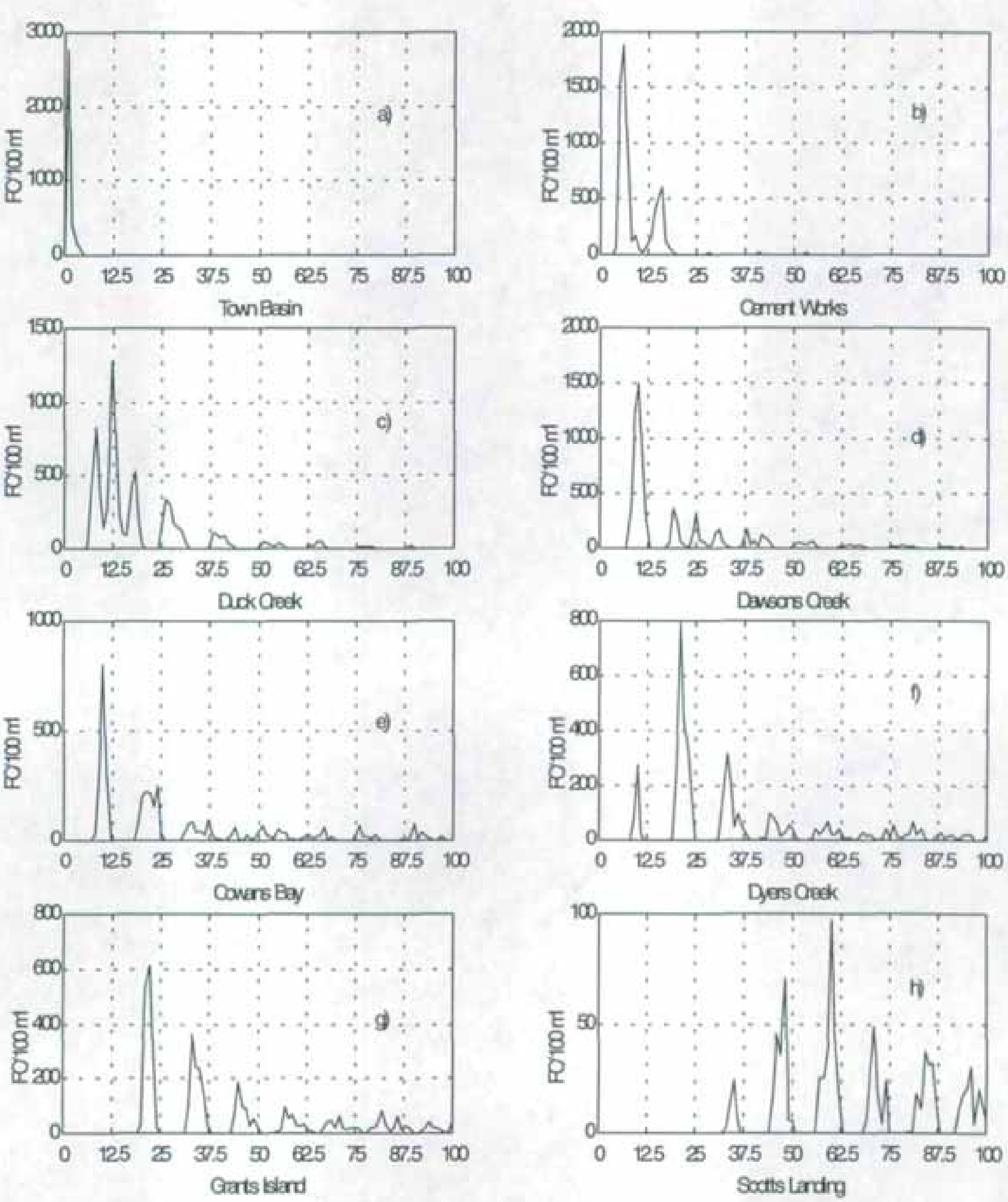


Figure 4. Predicted Faecal Coliform concentrations within the main channel for a half hour overflow event with 35 cumec freshwater inflows. (Horizontal axis is time in elapsed hours from the model start. Note: each tidal cycle = 12.5 hours).

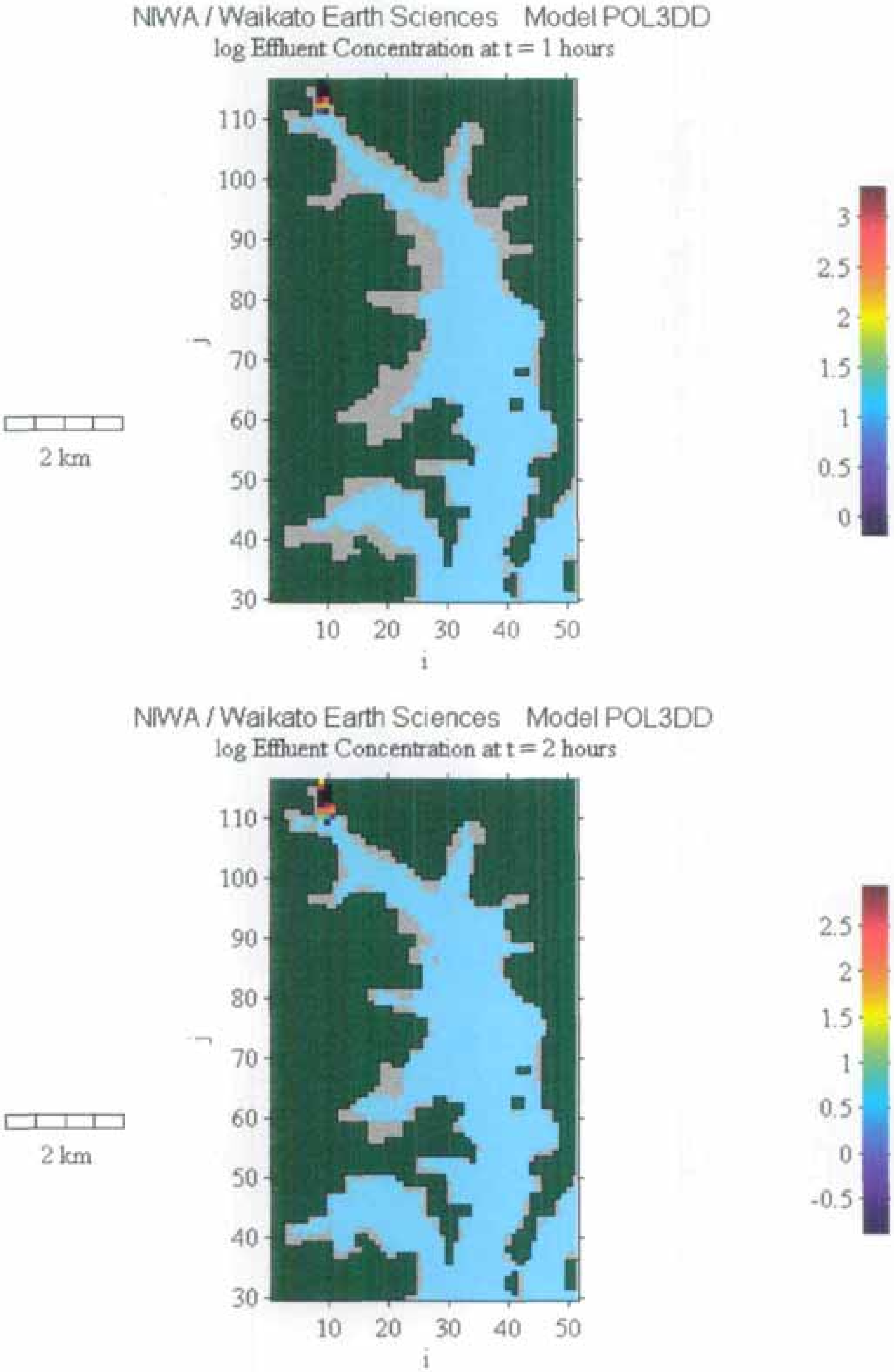


Figure 5a. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary at 1 hour and 2 hours after the start of a half hour overflow event with 35 cumecs freshwater inflows. (Examples: $2=10^2$ FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)

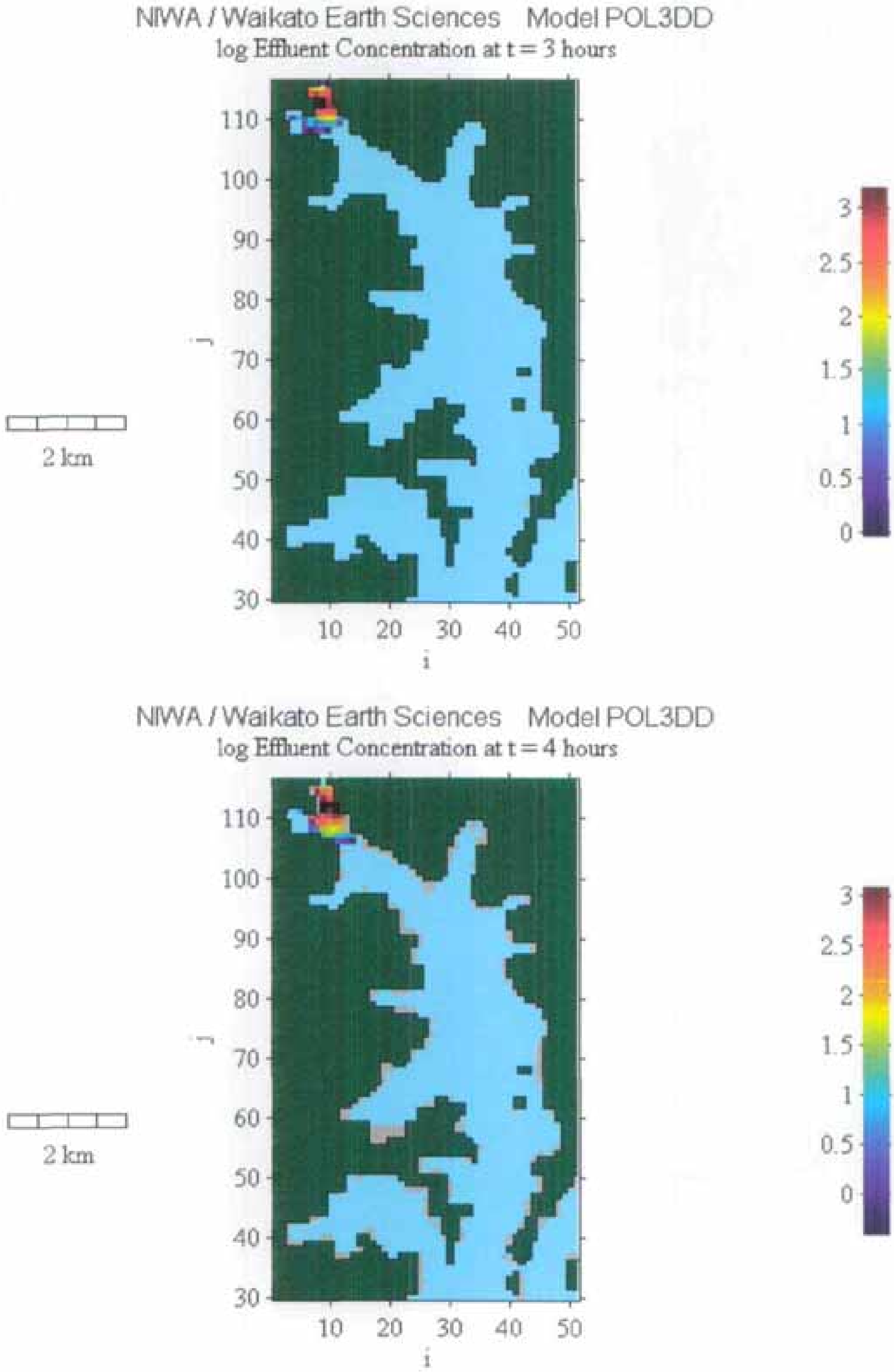


Figure 5b. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary at 3 hours and 4 hours after the start of a half hour overflow event with 35 cumecs freshwater inflows. (Examples: $2=10^2$ FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)

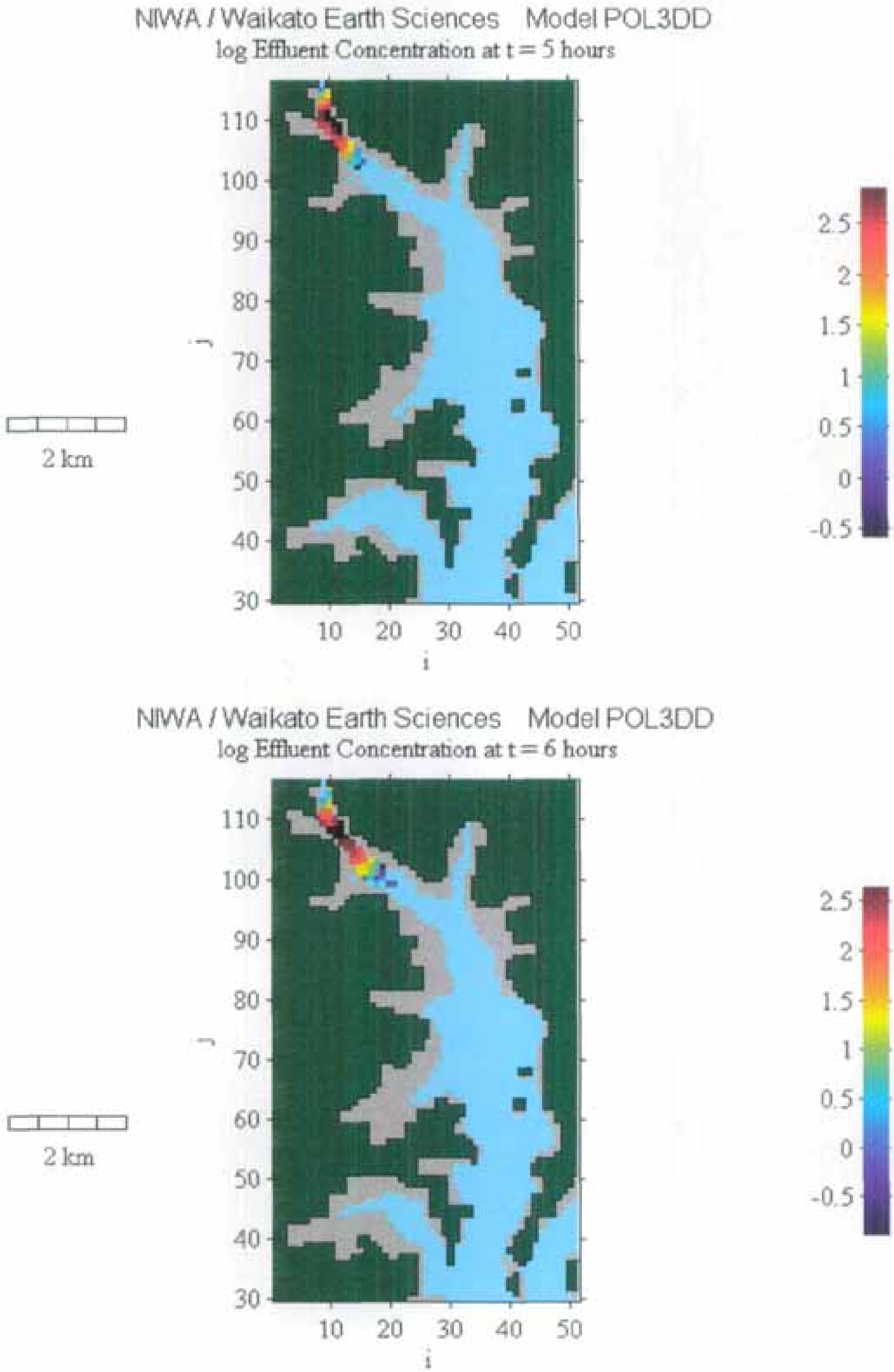


Figure 5c. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary at 5 hours and 6 hours after the start of a half hour overflow event with 35 cumecs freshwater inflows. (Examples: $2=10^2$ FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)

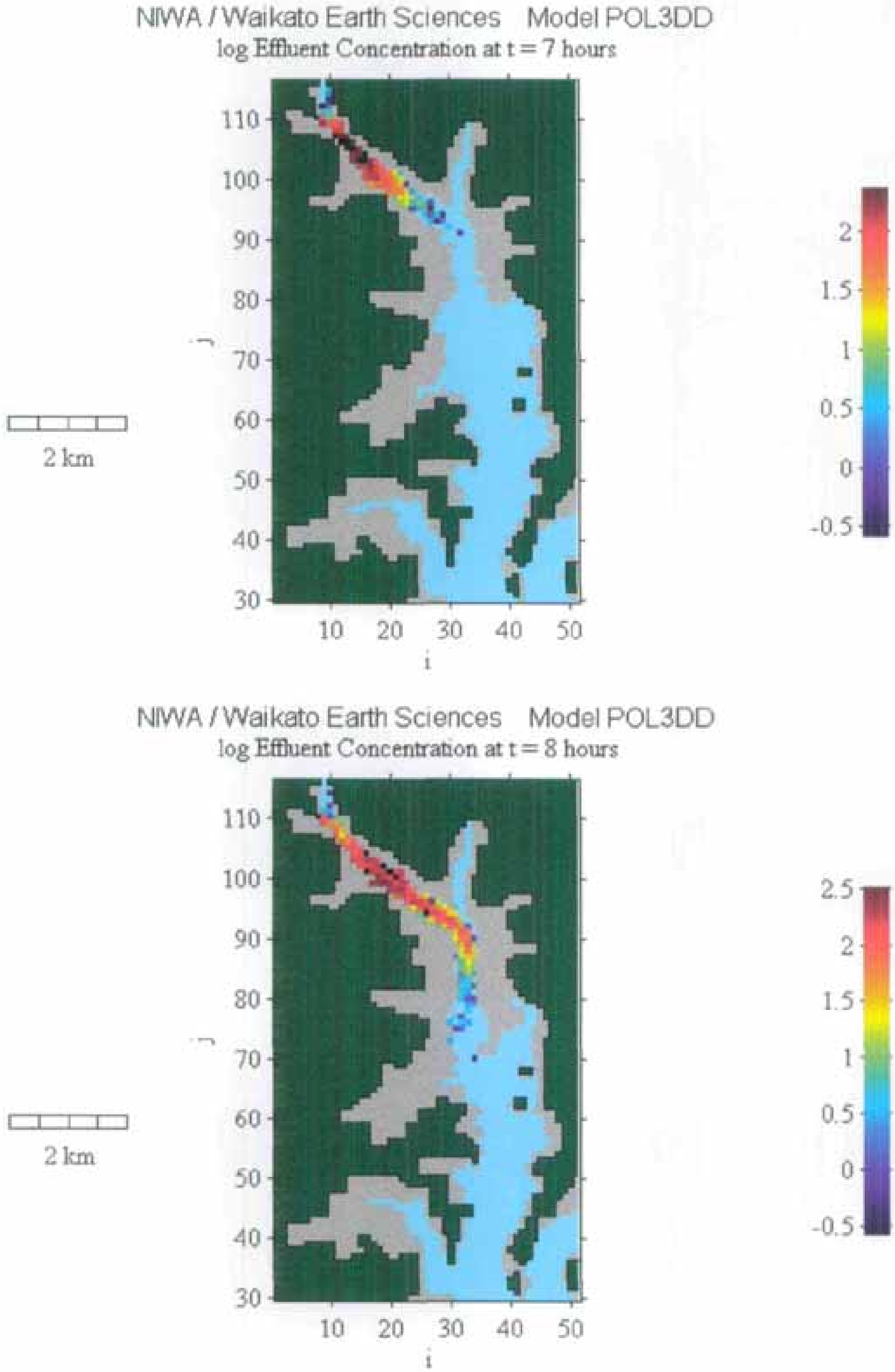


Figure 5d. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary at 7 hours and 8 hours after the start of a half hour overflow event with 35 cumecs freshwater inflows. (Examples: 2=10^2 FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)

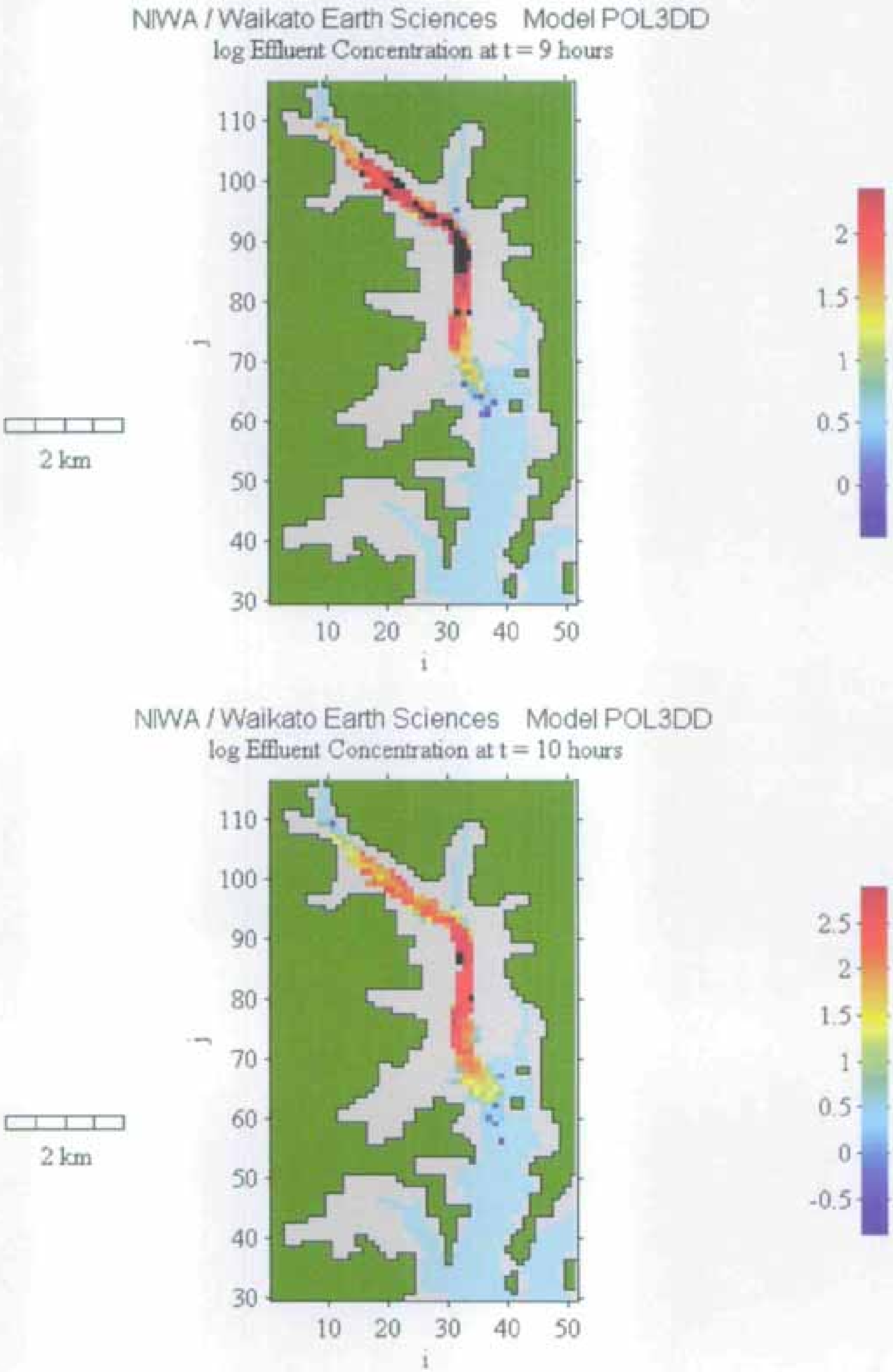
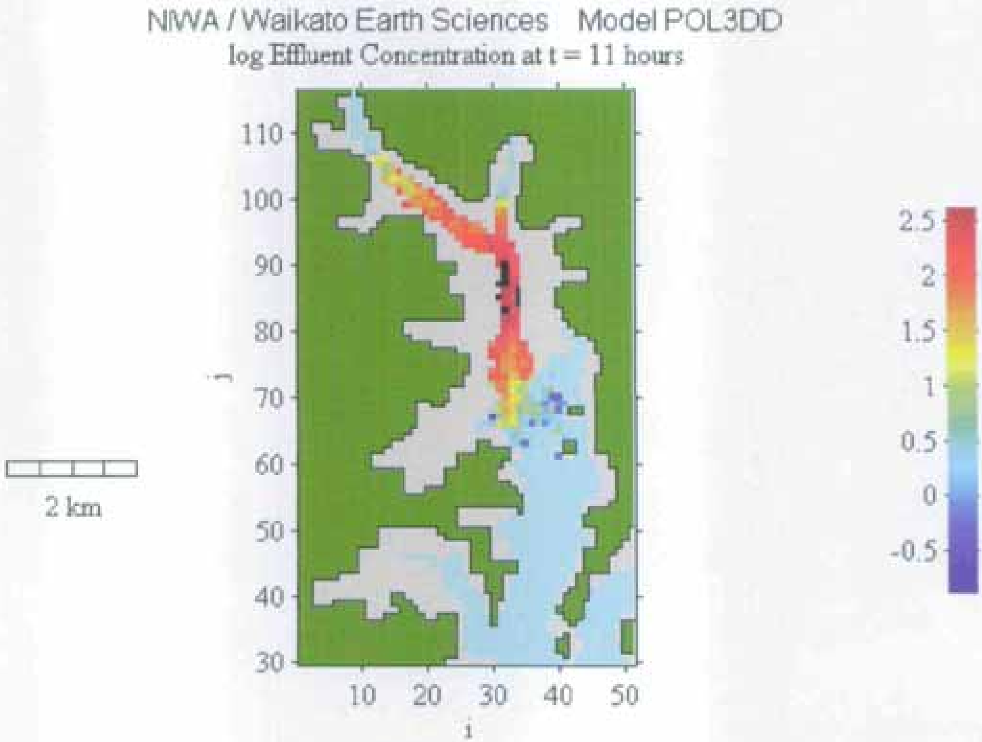


Figure 5e. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary at 9 hours and 10 hours after the start of a half hour overflow event with 35 cumecs freshwater inflows. (Examples: 2=10^2 FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)



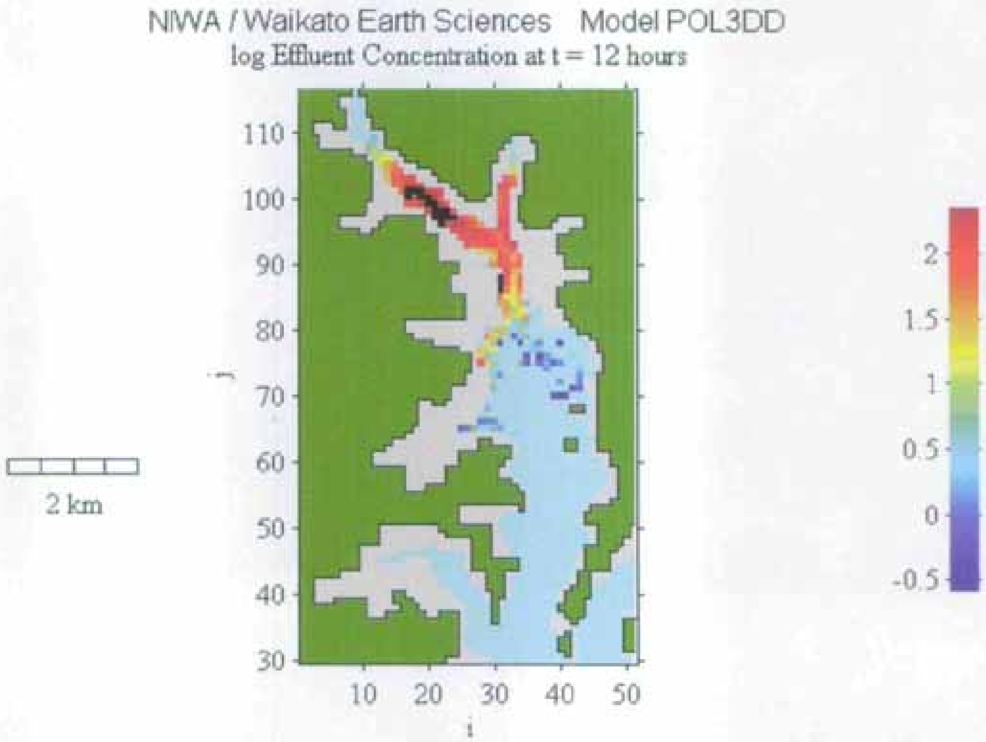


Figure 5f. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary at 11 hours and 12 hours after the start of a half hour overflow event with 35 cumecs freshwater inflows. (Examples: $2=10^2$ FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)

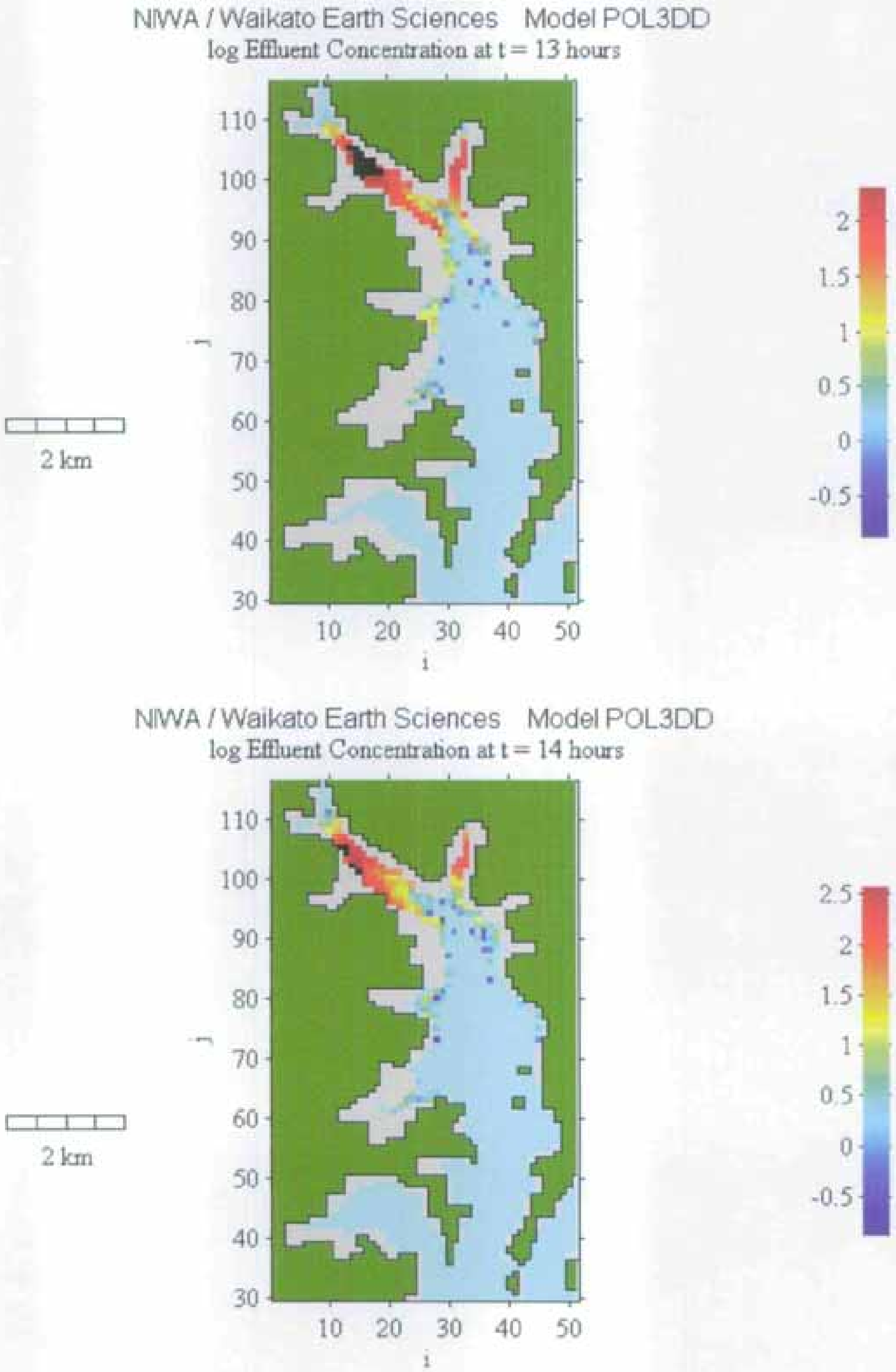


Figure 5g. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary at 13 hours and 14 hours after the start of a half hour overflow event with 35 cumecs freshwater inflows. (Examples: $2=10^2$ FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)

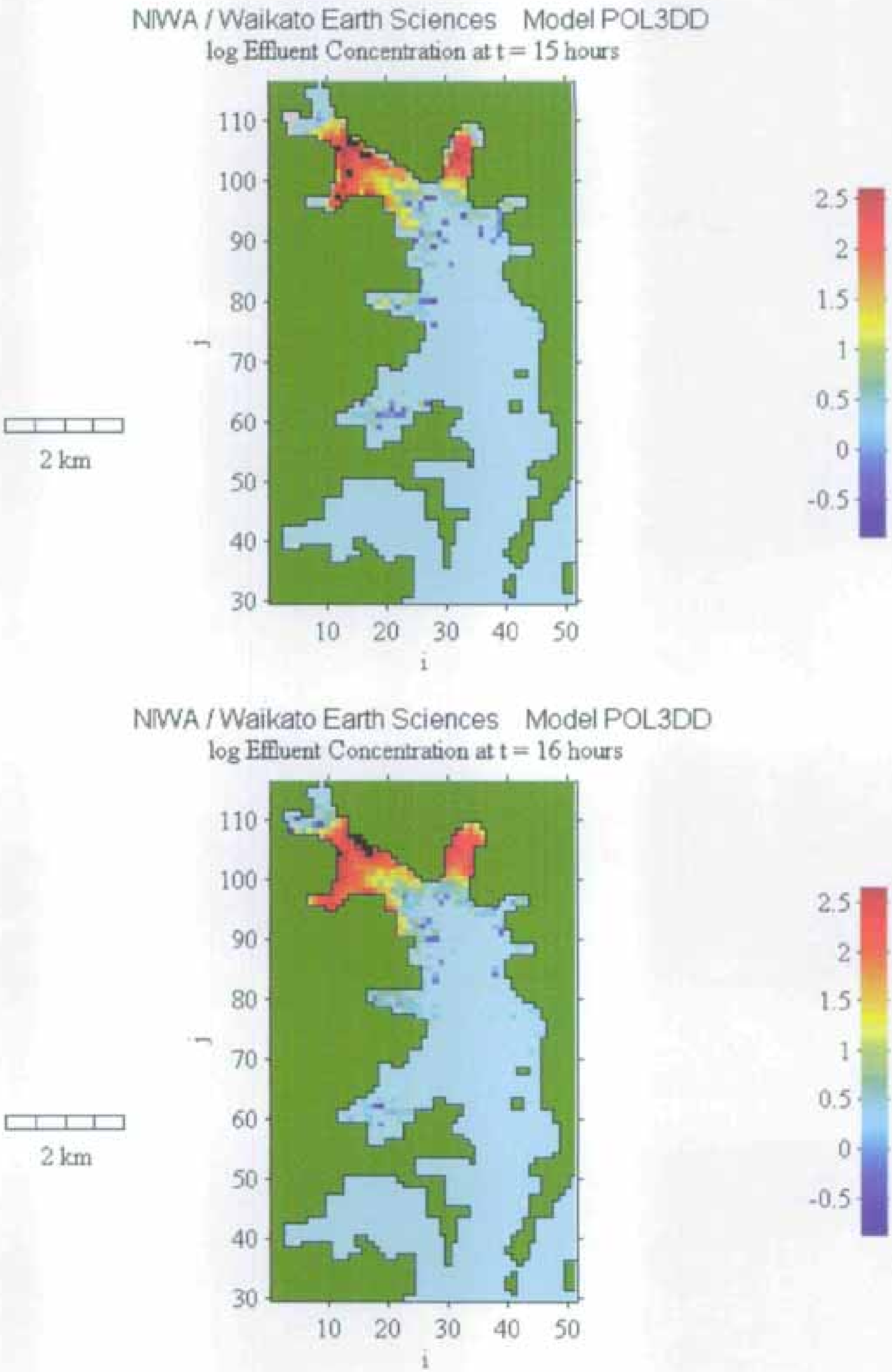


Figure 5h. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary at 15 hours and 16 hours after the start of a half hour overflow event with 35 cumecs freshwater inflows. (Examples: $2=10^2$ FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)

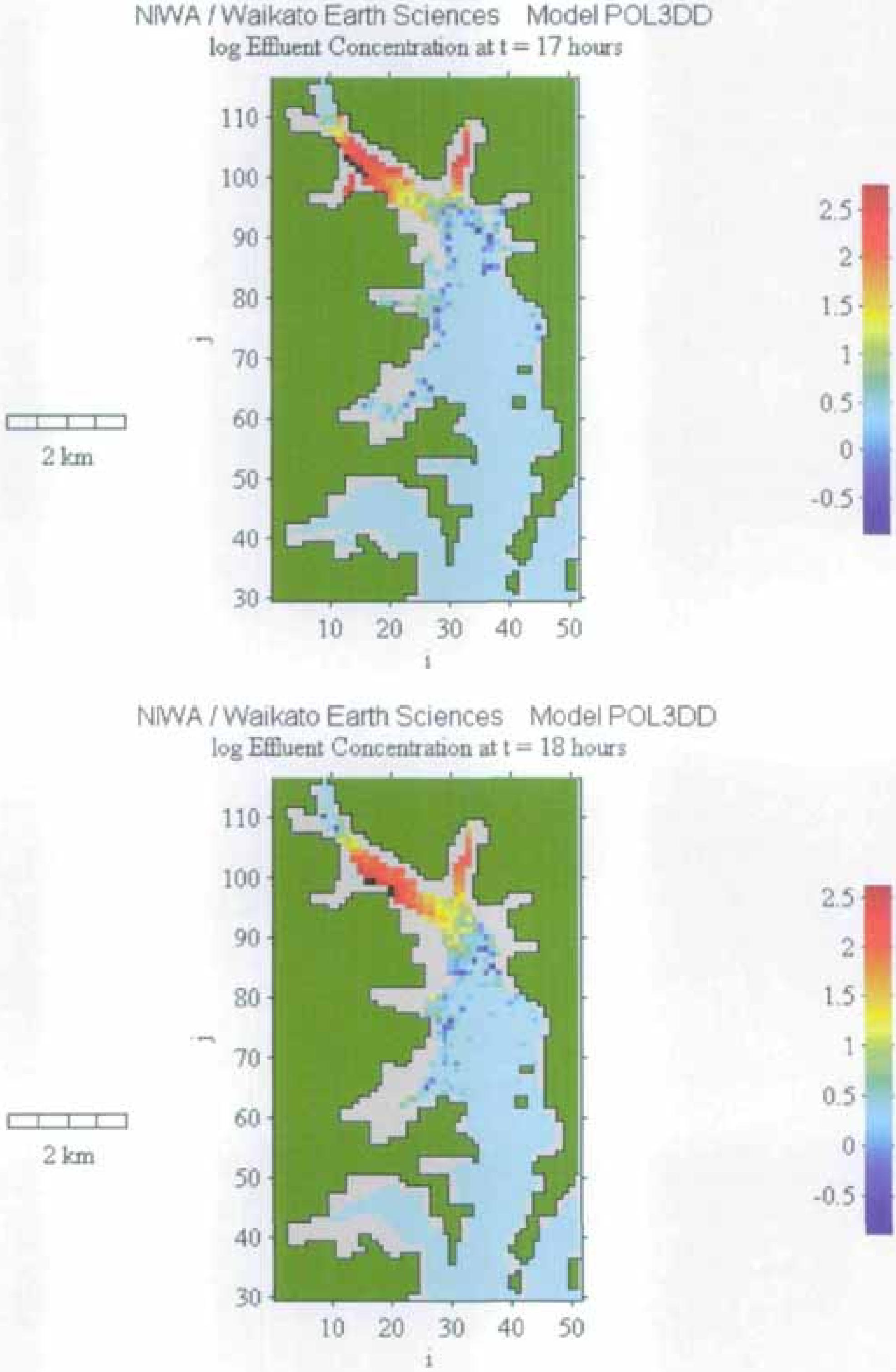


Figure 5i. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary at 17 hours and 18 hours after the start of a half hour overflow event with 35 cumecs freshwater inflows. (Examples: $2=10^2$ FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)

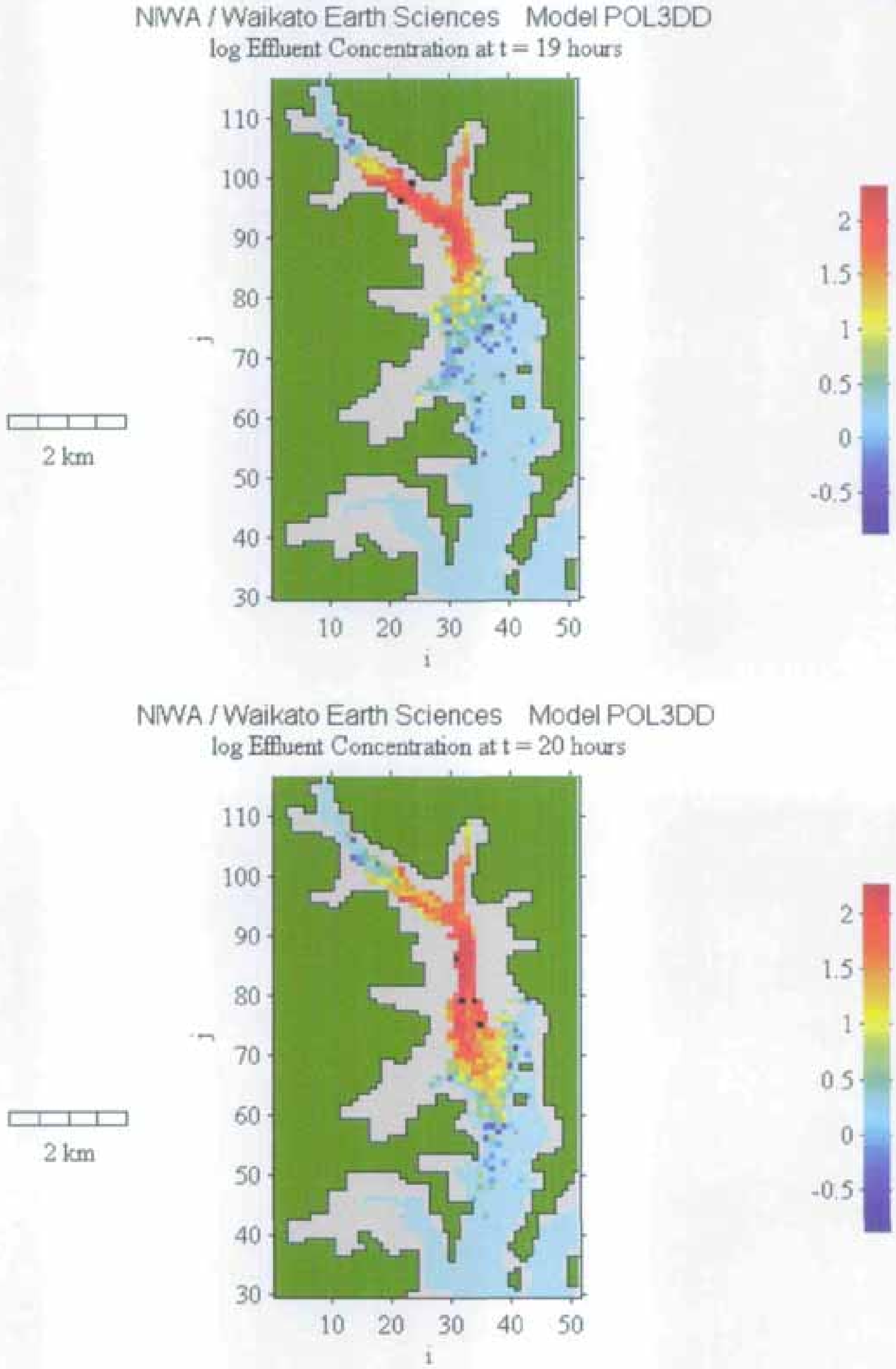


Figure 5j. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary at 19 hours and 20 hours after the start of a half hour overflow event with 35 cumecs freshwater inflows. (Examples: 2=10^2 FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)

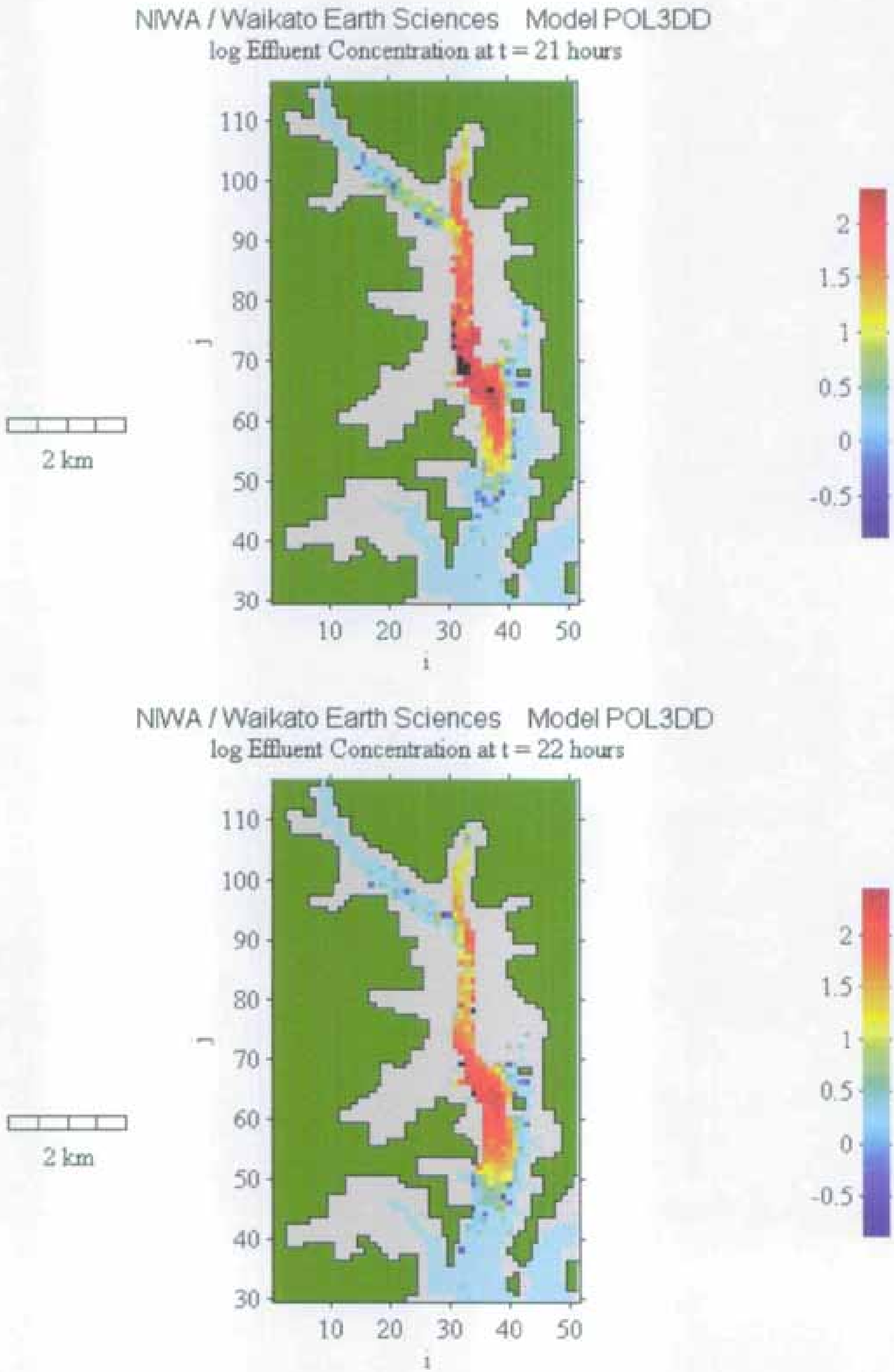


Figure 5k. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary at 21 hours and 22 hours after the start of a half hour overflow event with 35 cumecs freshwater inflows. (Examples: $2=10^2$ FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)

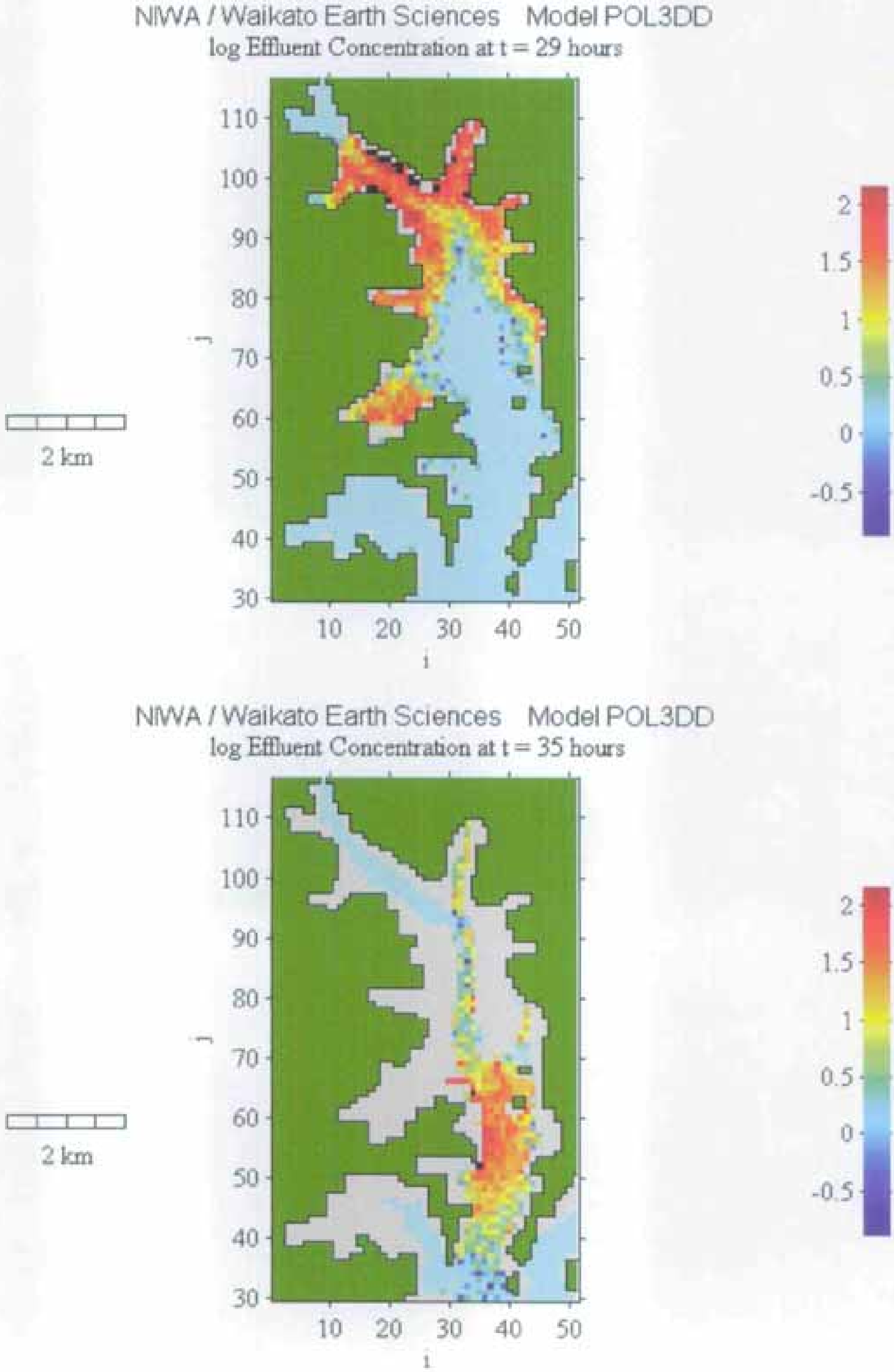


Figure 5l. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary for the 3rd high and low waters after the start of a half hour overflow event with 35 cumecs freshwater inflows. (Examples: $2=10^2$ FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)

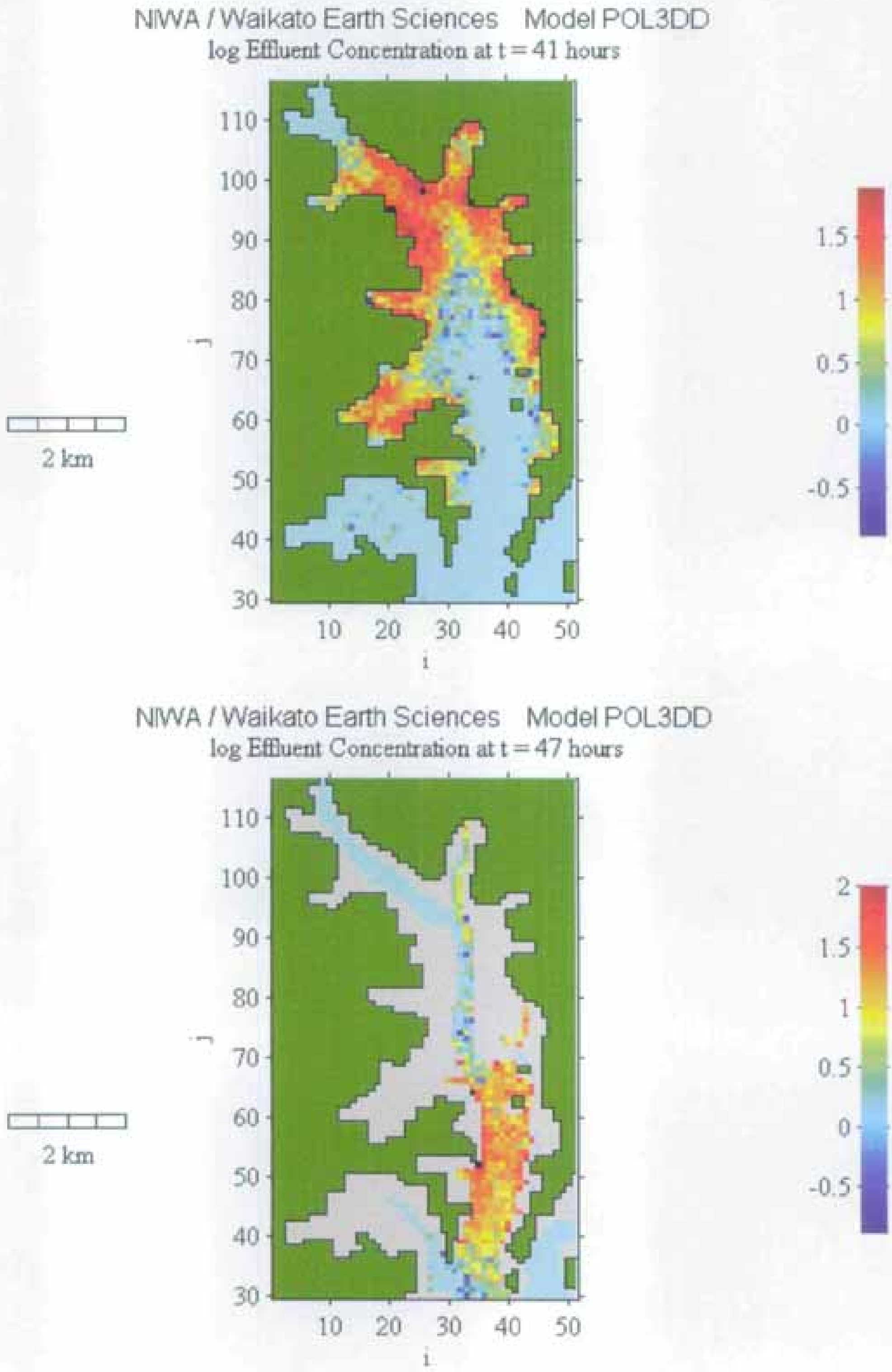


Figure 5m. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary for the 4th high and low waters after the start of a half hour overflow event with 35 cumecs freshwater inflows. (Examples: $2=10^2$ FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)

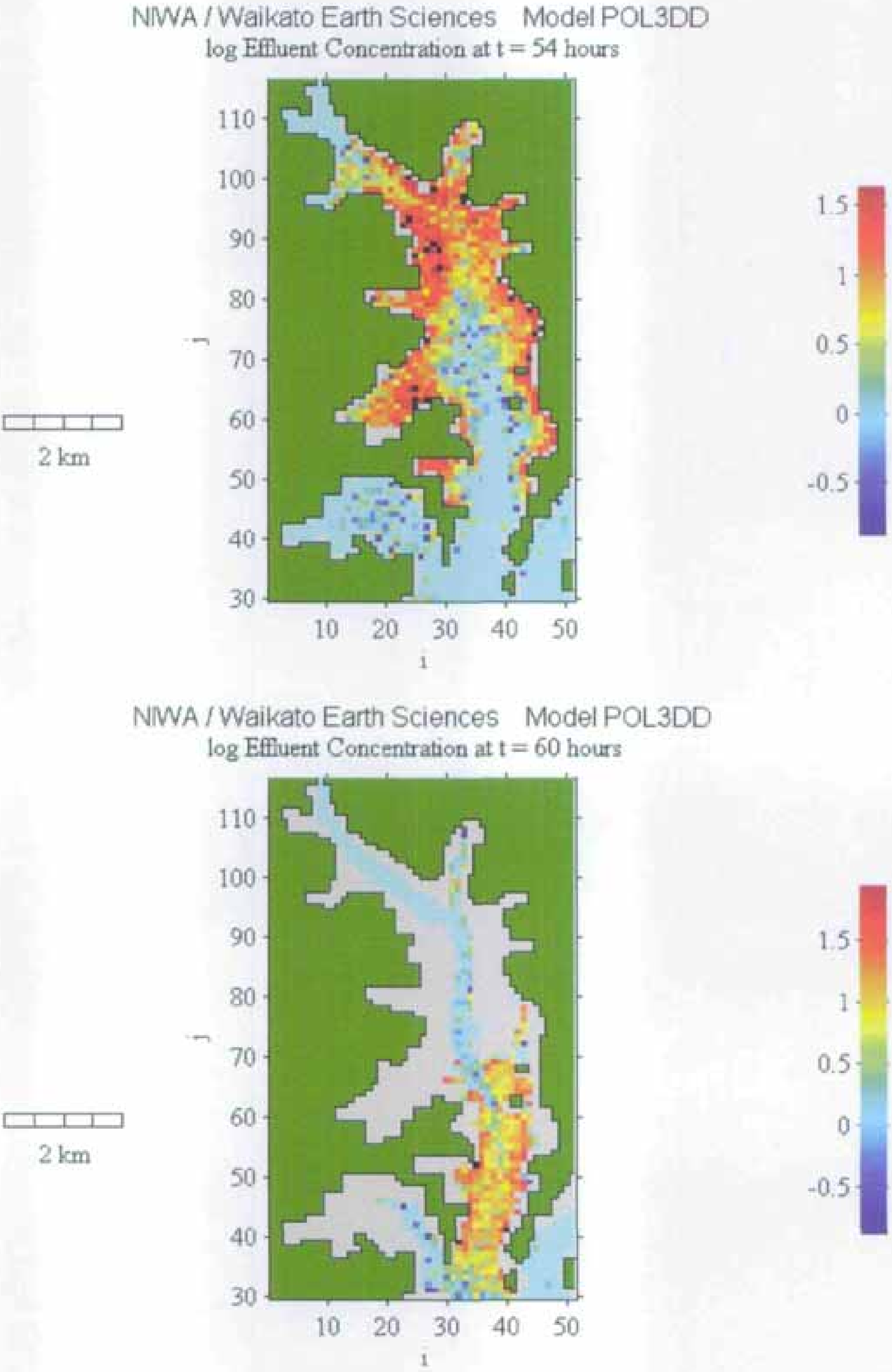


Figure 5n. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary for the 5th high and low waters after the start of a half hour overflow event with 35 cumecs freshwater inflows. (Examples: $2=10^2$ FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)

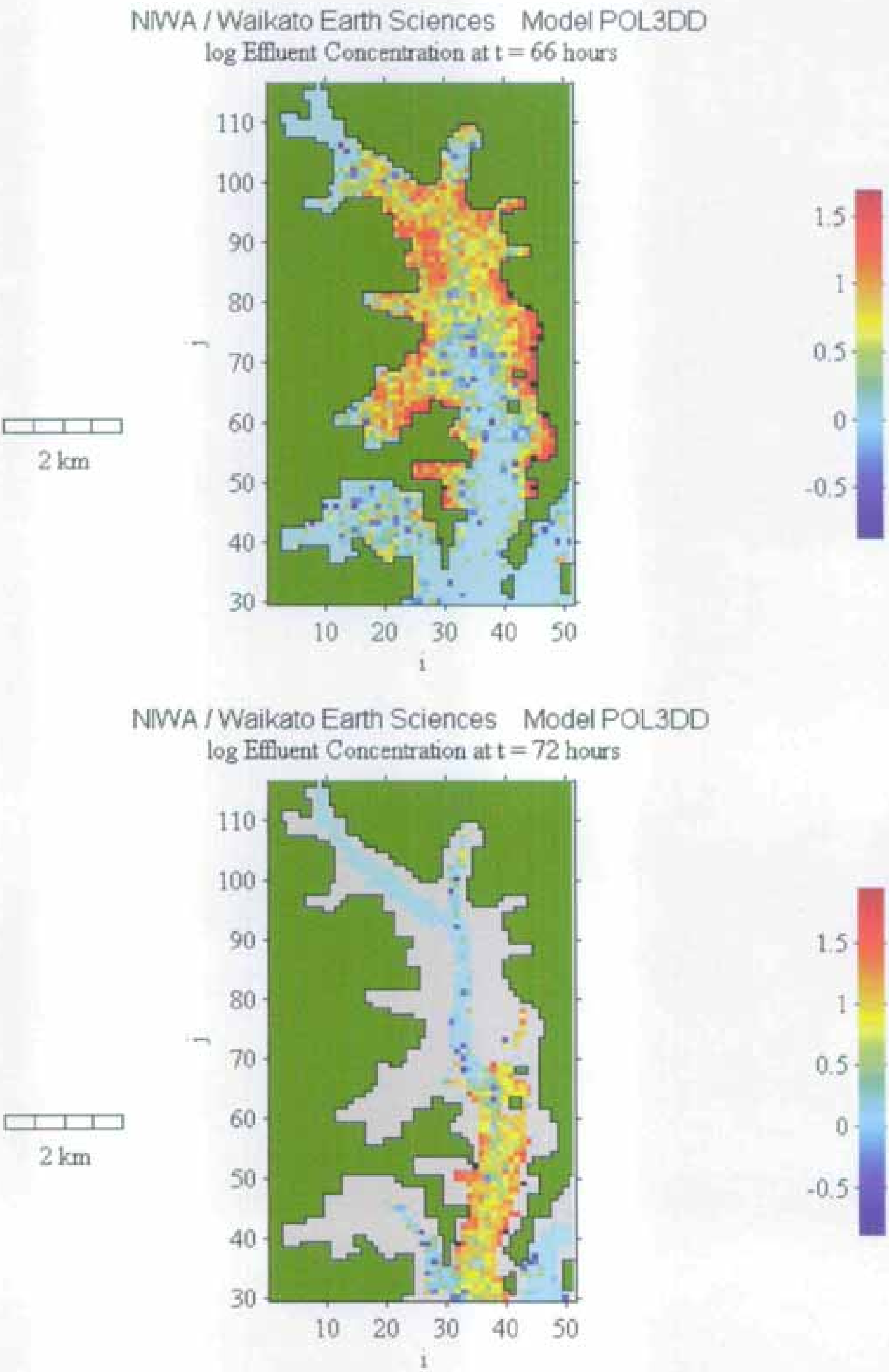


Figure 5o. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary for the 6th high and low waters after the start of a half hour overflow event with 35 cumecs freshwater inflows. (Examples: $2=10^2$ FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)

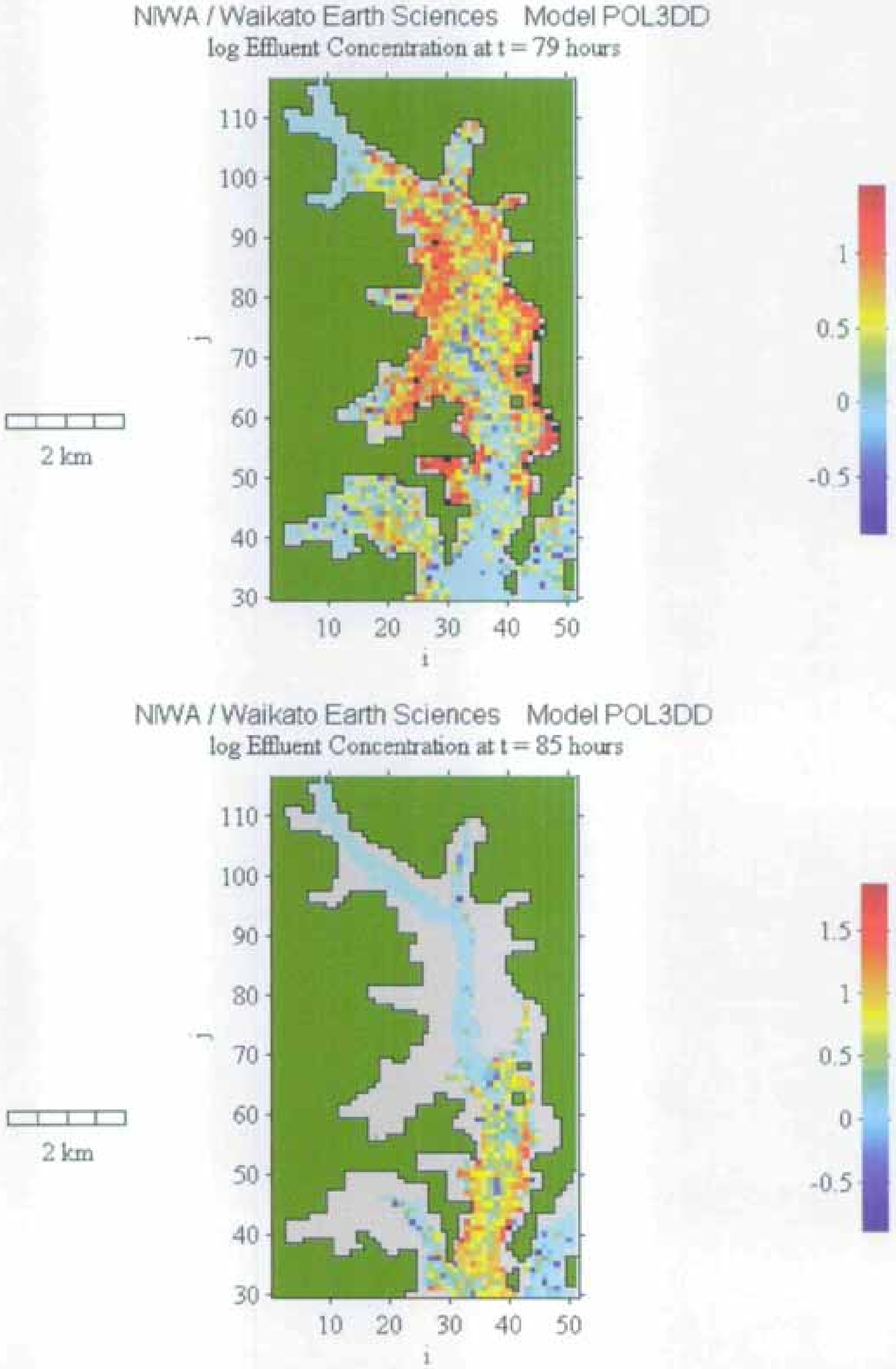


Figure 5p. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary for the 7th high and low waters after the start of a half hour overflow event with 35 cumecs freshwater inflows. (Examples: $2=10^2$ FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)

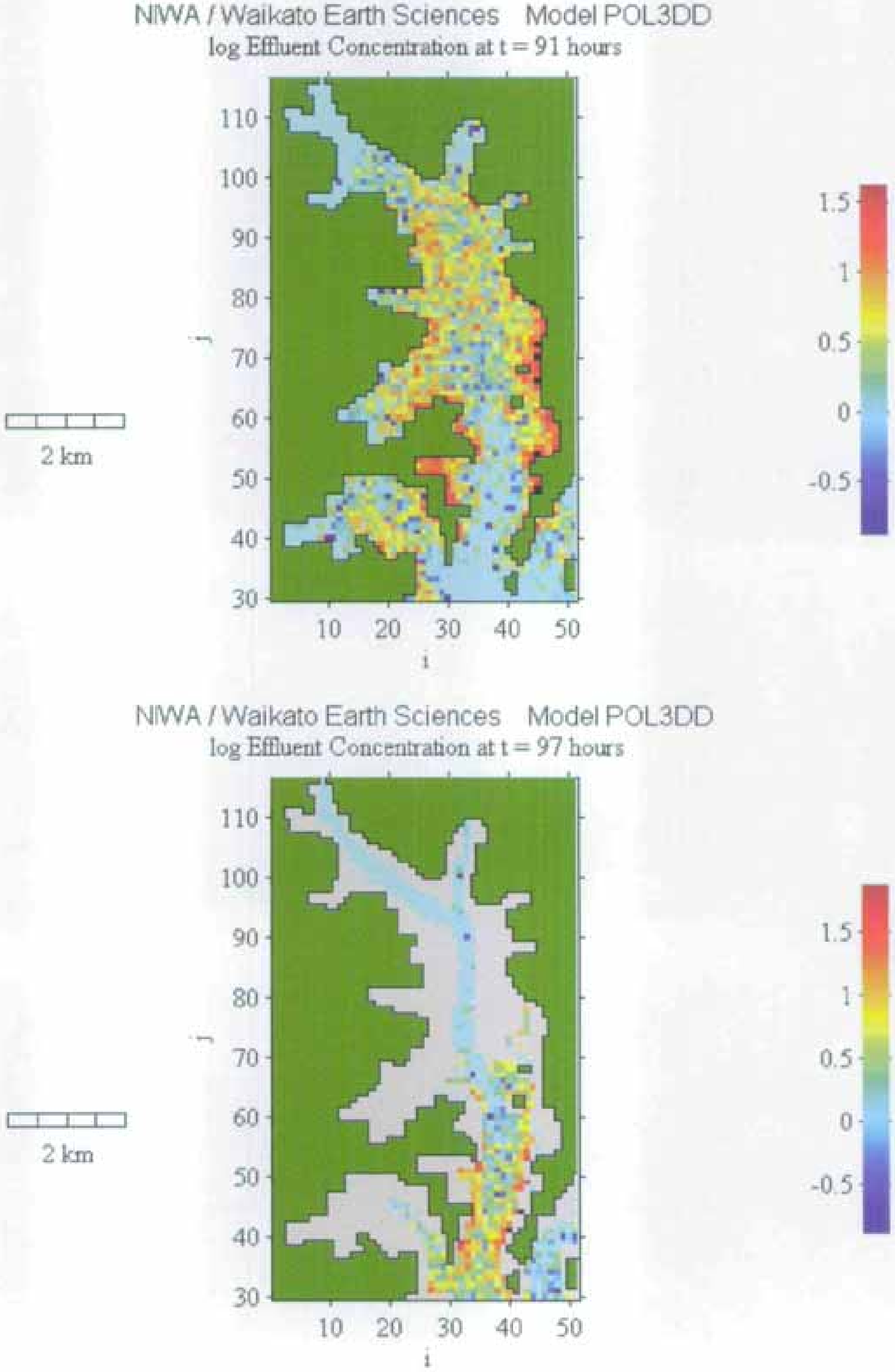


Figure 5q. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary for the 8th high and low waters after the start of a half hour overflow event with 35 cumecs freshwater inflows. (Examples: $2=10^2$ FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)

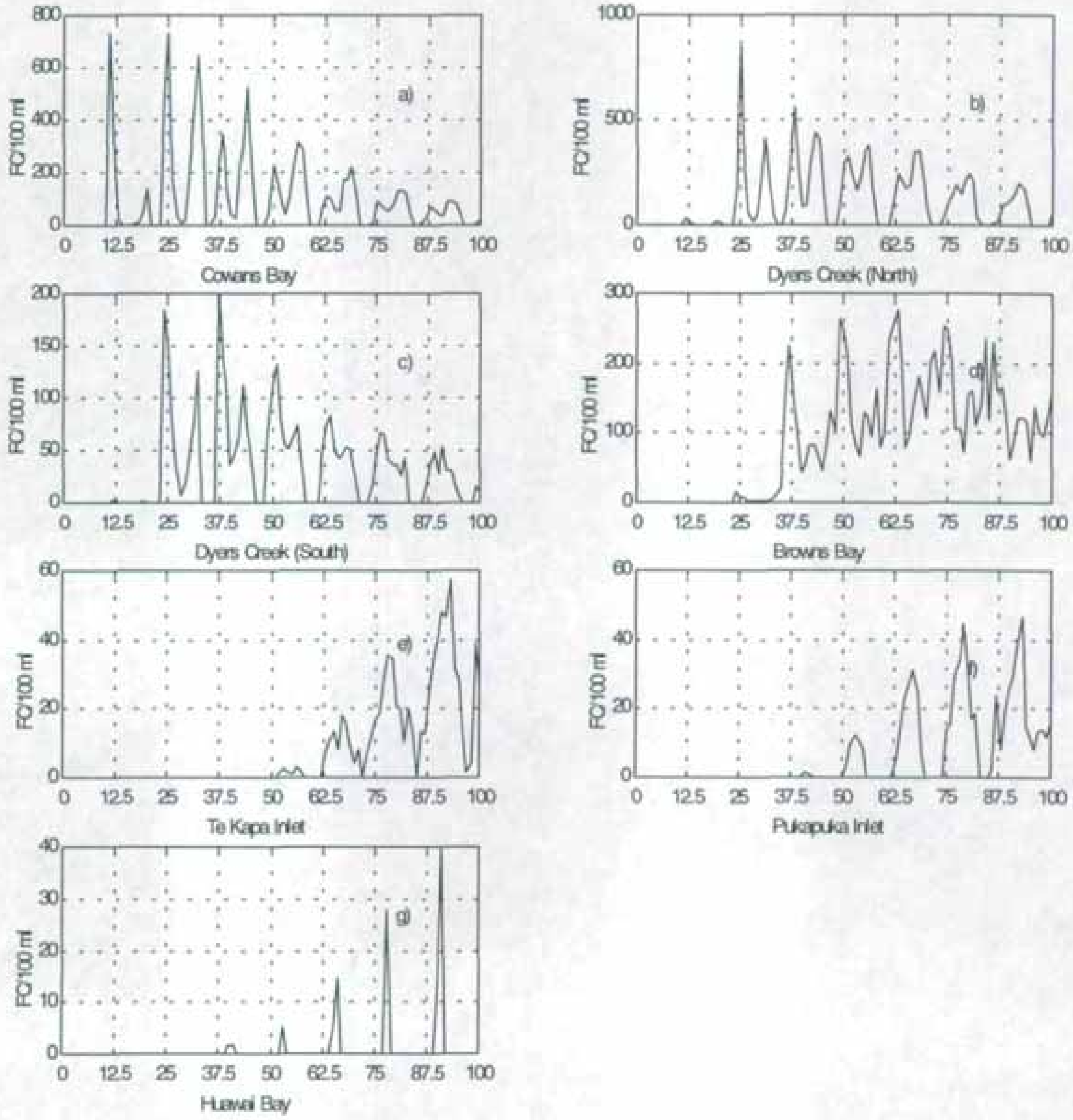


Figure 6. Predicted Faecal Coliform concentrations within the oyster farms for a one hour overflow event with 35 cumec freshwater inflows. (Horizontal axis is time in elapsed hours from the model start. Note: each tidal cycle = 12.5 hours).

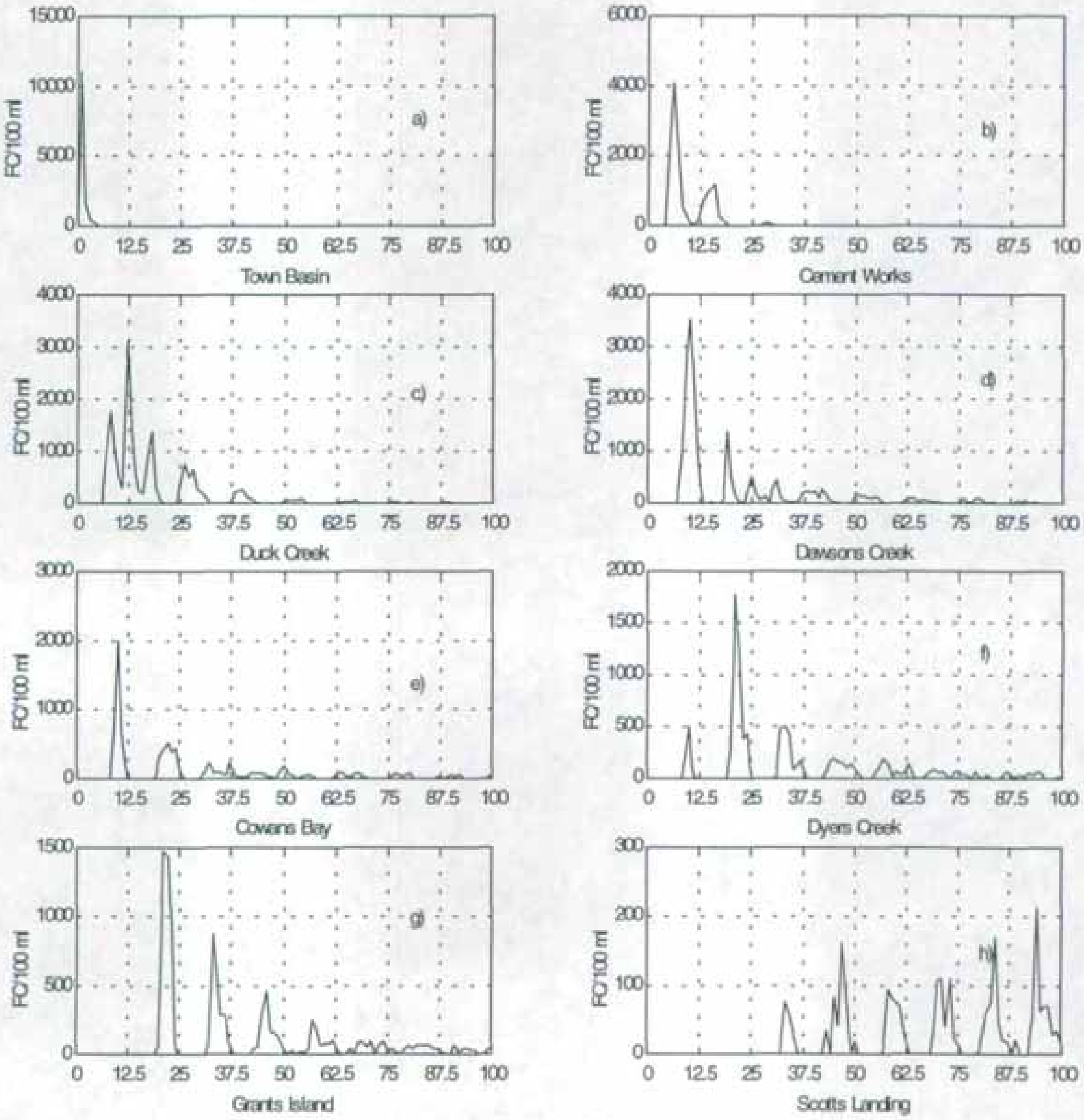
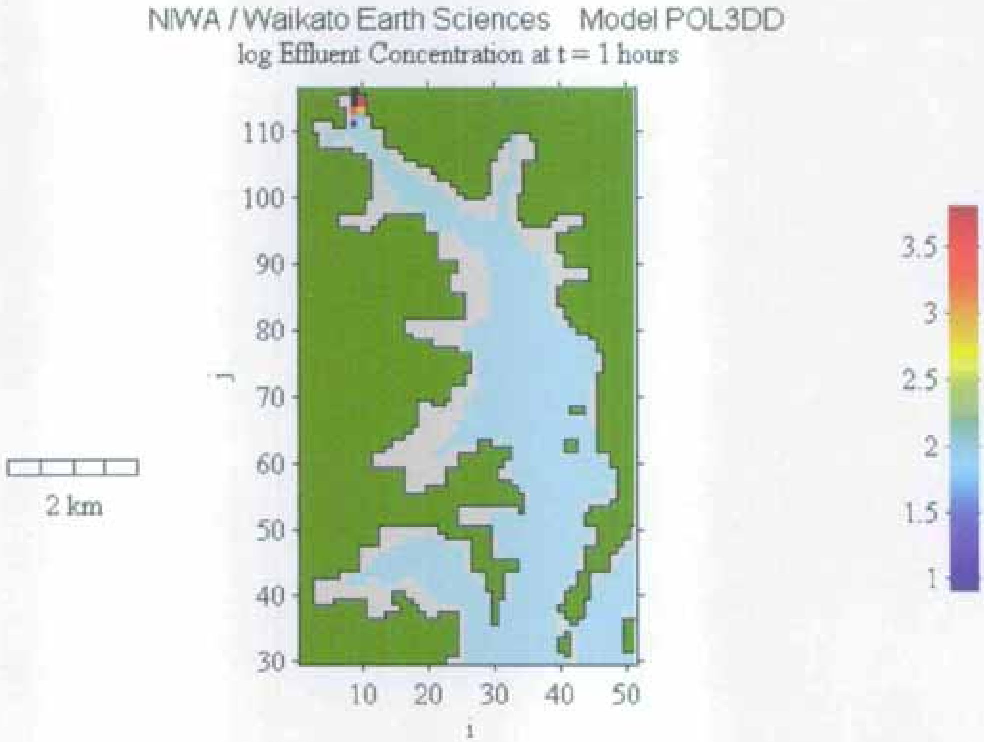


Figure 7. Predicted Faecal Coliform concentrations within the main channel for a one hour overflow event with 35 cumec freshwater inflows. (Horizontal axis is time in elapsed hours from the model start. Note: each tidal cycle = 12.5 hours).



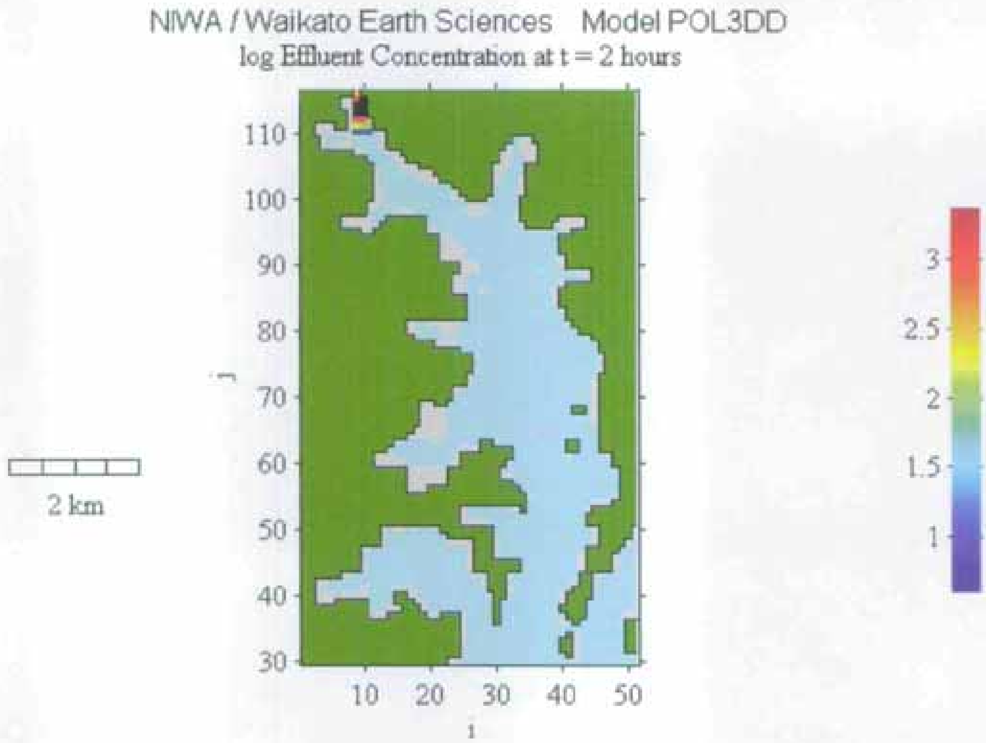


Figure 8a. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary at 1 hour and 2 hours after the start of a one hour overflow event with 35 cumecs freshwater inflows. (Examples: $2=10^2$ FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)

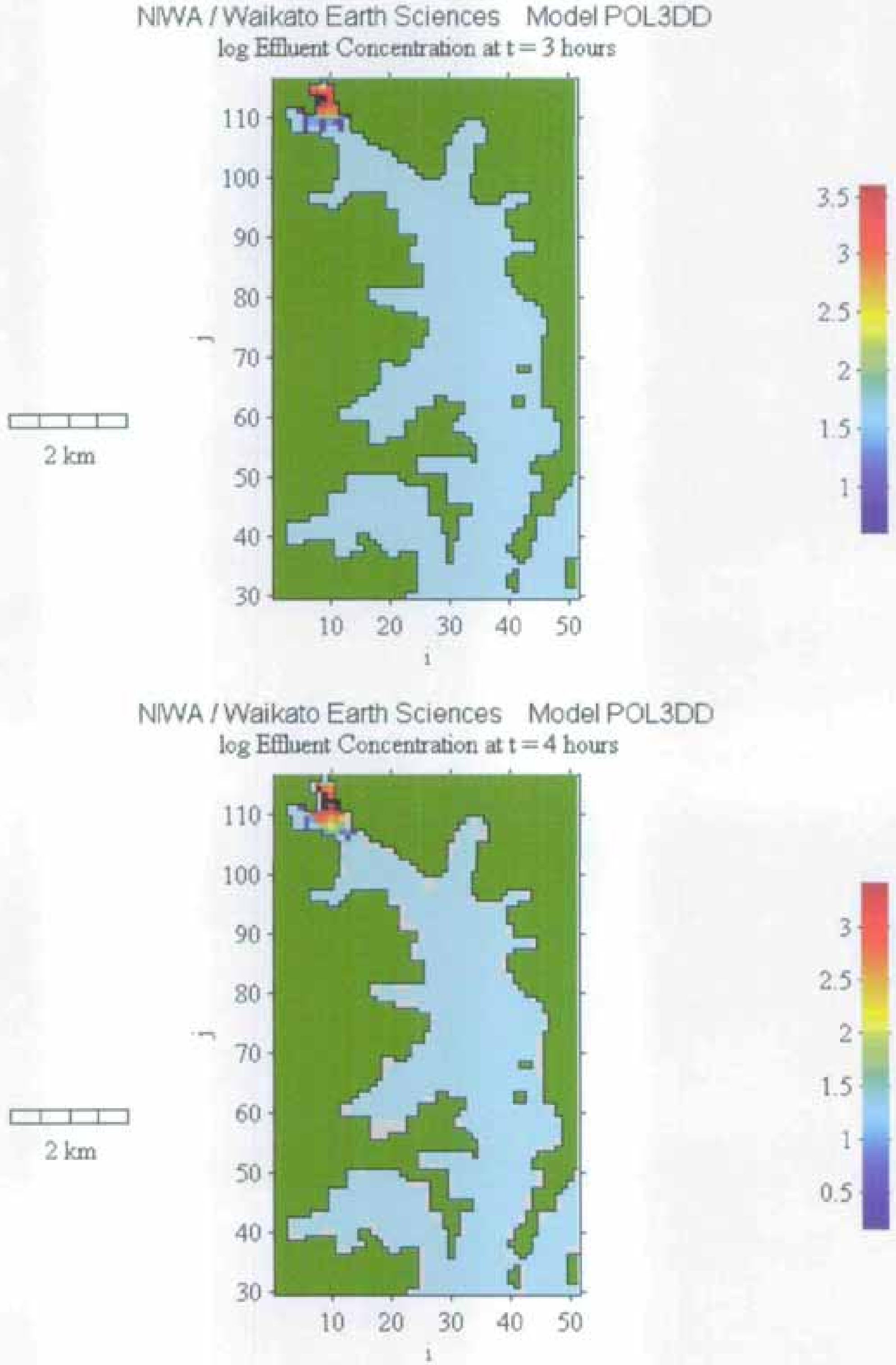


Figure 8b. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary at 3 hours and 4 hours after the start of a one hour overflow event with 35 cumecs freshwater inflows. (Examples: 2=10^2 FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)

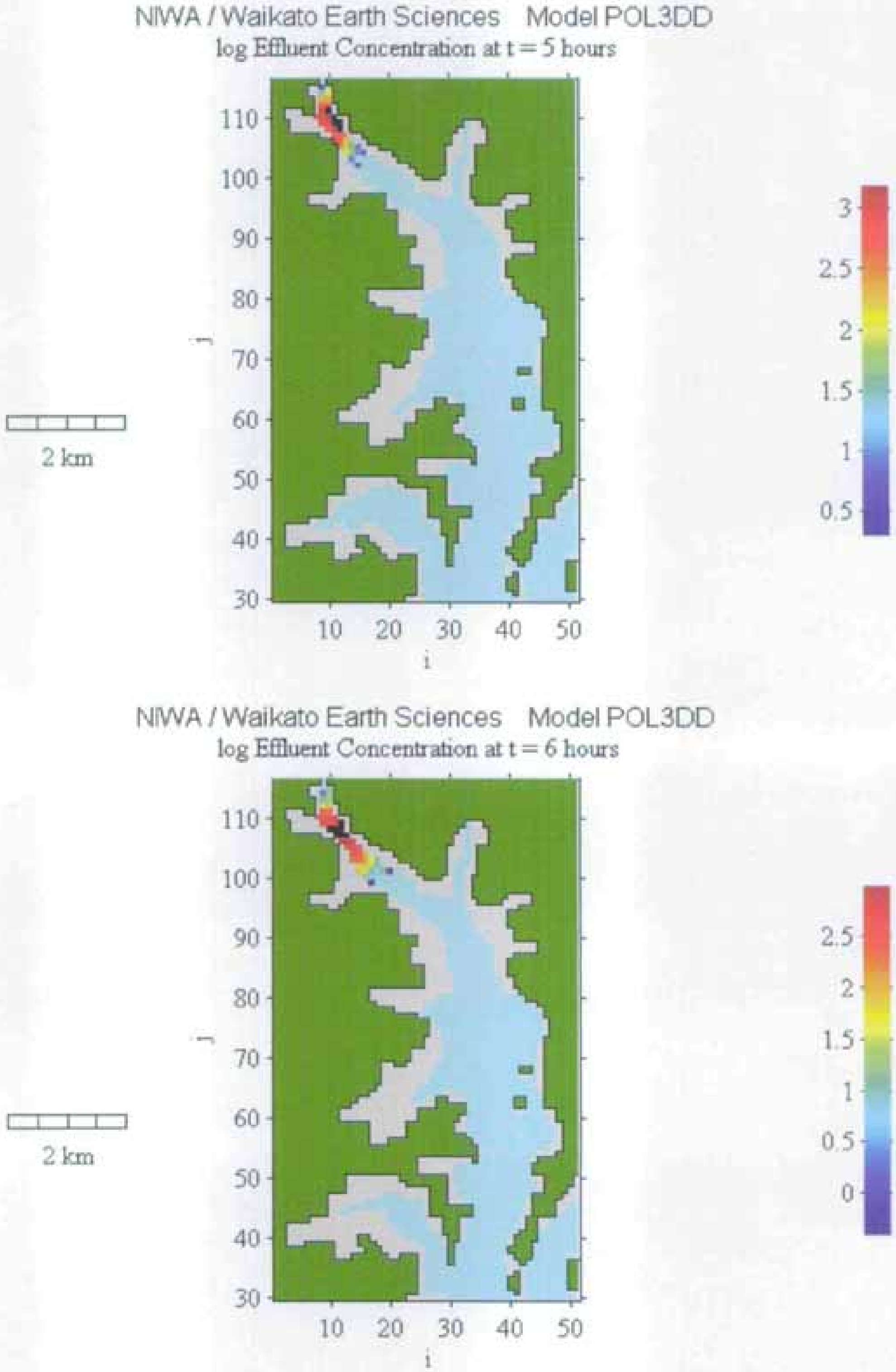


Figure 8c. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary at 5 hours and 6 hours after the start of a one hour overflow event with 35 cumecs freshwater inflows. (Examples: $2=10^2$ FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)

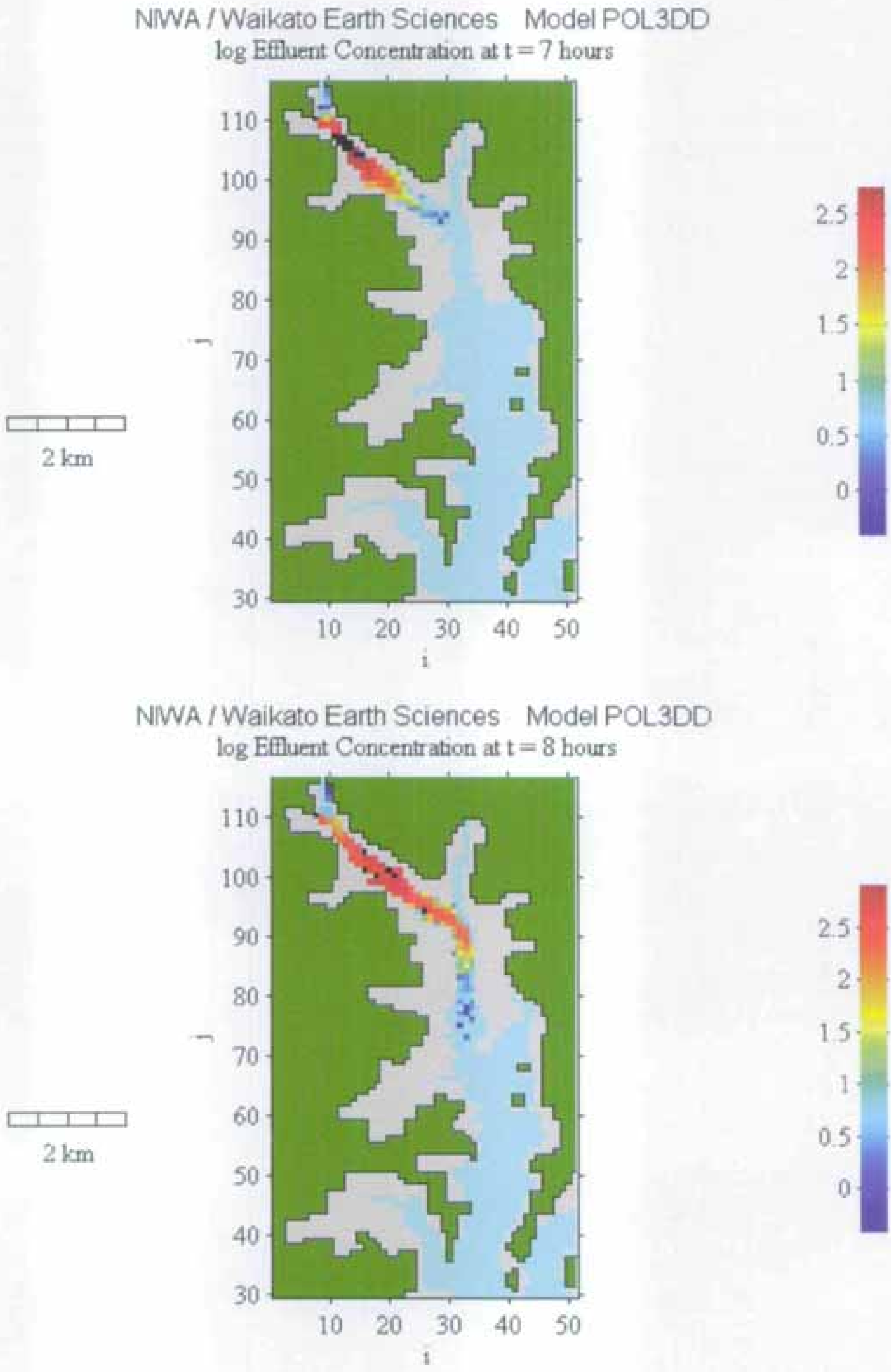


Figure 8d. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary at 7 hours and 8 hours after the start of a one hour overflow event with 35 cumecs freshwater inflows. (Examples: $2=10^2$ FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)

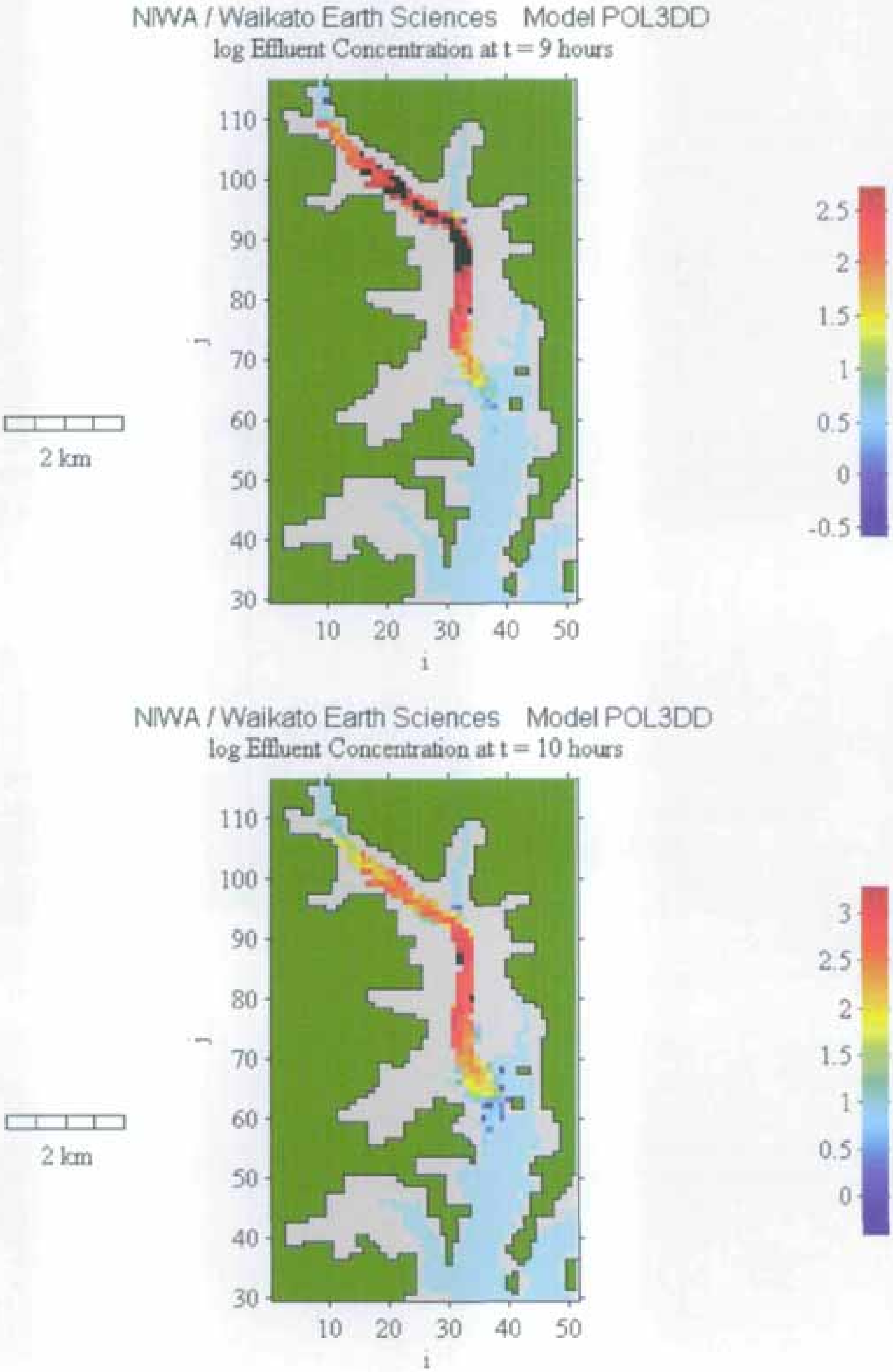


Figure 8e. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary at 9 hours and 10 hours after the start of a one hour overflow event with 35 cumecs freshwater inflows. (Examples: $2=10^2$ FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)

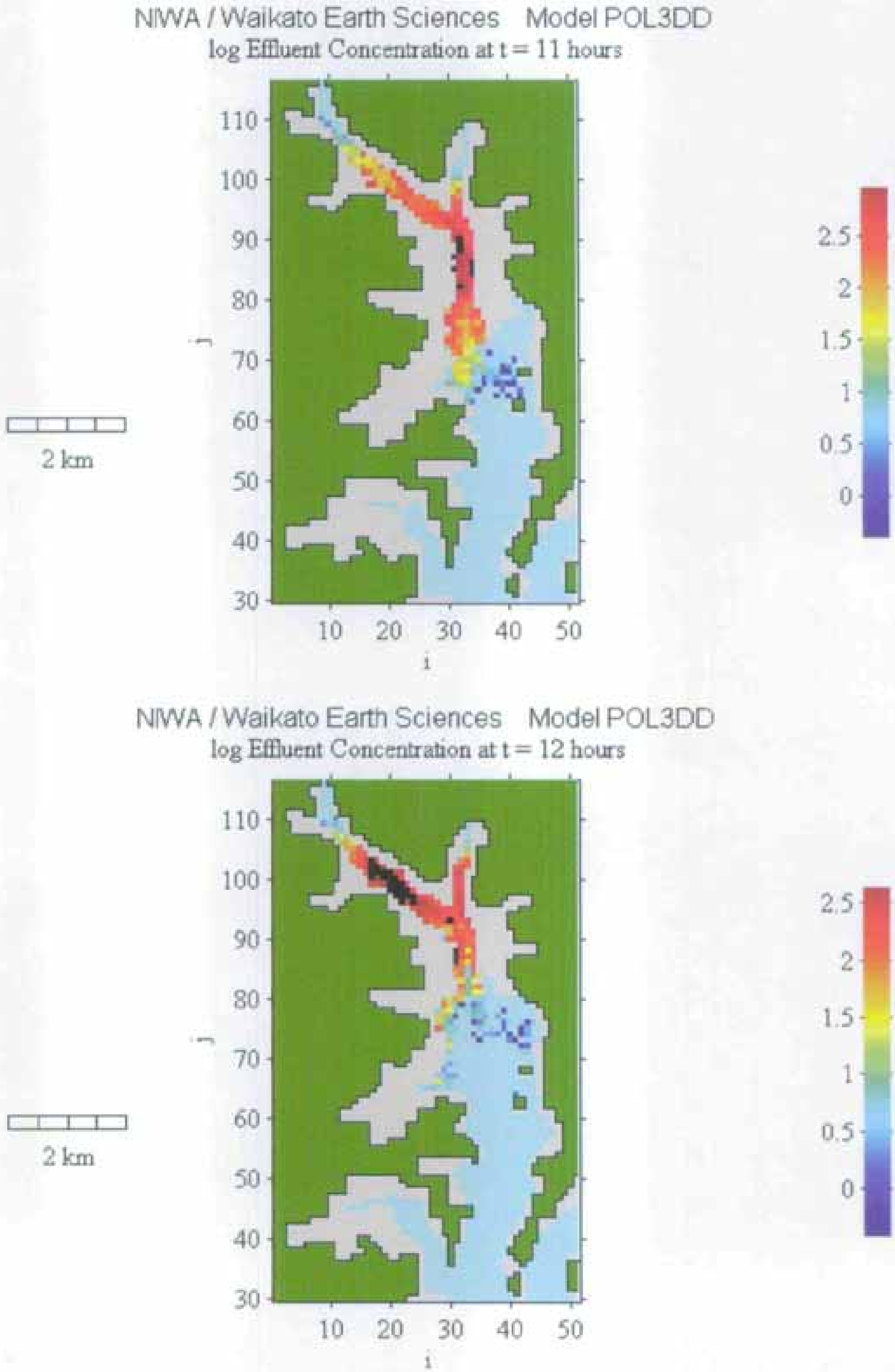


Figure 8f. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary at 11 hours and 12 hours after the start of a one hour overflow event with 35 cumecs freshwater inflows. (Examples: $2=10^2$ FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)

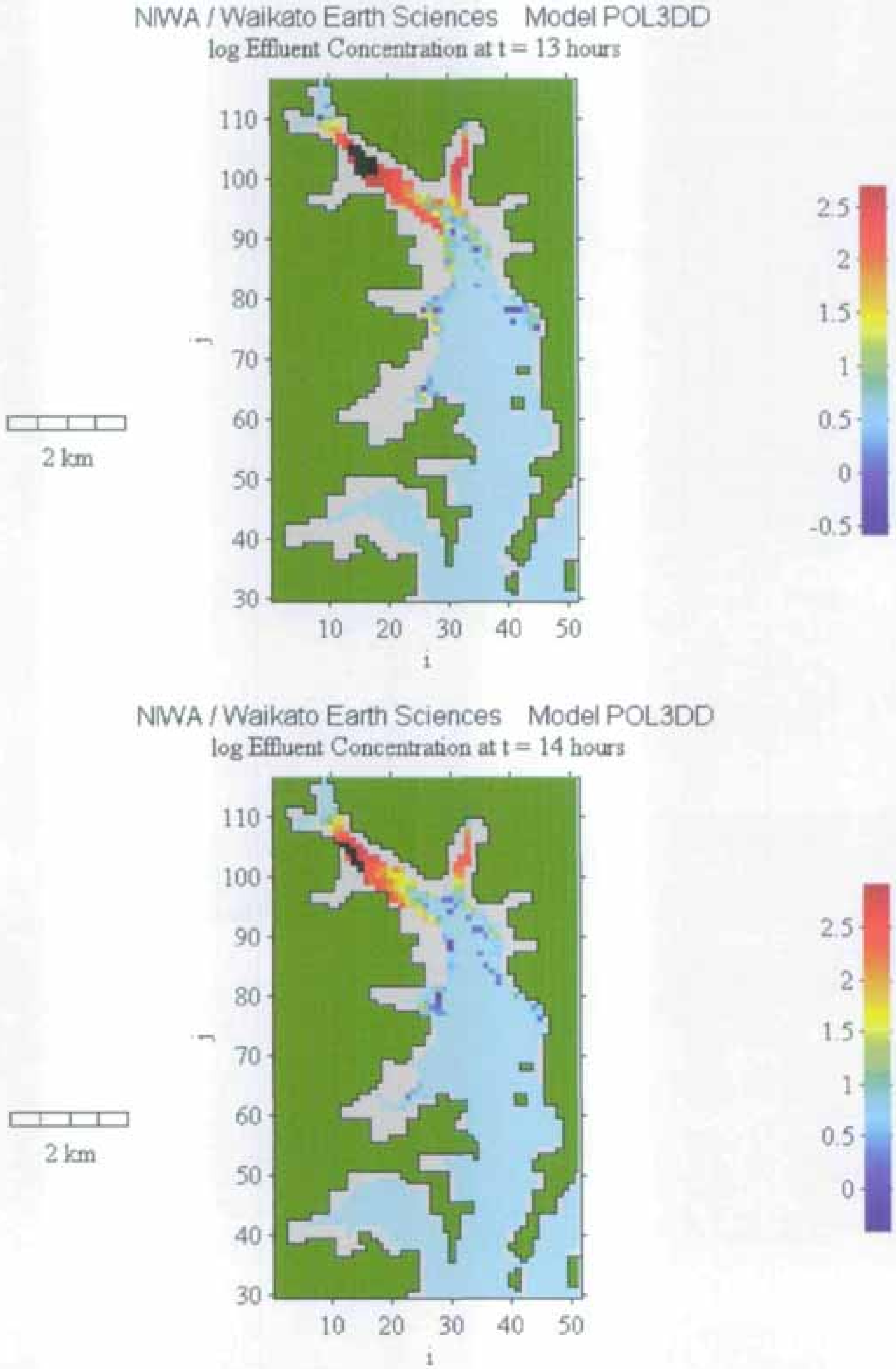


Figure 8g. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary at 13 hours and 14 hours after the start of a one hour overflow event with 35 cumecs freshwater inflows. (Examples: $2=10^2$ FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)

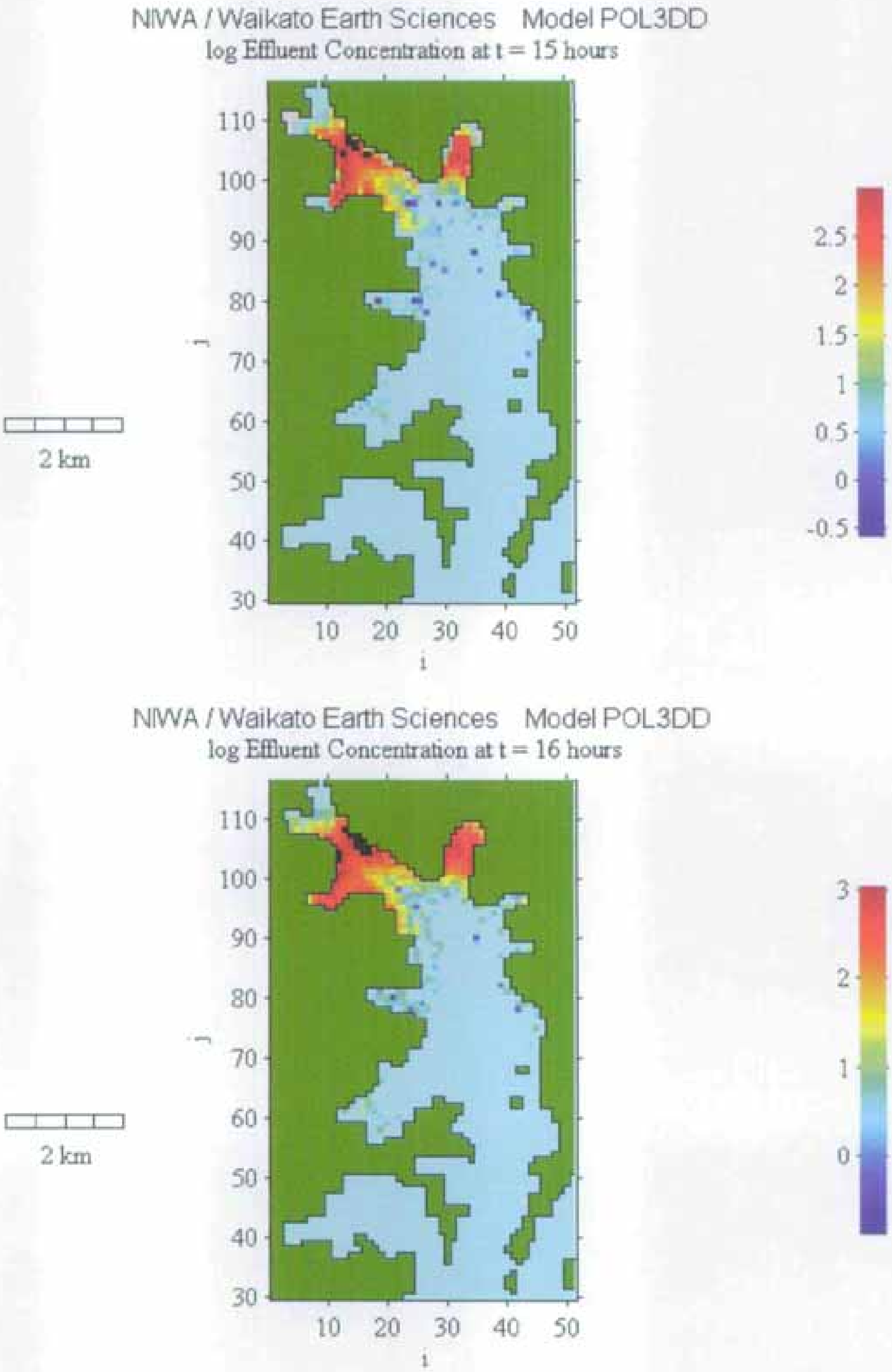


Figure 8h. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary at 15 hours and 16 hours after the start of a one hour overflow event with 35 cumecs freshwater inflows. (Examples: $2=10^2$ FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)

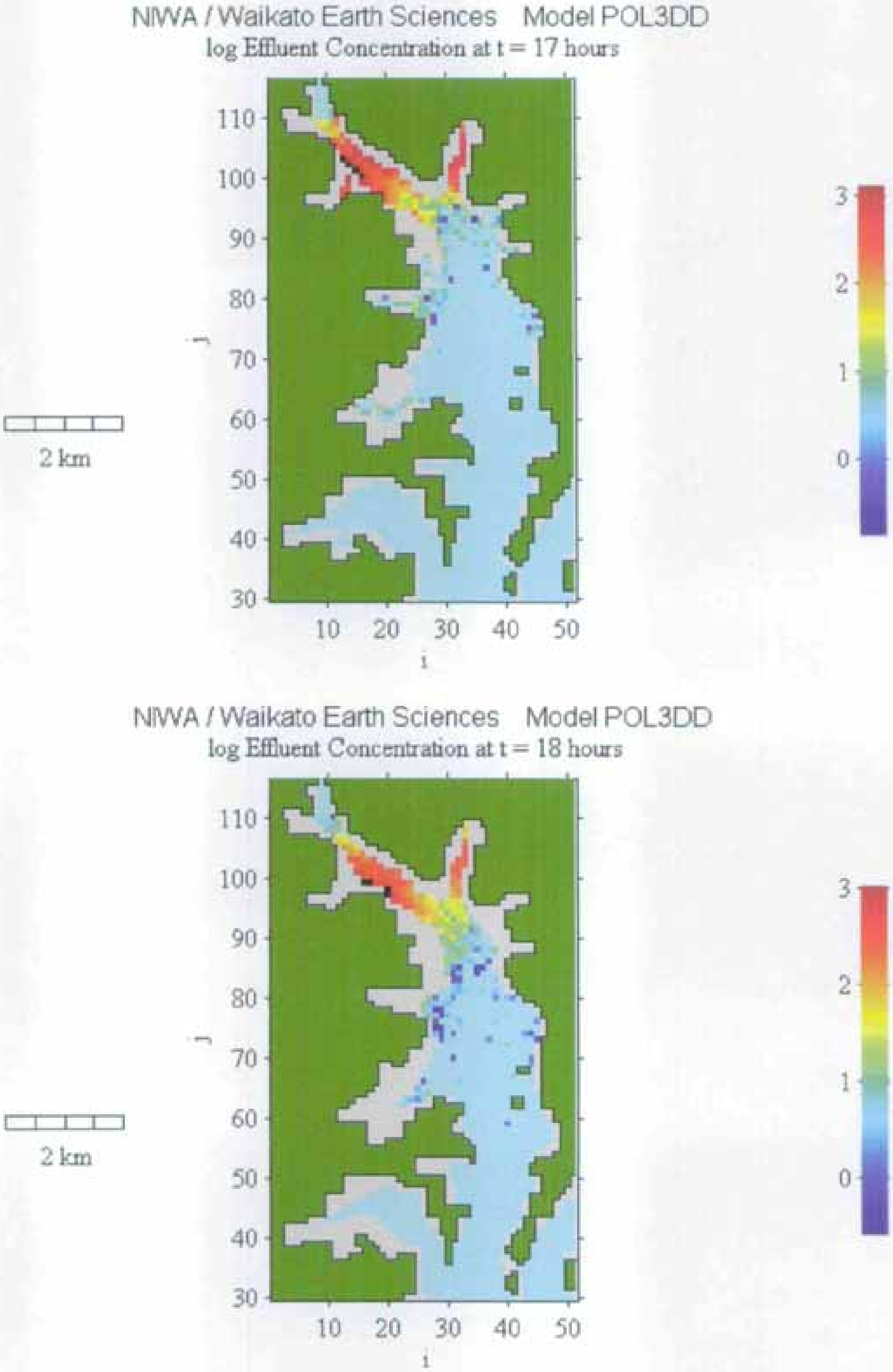
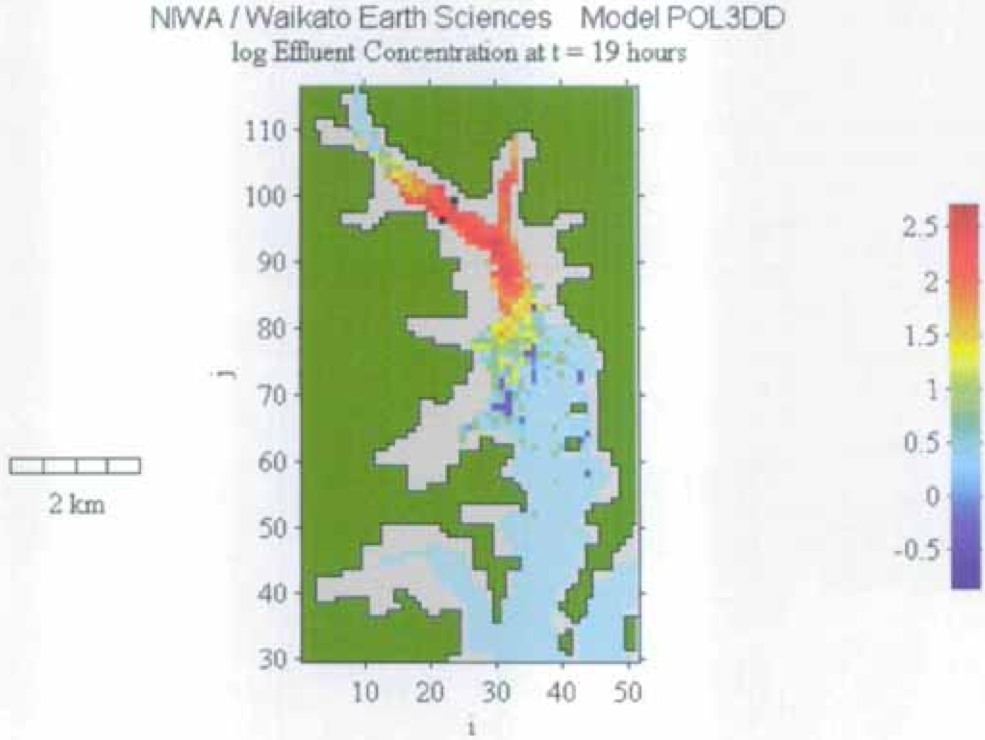


Figure 8i. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary at 17 hours and 18 hours after the start of a one hour overflow event with 35 cumecs freshwater inflows. (Examples: 2=10^2 FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)



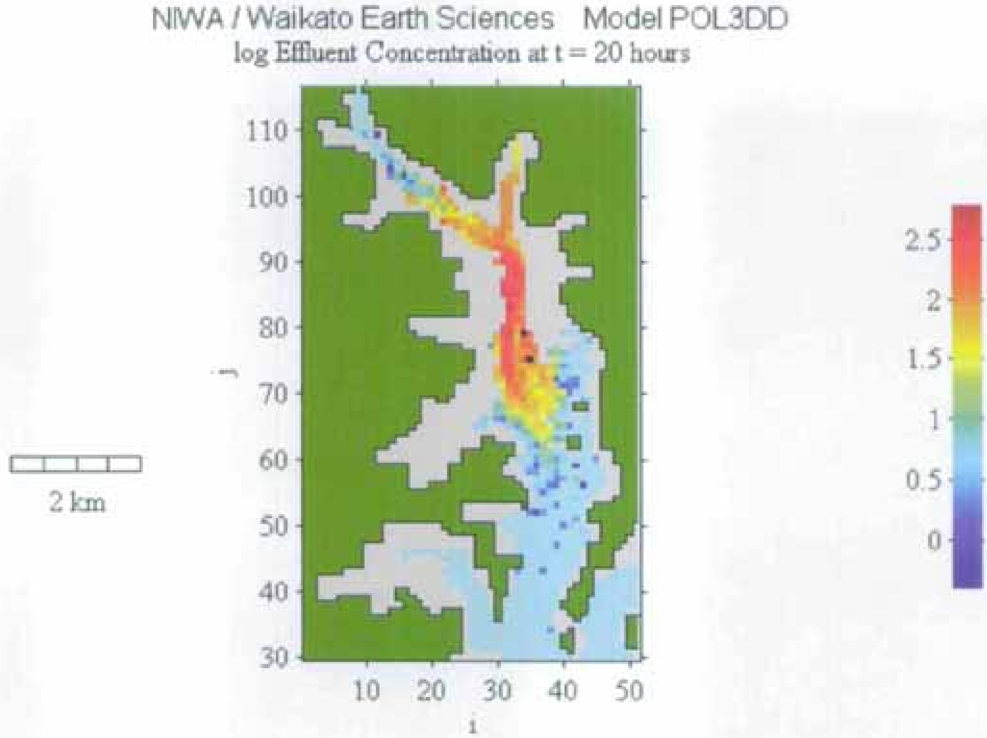


Figure 8j. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary at 19 hours and 20 hours after the start of a one hour overflow event with 35 cumecs freshwater inflows. (Examples: $2=10^2$ FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)

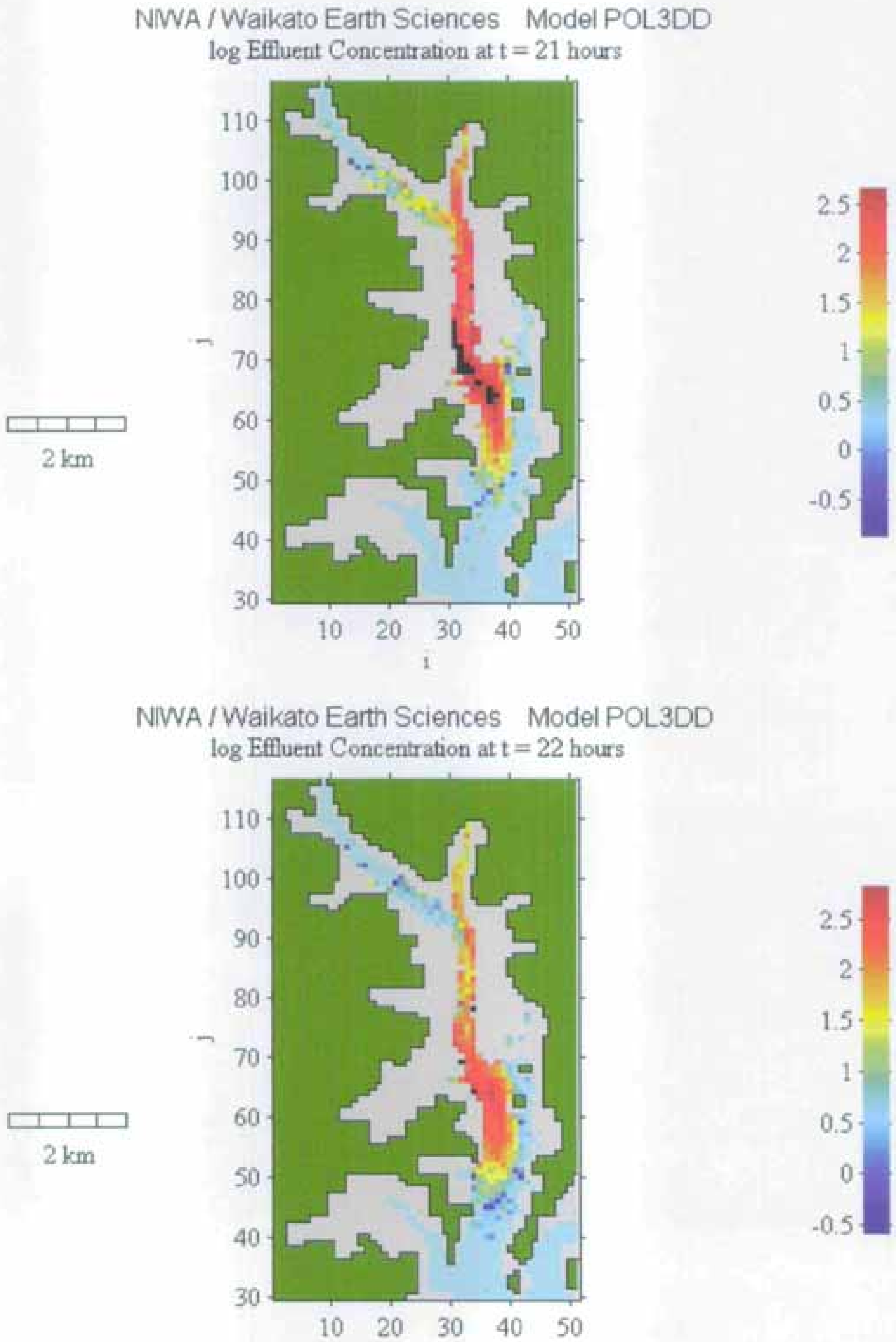


Figure 8k. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary at 21 hours and 22 hours after the start of a one hour overflow event with 35 cumecs freshwater inflows. (Examples: $2=10^2$ FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)

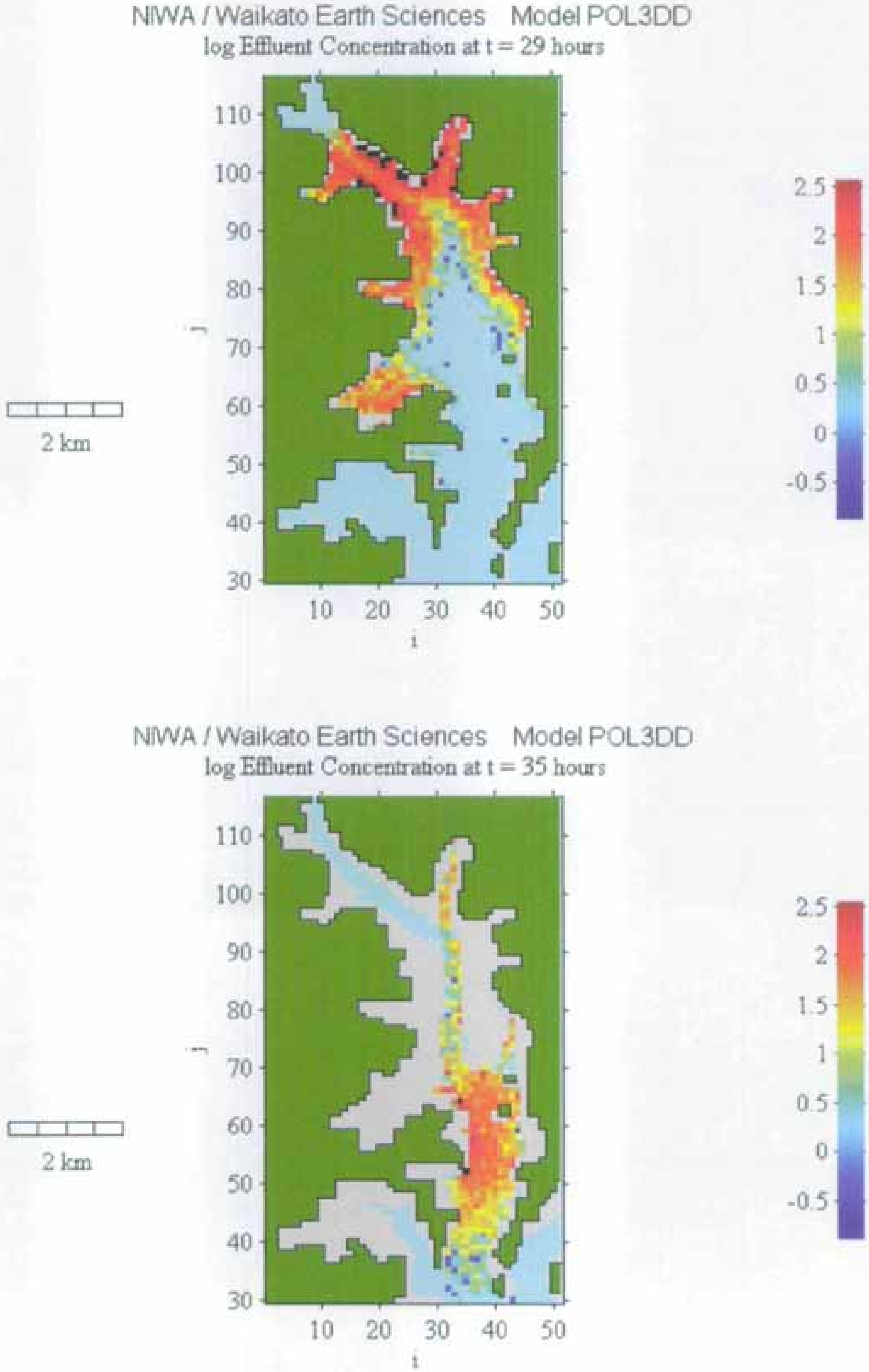


Figure 8l. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary for the 3rd high and low waters after the start of a one hour overflow event with 35 cumecs freshwater inflows. (Examples: $2=10^2$ FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)

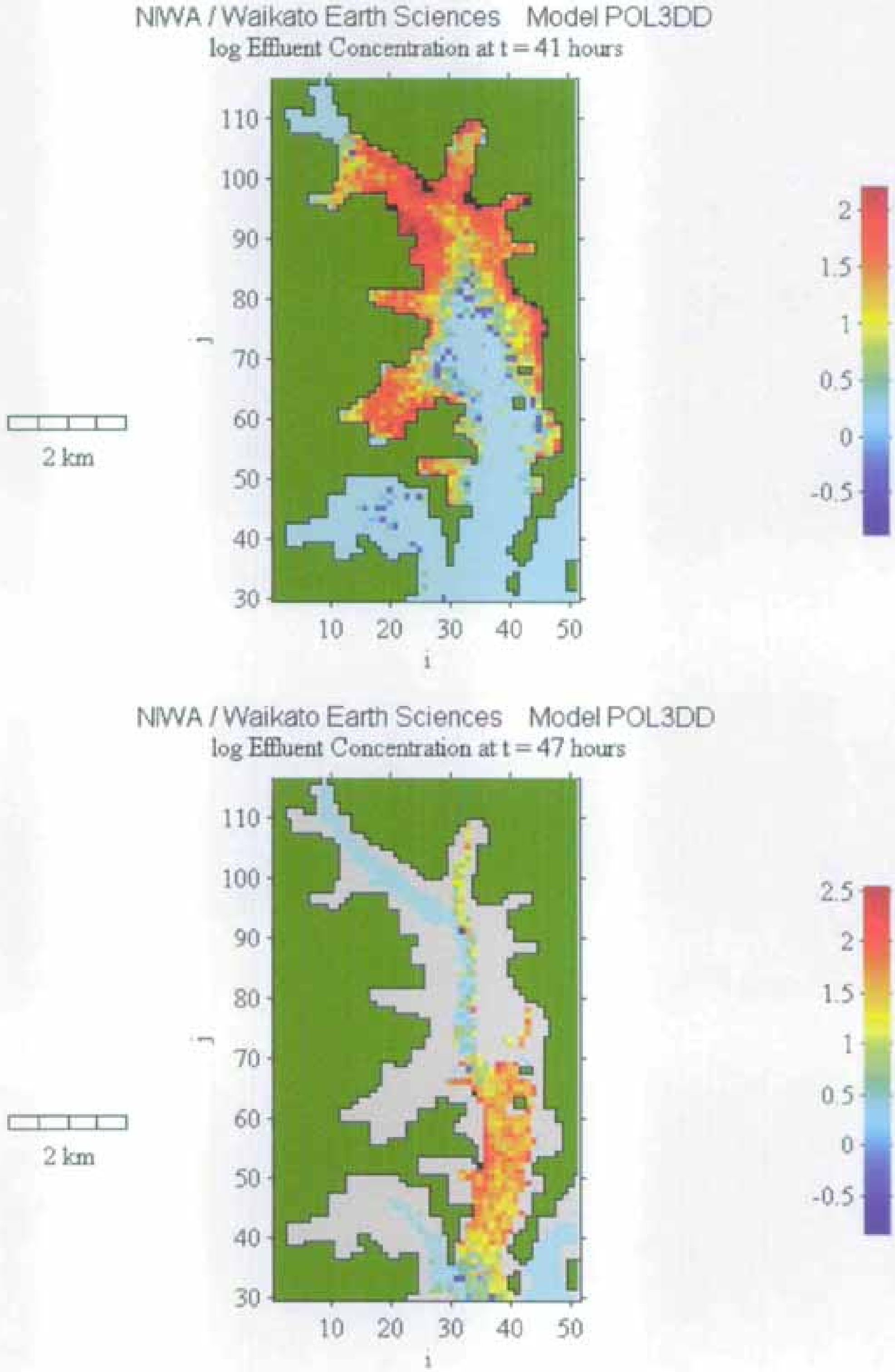


Figure 8m. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary for the 4th high and low waters after the start of a one hour overflow event with 35 cumecs freshwater inflows. (Examples: $2=10^2$ FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)

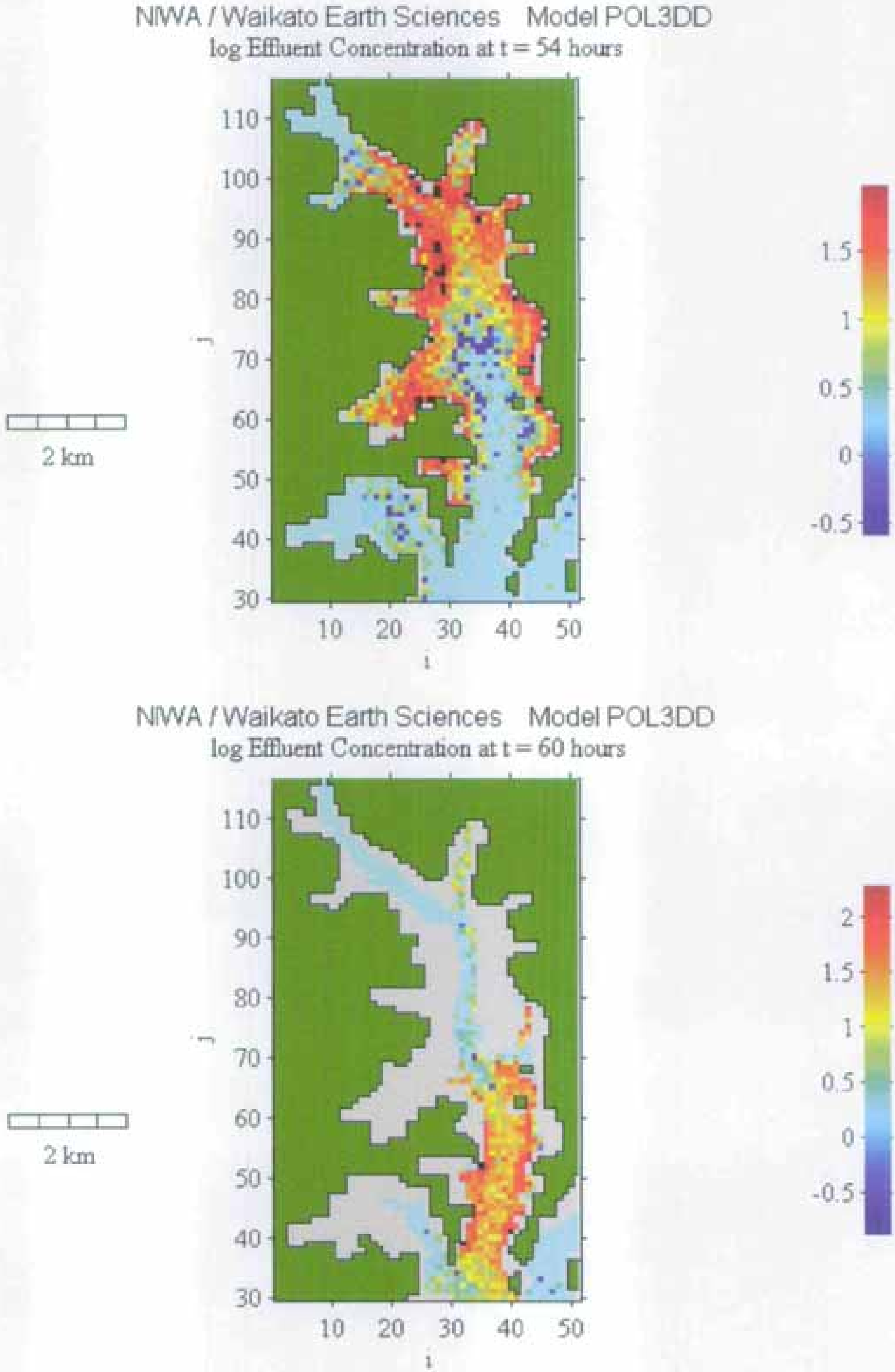


Figure 8n. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary for the 5th high and low waters after the start of a one hour overflow event with 35 cumecs freshwater inflows. (Examples: $2=10^2$ FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)

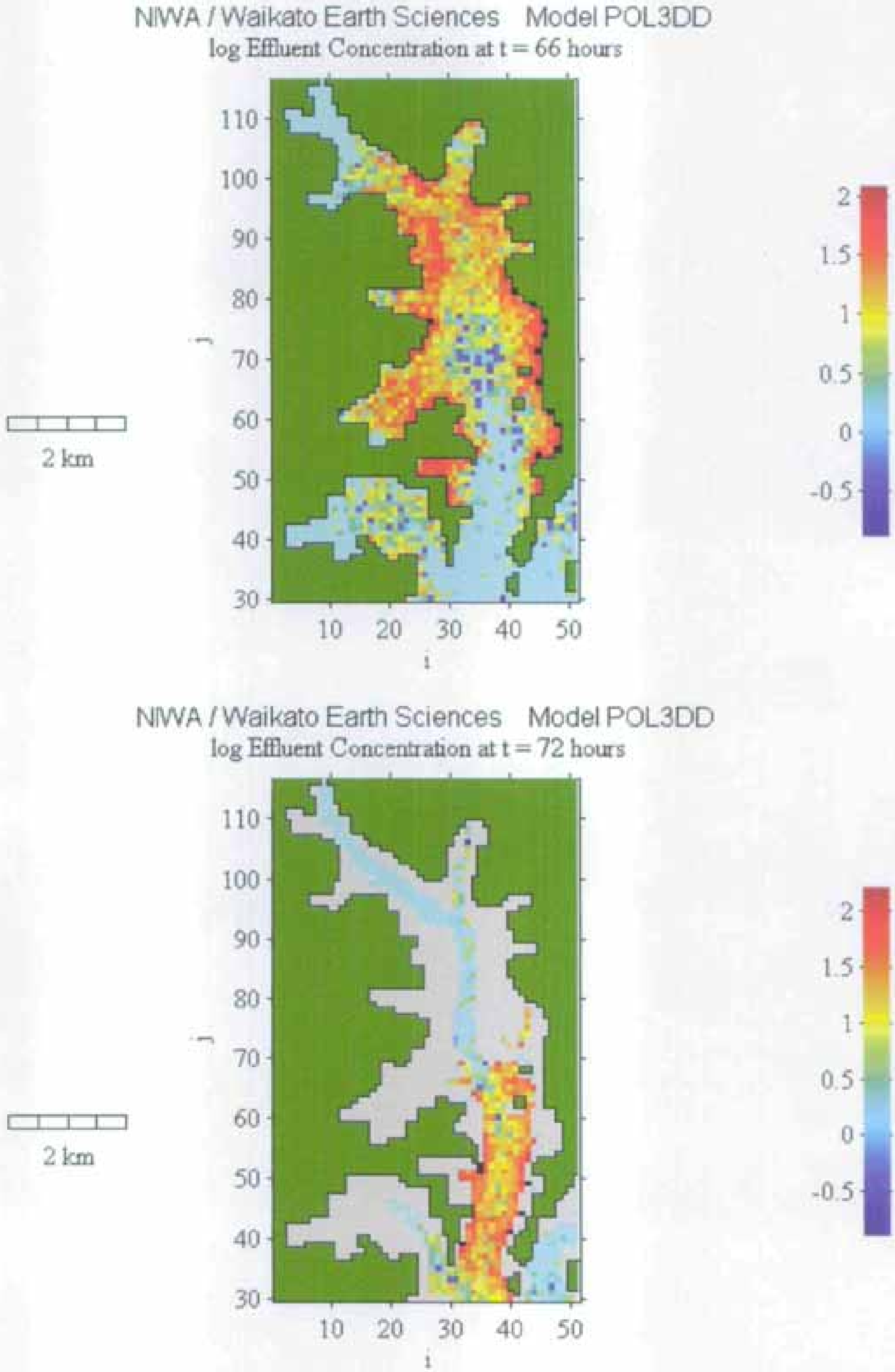


Figure 8o. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary for the 6th high and low waters after the start of a one hour overflow event with 35 cumecs freshwater inflows. (Examples: $2=10^2$ FC/100 ml and $0=1$ FC/100 ml. Intertidal areas are shaded a grey colour)

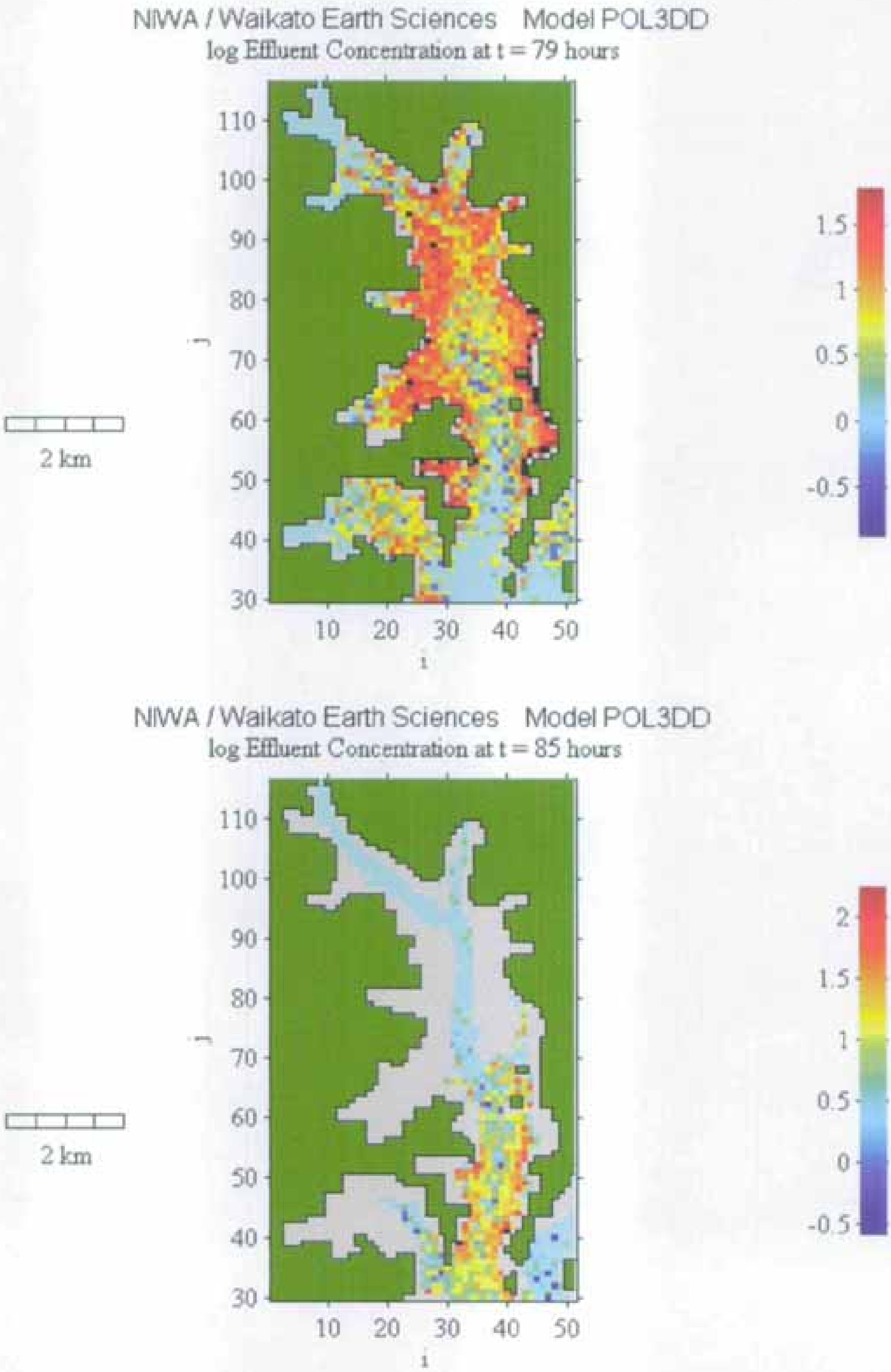


Figure 8p. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary for the 7th high and low waters after the start of a one hour overflow event with 35 cumecs freshwater inflows. (Examples: $2=10^2$ FC/100 ml and $0=1$ FC/100 ml. Intertidal areas are shaded a grey colour)

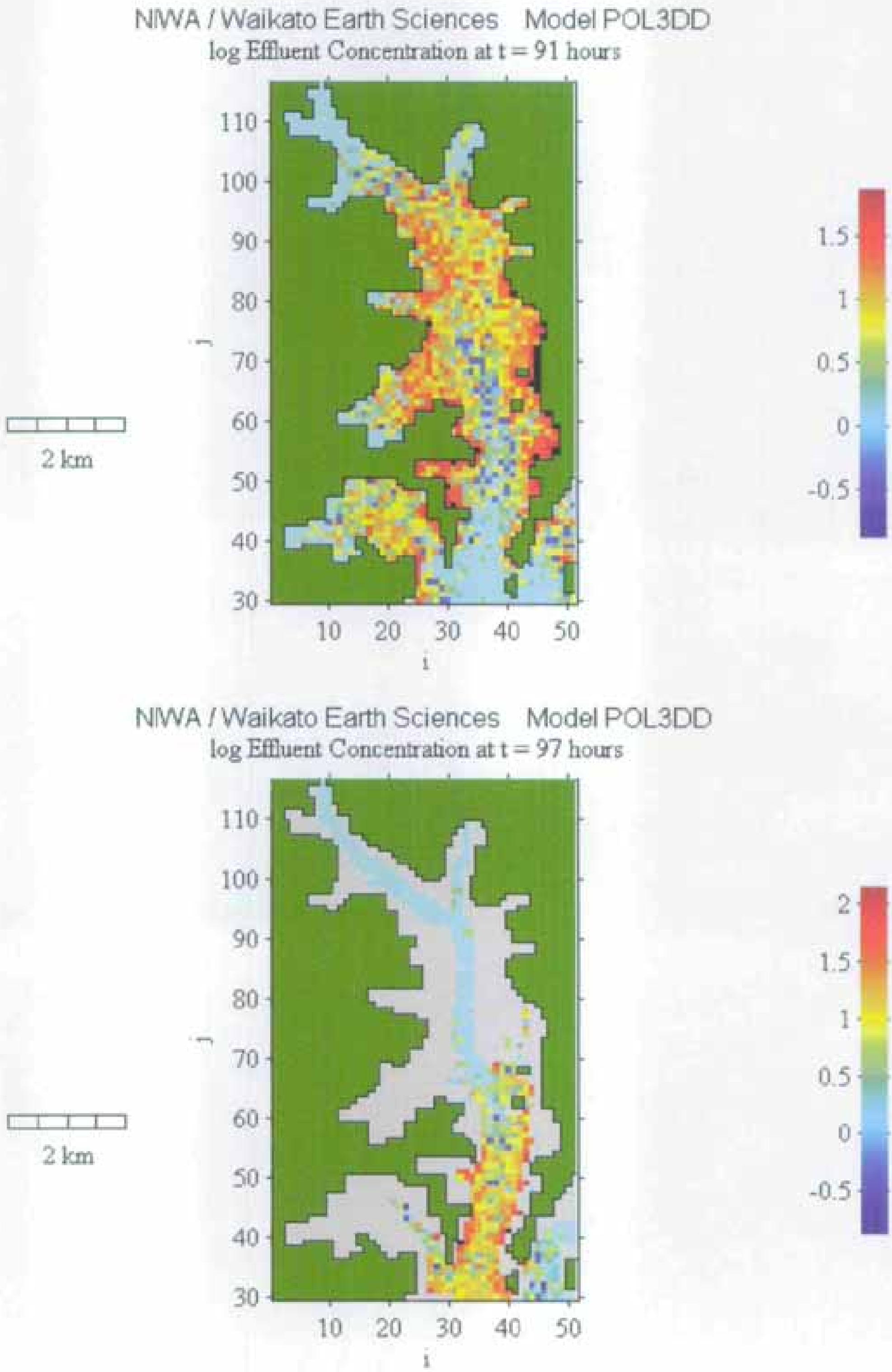


Figure 8q. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary for the 8th high and low waters after the start of a one hour overflow event with 35 cumecs freshwater inflows. (Examples: $2=10^2$ FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)

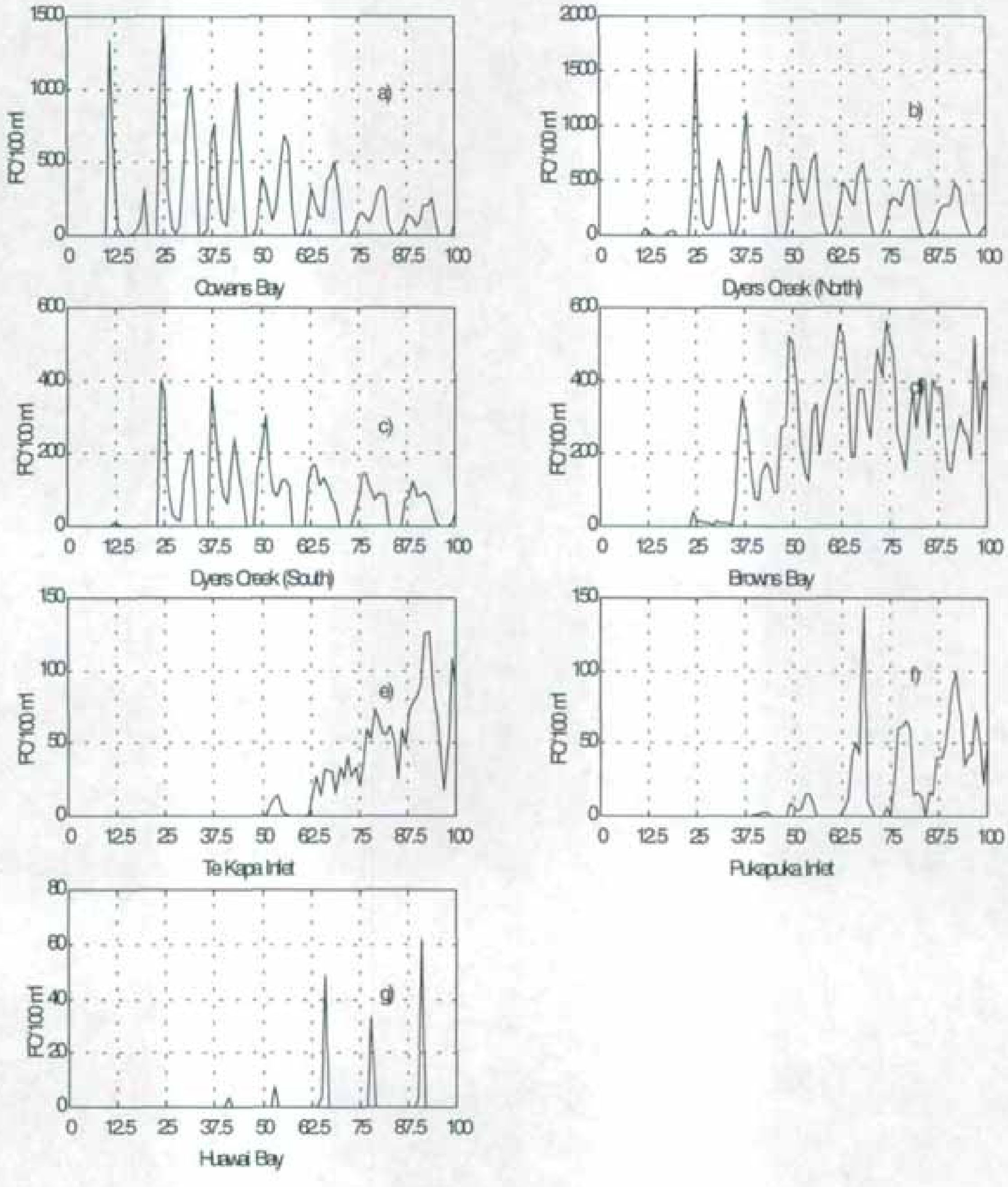


Figure 9. Predicted Faecal Coliform concentrations within the oyster farms for a two hour overflow event with 35 cumec freshwater inflows. (Horizontal axis is time in elapsed hours from the model start. Note: each tidal cycle = 12.5 hours).

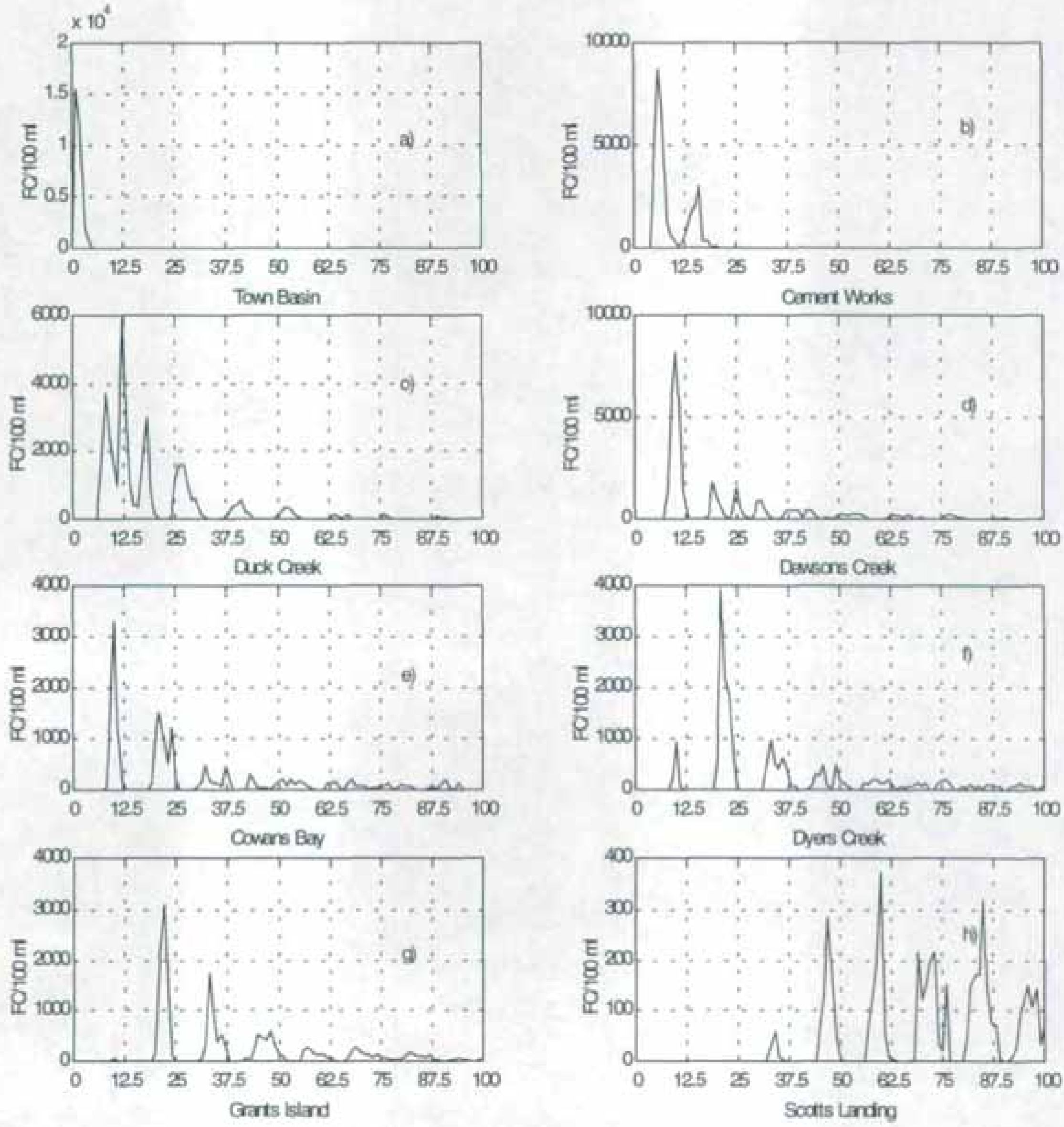


Figure 10. Predicted Faecal Coliform concentrations within the main channel for a two hour overflow event with 35 cumec freshwater inflows. (Horizontal axis is time in elapsed hours from the model start. Note: each tidal cycle = 12.5 hours).

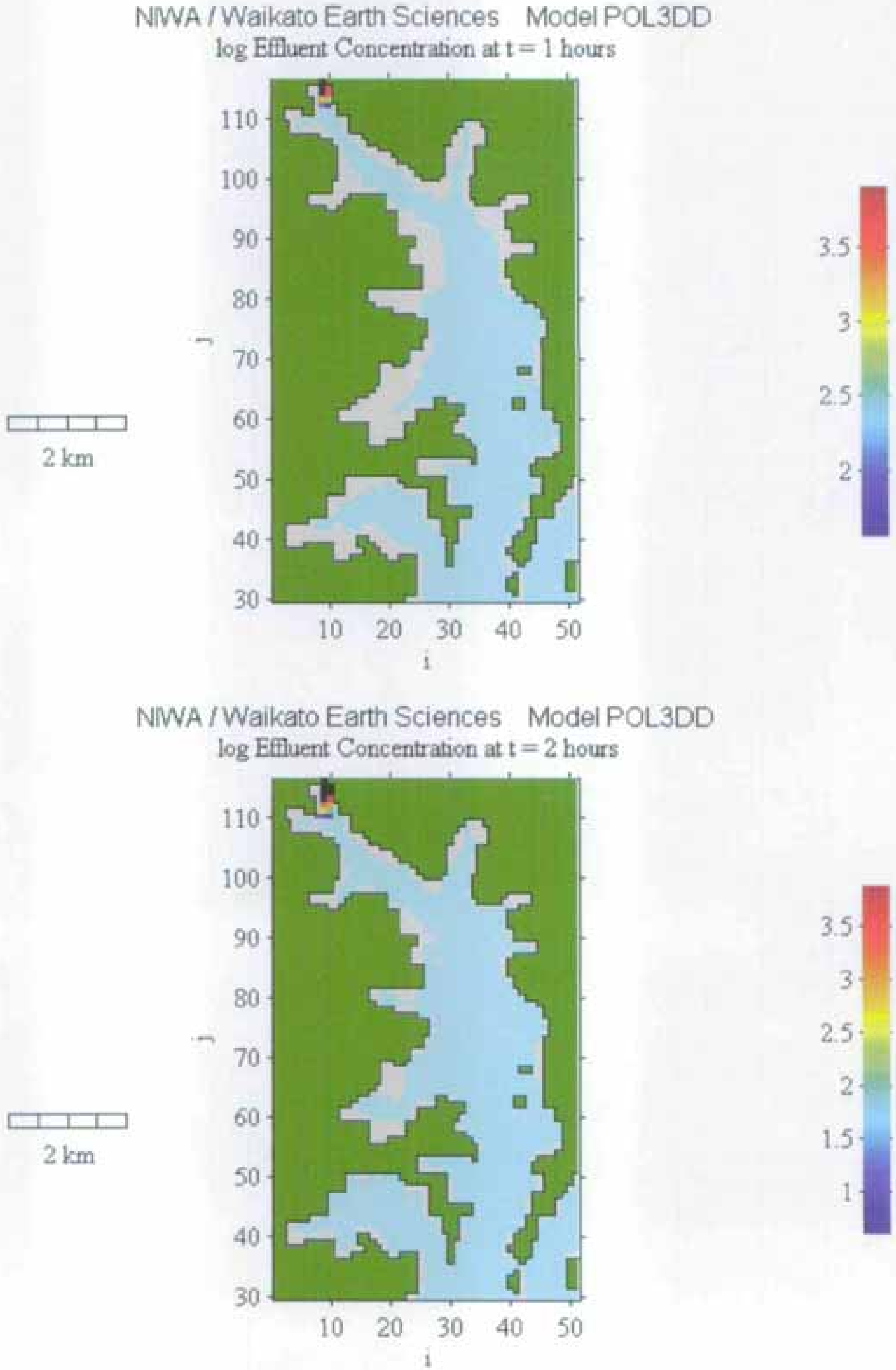


Figure 11a. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary at 1 hour and 2 hours after the start of a two hour overflow event with 35 cumecs freshwater inflows. (Examples: $2=10^2$ FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)

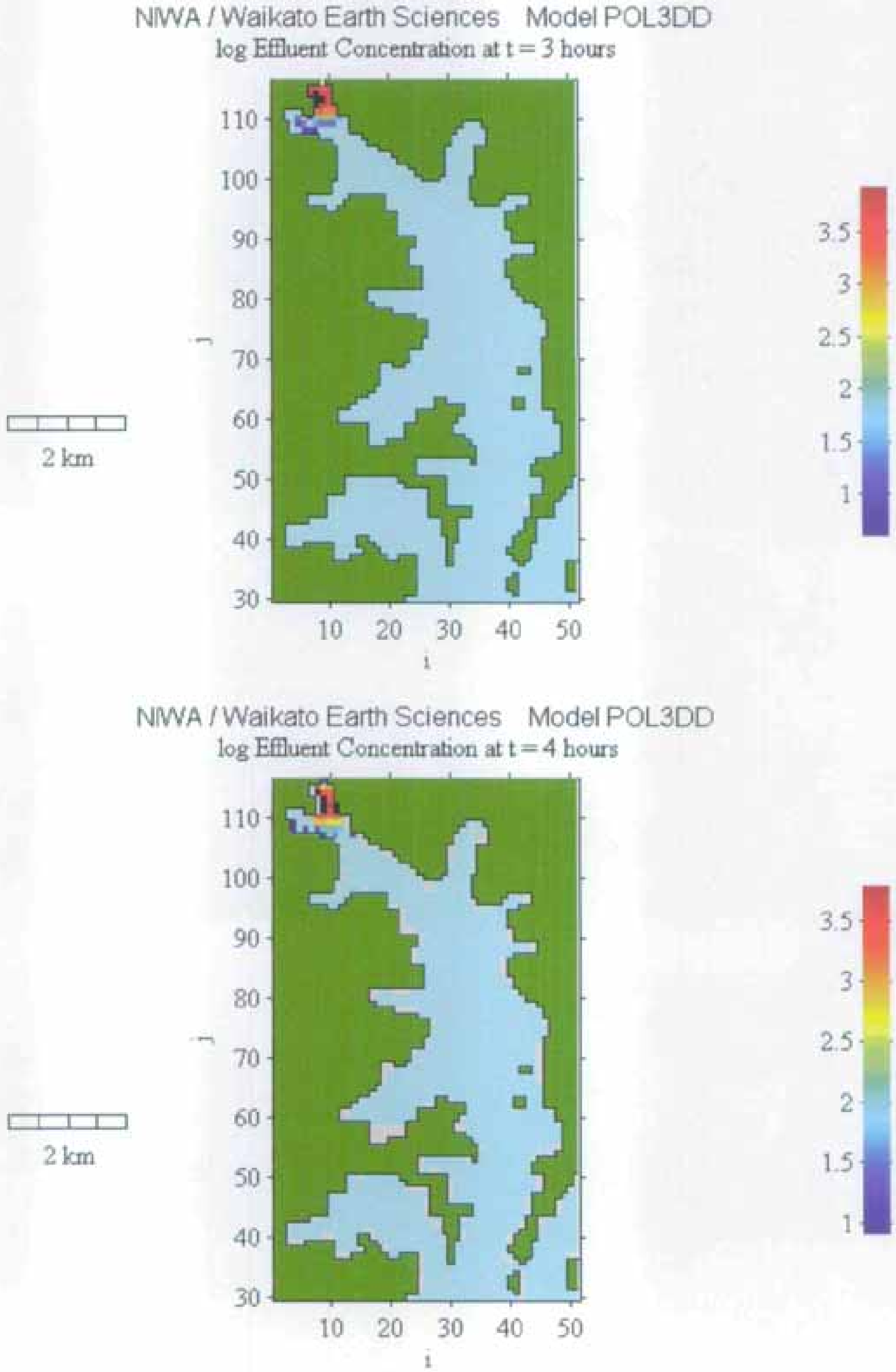
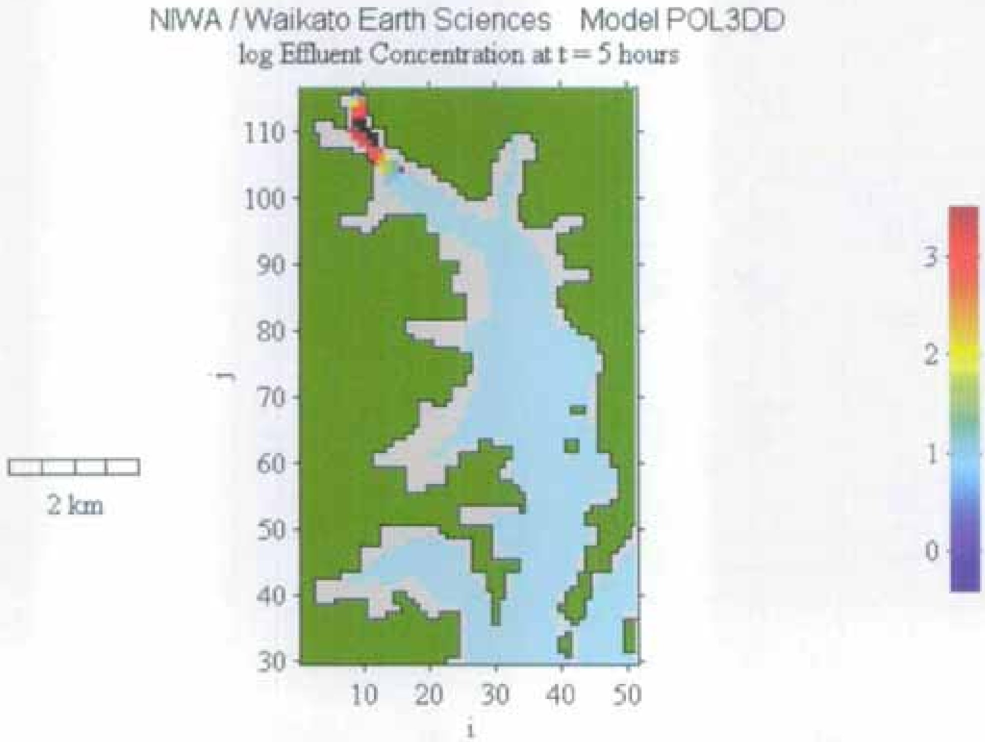


Figure 11b. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary at 3 hours and 4 hours after the start of a two hour overflow event with 35 cumecs freshwater inflows. (Examples: $2=10^2$ FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)



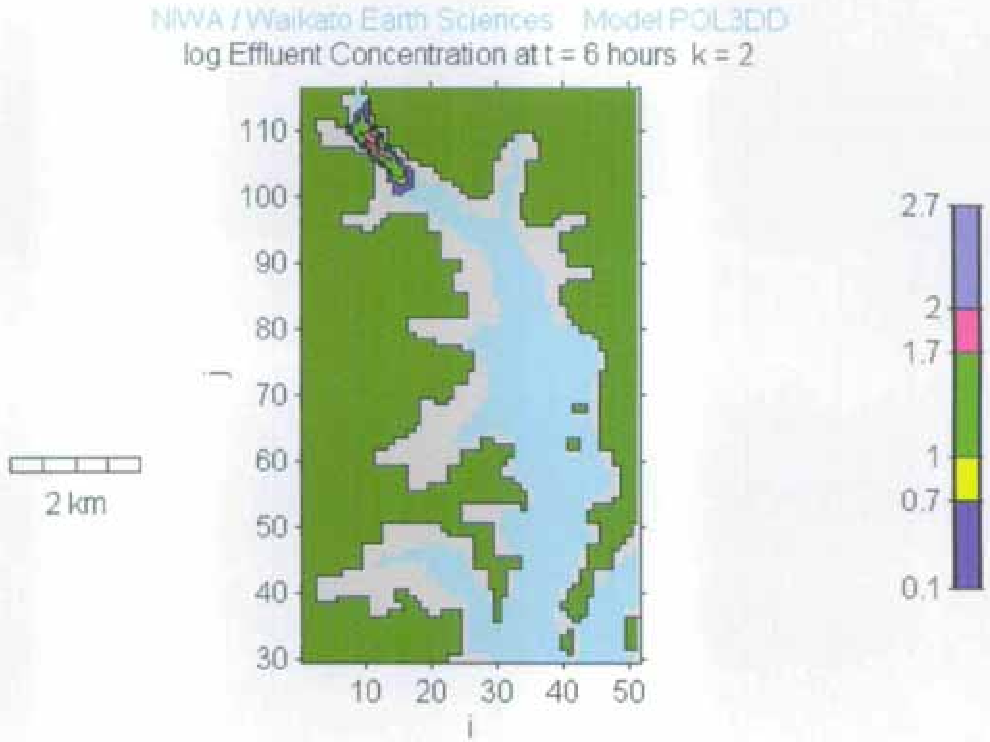


Figure 11c. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary at 5 hours and 6 hours after the start of a two hour overflow event with 35 cumecs freshwater inflows. (Examples: $2=10^2$ FC/100 ml and $0=1$ FC/100 ml. Intertidal areas are shaded a grey colour)

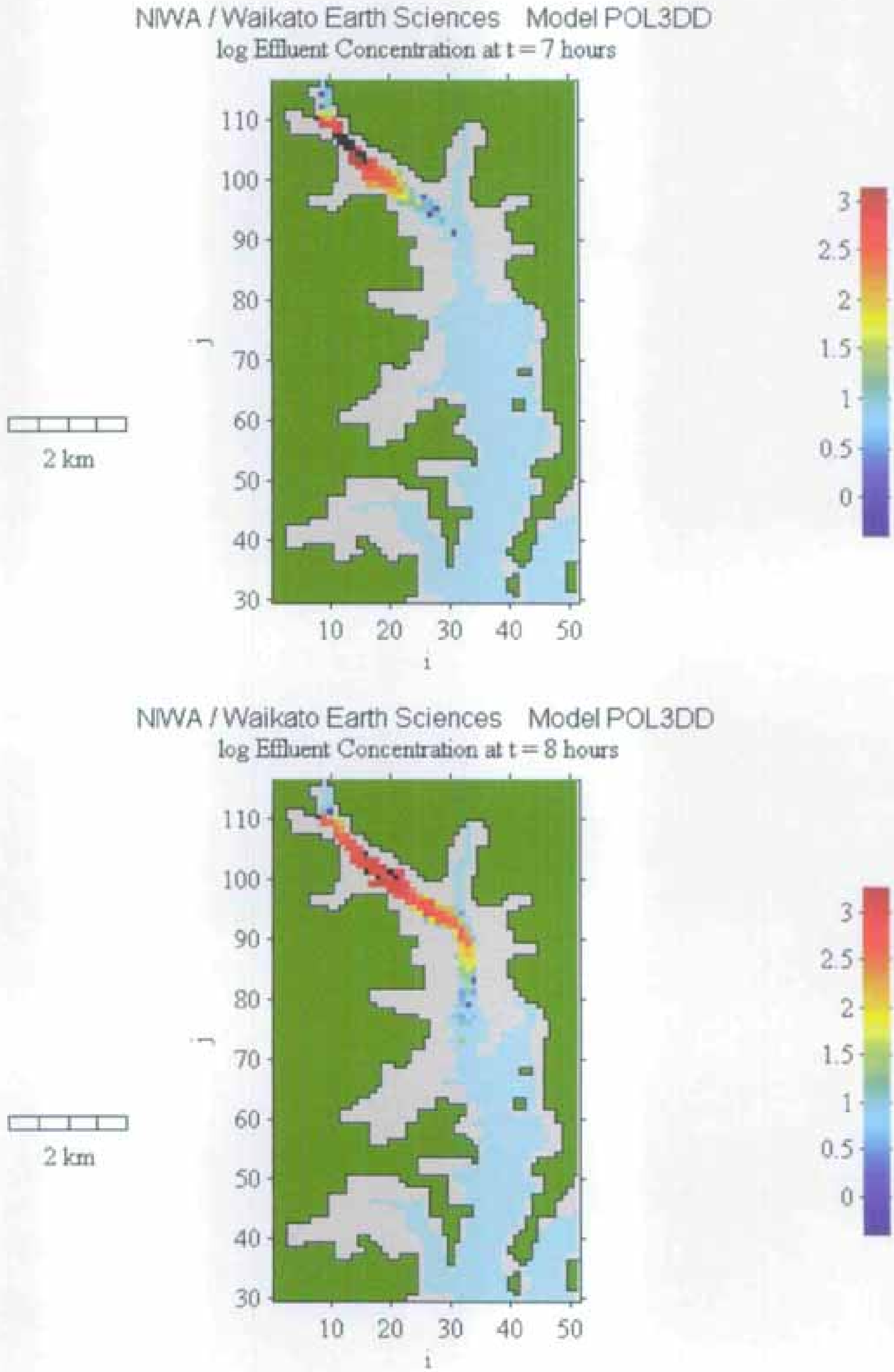


Figure 11d. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary at 7 hours and 8 hours after the start of a two hour overflow event with 35 cumecs freshwater inflows. (Examples: $2=10^2$ FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)

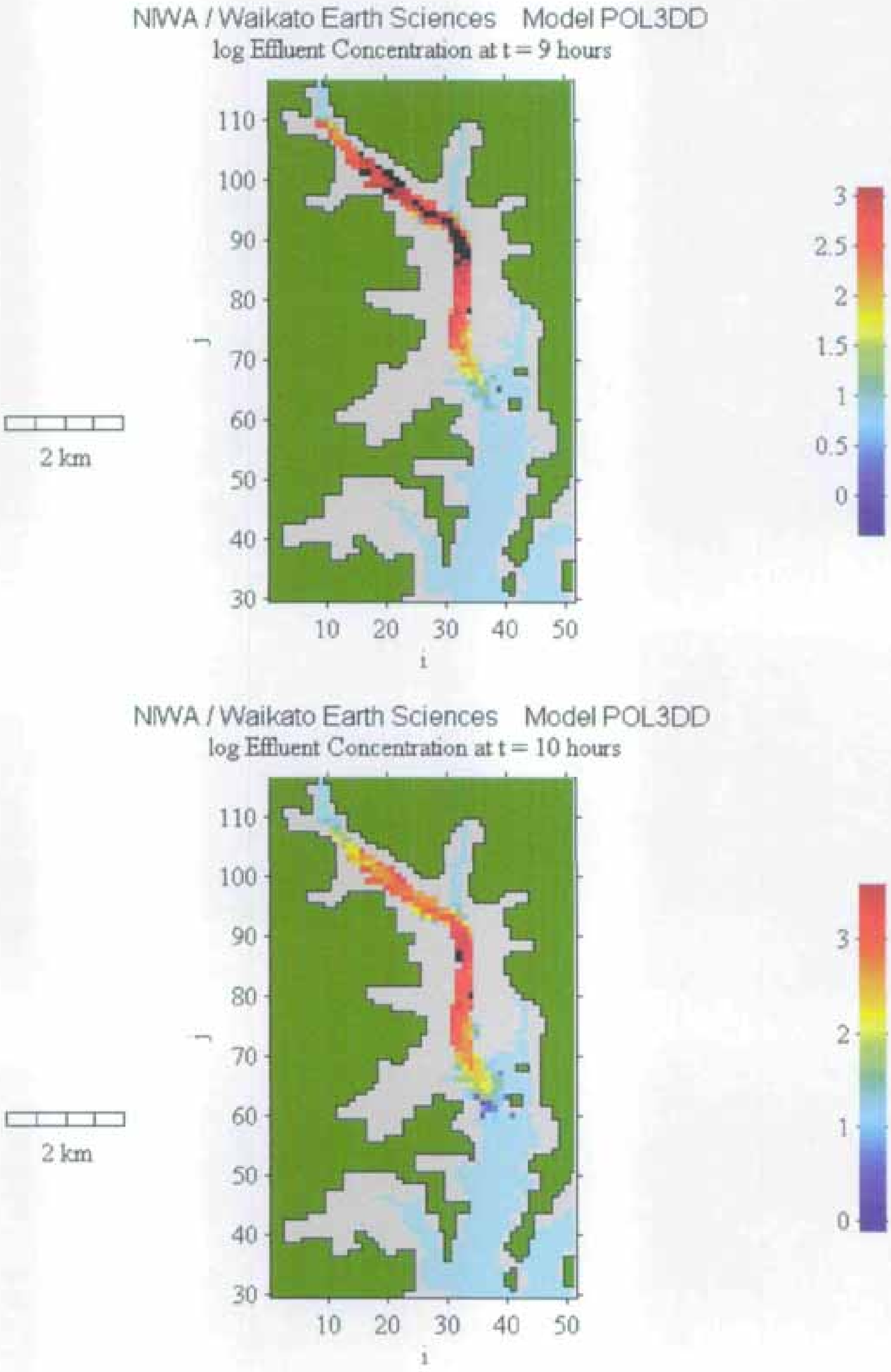


Figure 11e. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary at 9 hours and 10 hours after the start of a two hour overflow event with 35 cumecs freshwater inflows. (Examples: $2=10^2$ FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)

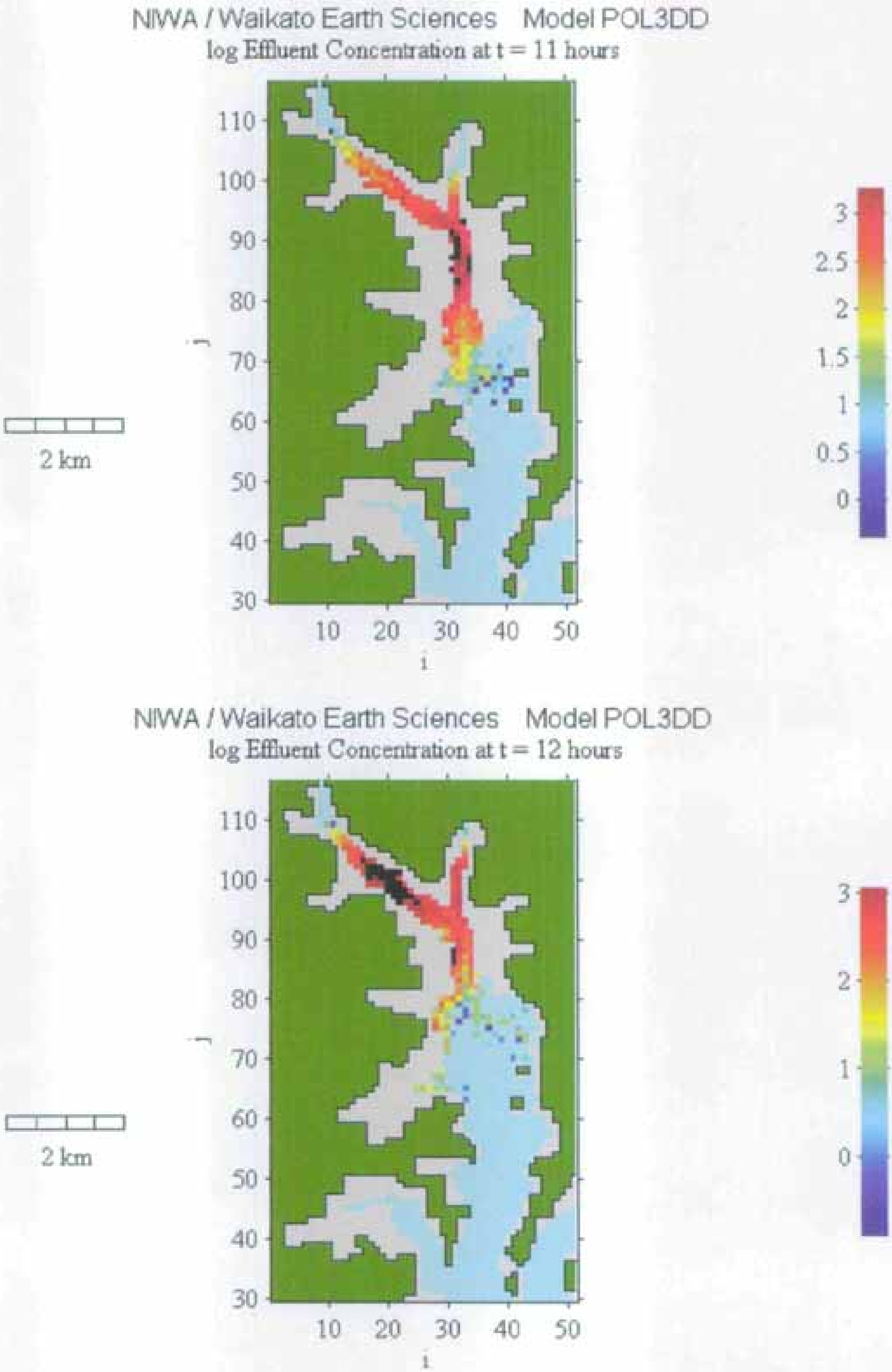


Figure 11f. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary at 11 hours and 12 hours after the start of a two hour overflow event with 35 cumecs freshwater inflows. (Examples: $2=10^2$ FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)

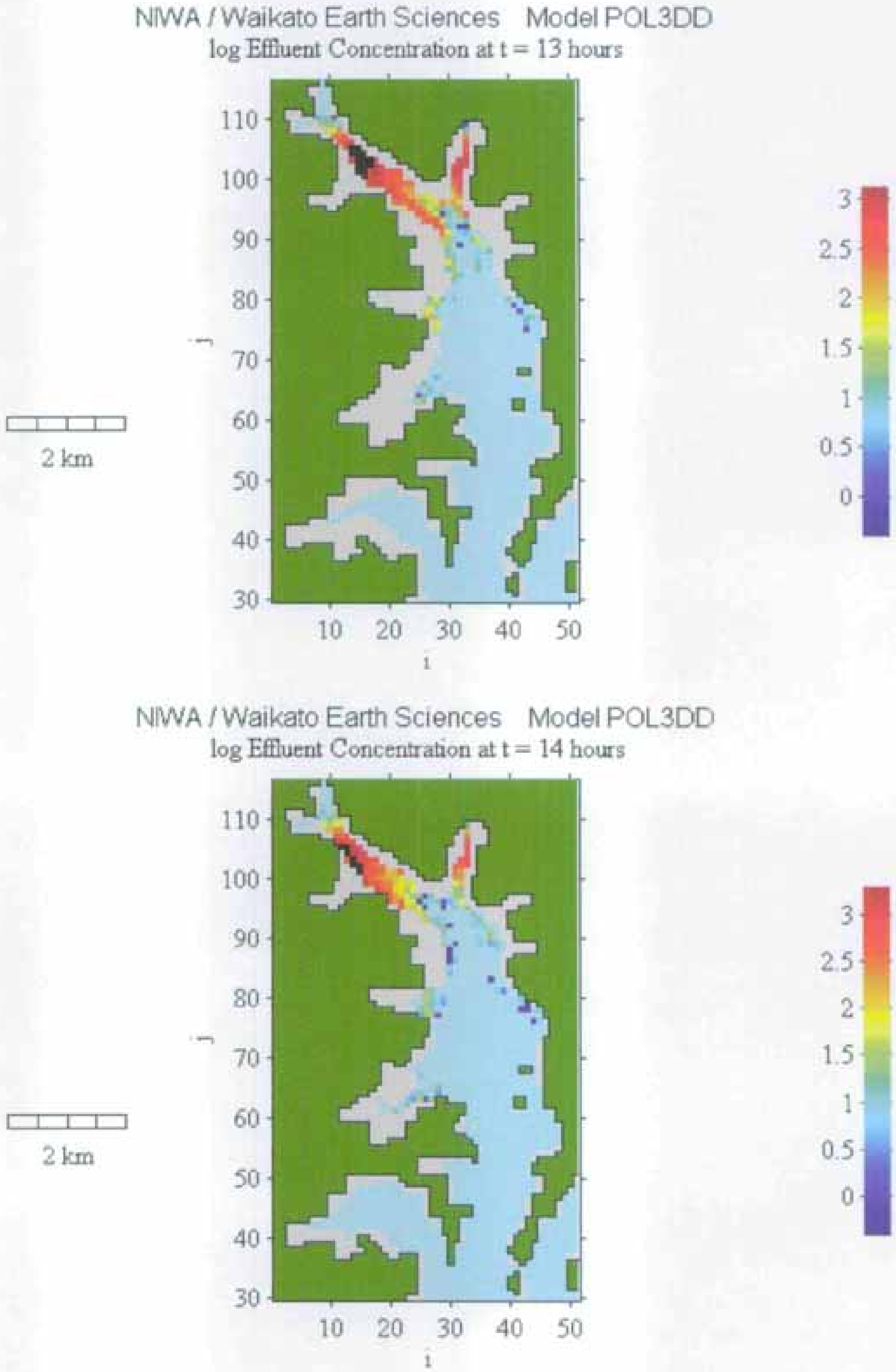


Figure 11g. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary at 13 hours and 14 hours after the start of a two hour overflow event with 35 cumecs freshwater inflows. (Examples: $2=10^2$ FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)

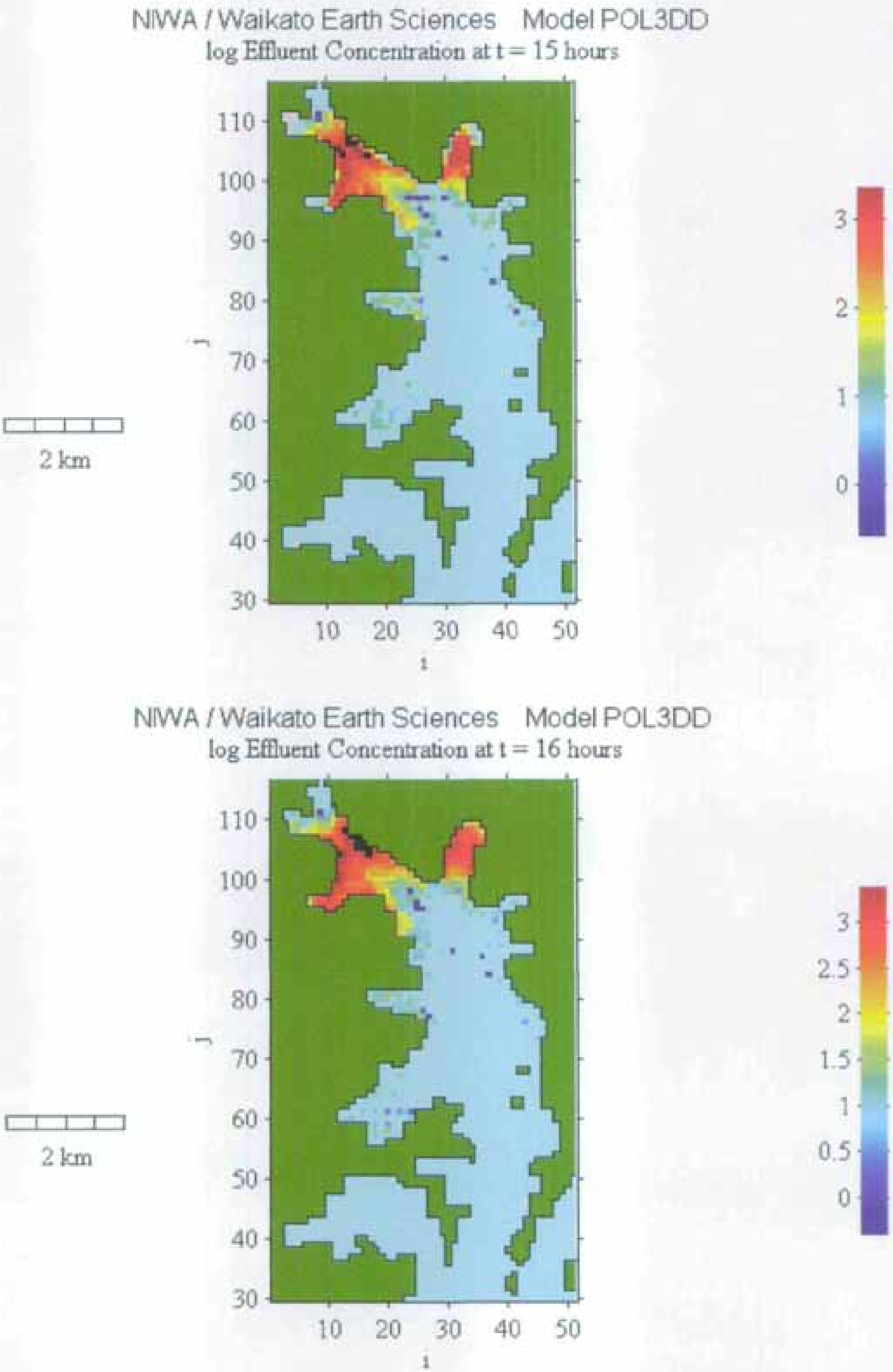


Figure 11h. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary at 15 hours and 16 hours after the start of a two hour overflow event with 35 cumecs freshwater inflows. (Examples: $2=10^2$ FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)

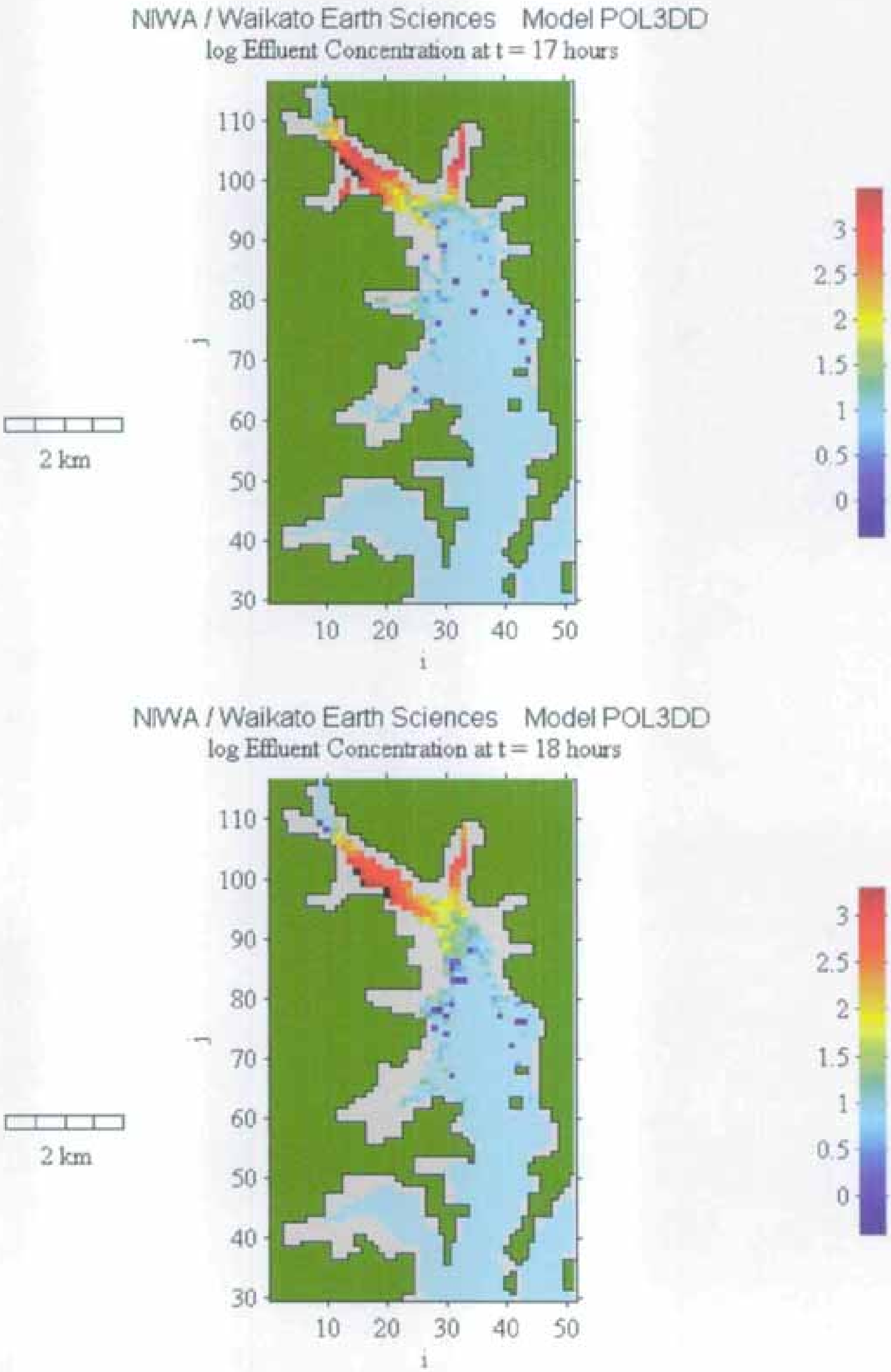


Figure 11i. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary at 17 hours and 18 hours after the start of a two hour overflow event with 35 cumecs freshwater inflows. (Examples: $2=10^2$ FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)

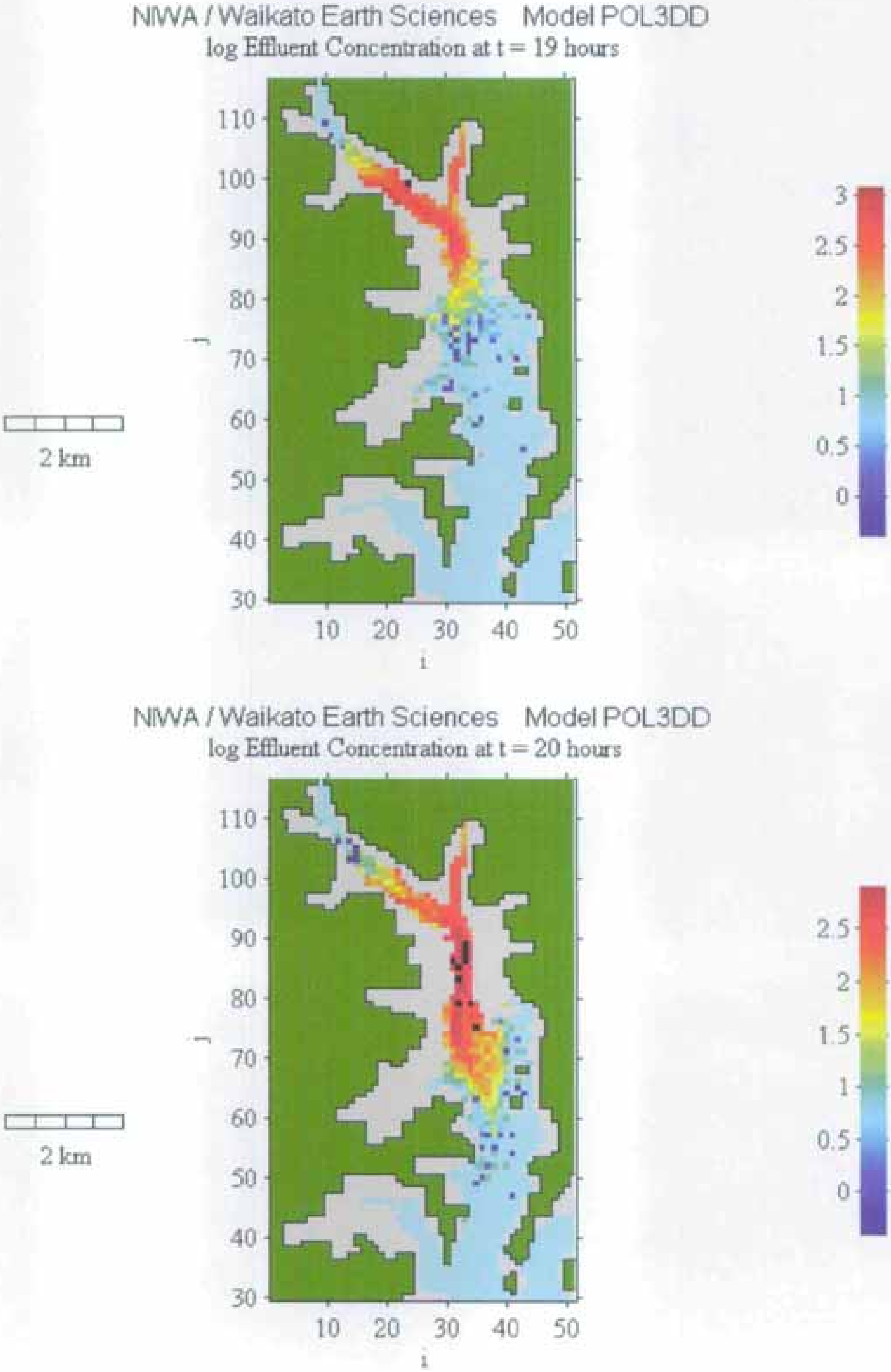


Figure 11j. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary at 19 hours and 20 hours after the start of a two hour overflow event with 35 cumecs freshwater inflows. (Examples: $2=10^2$ FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)

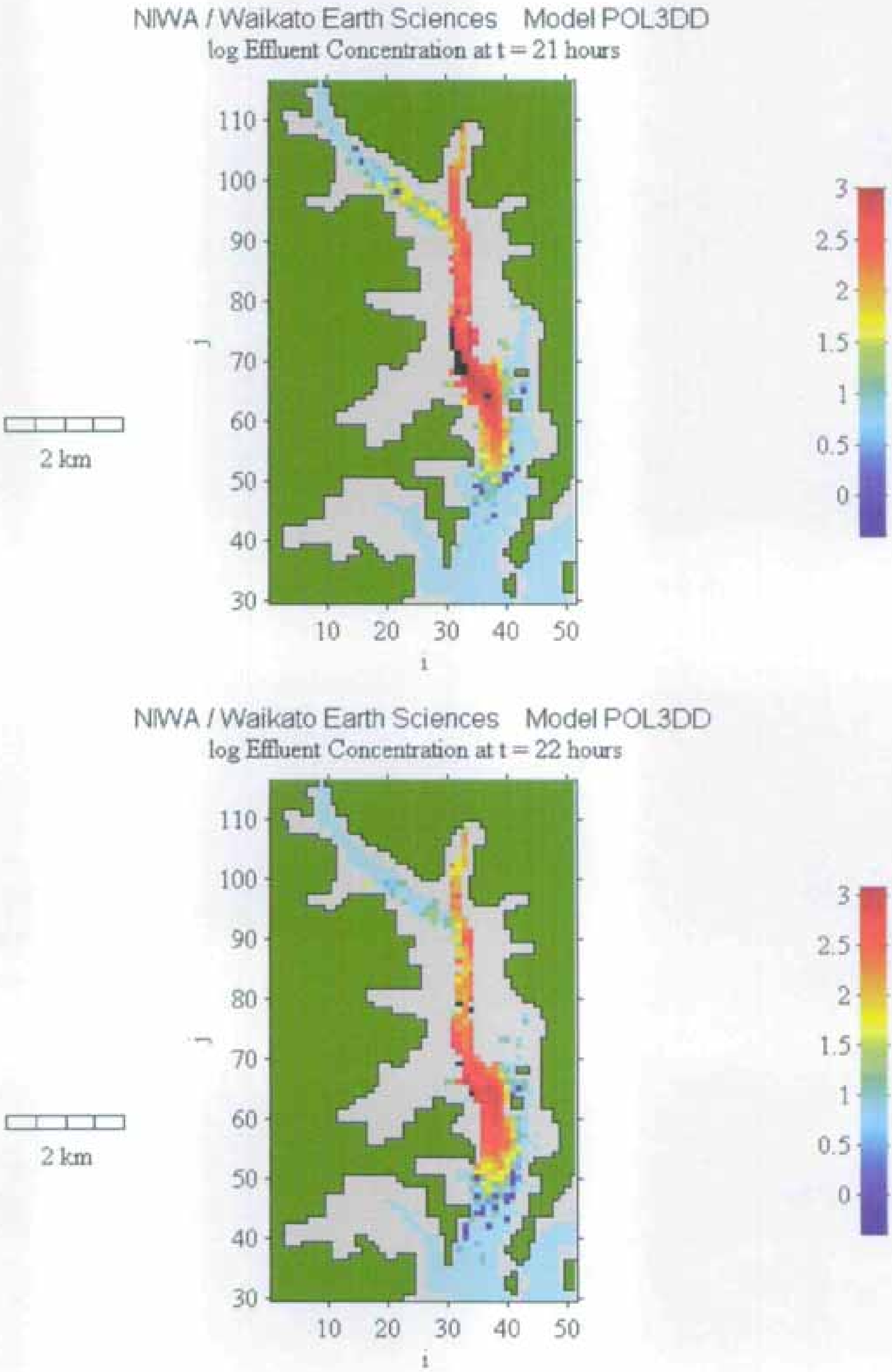


Figure 11k. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary at 21 hours and 22 hours after the start of a two hour overflow event with 35 cumecs freshwater inflows. (Examples: $2=10^2$ FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)

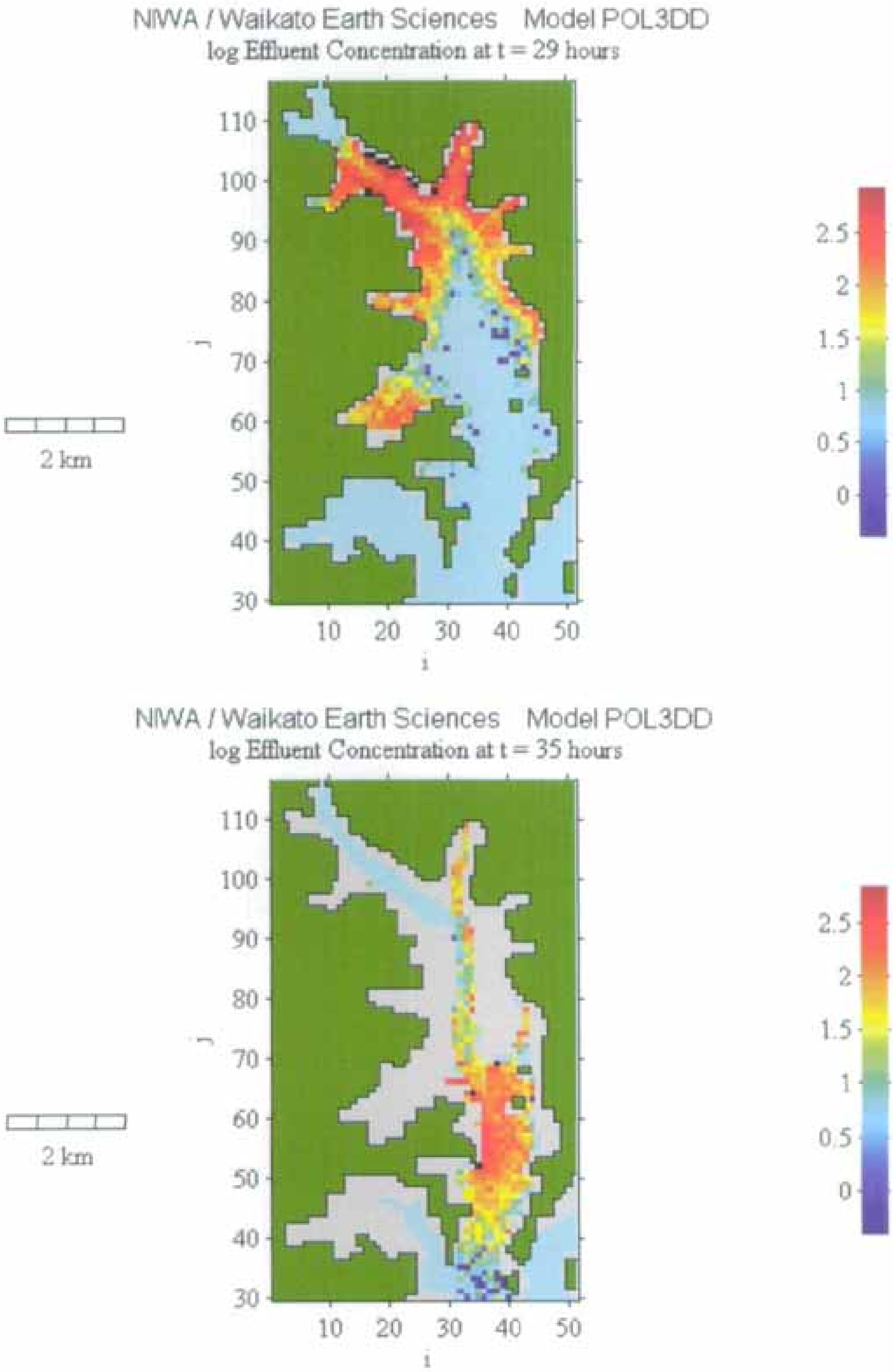
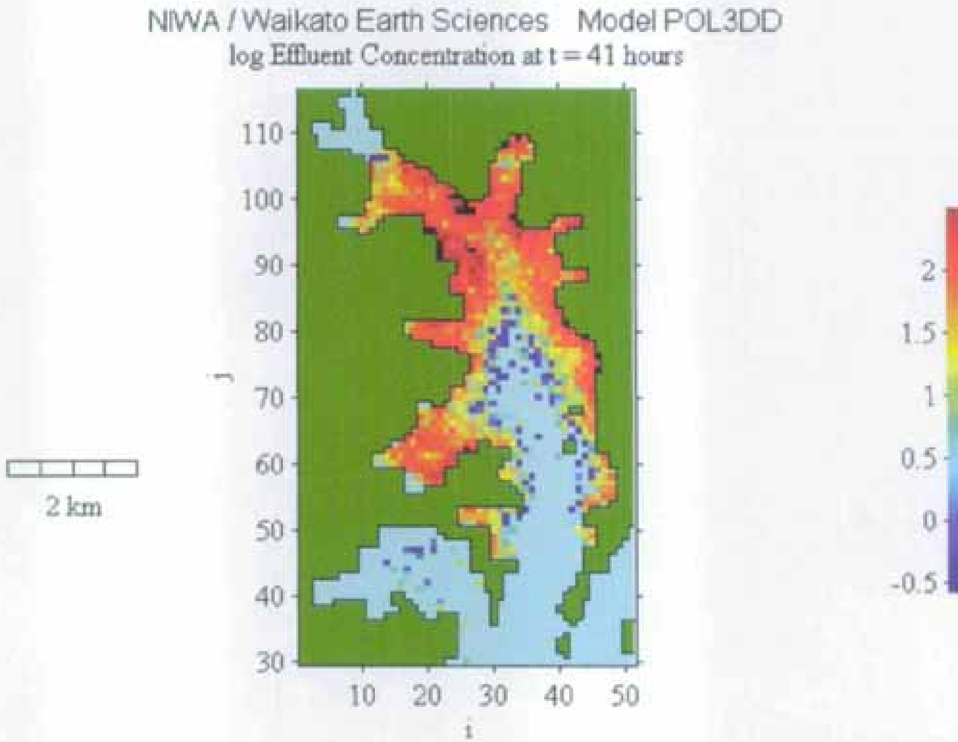


Figure 11I. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary for the 3rd high and low waters after the start of a two hour overflow event with 35 cumecs freshwater inflows. (Examples: $2=10^2$ FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)



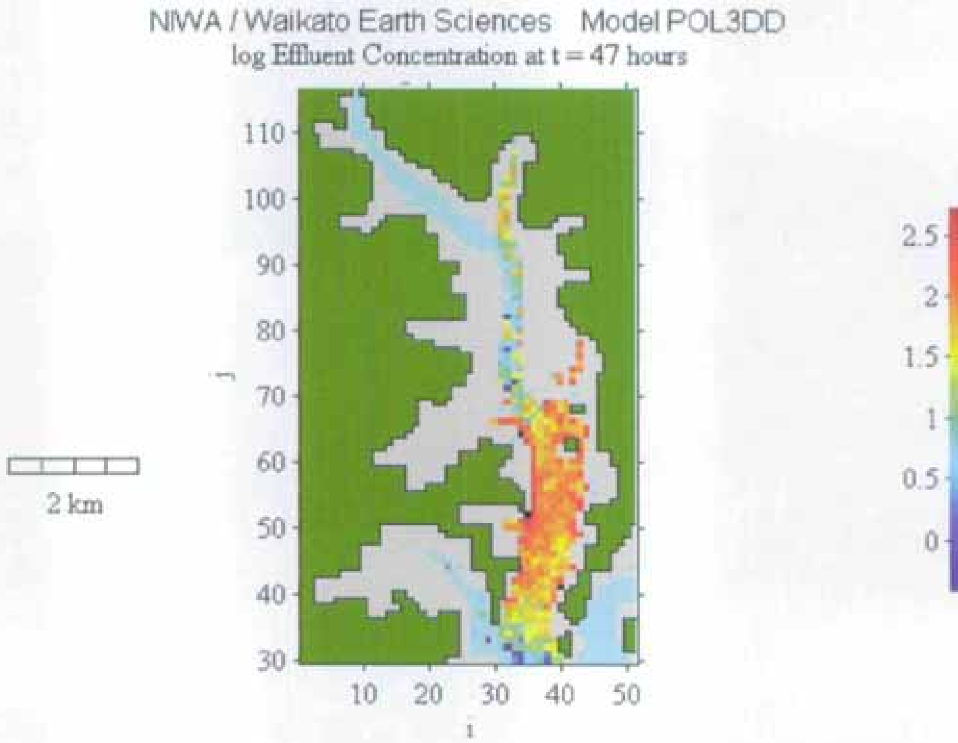
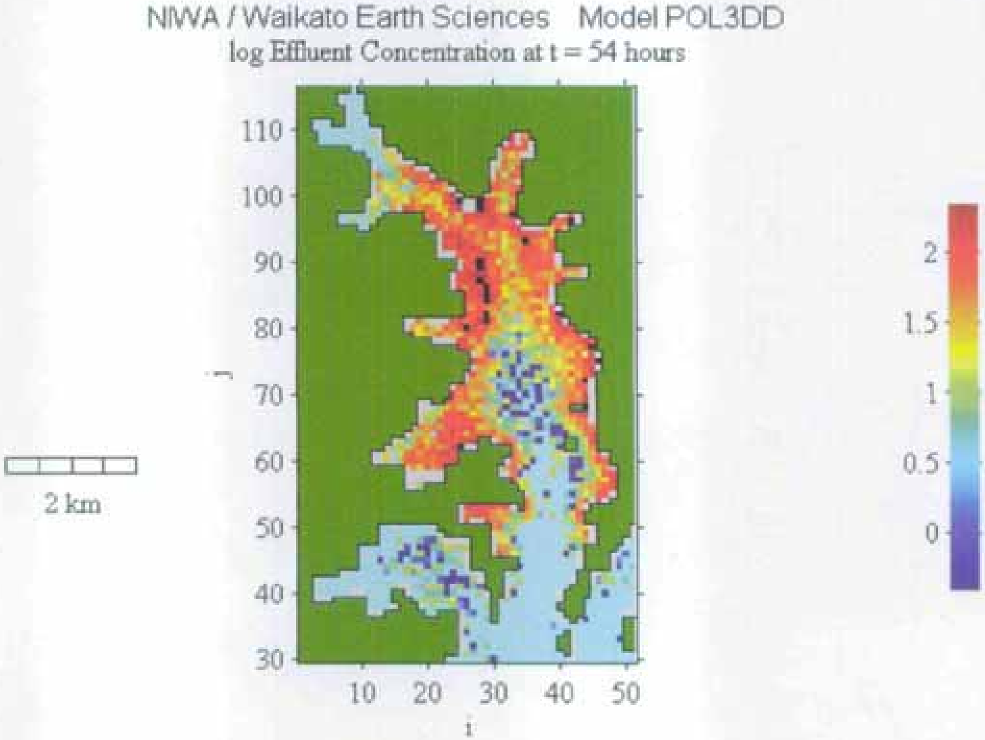


Figure 11m. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary for the 4th high and low waters after the start of a two hour overflow event with 35 cumecs freshwater inflows. (Examples: $2=10^2$ FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)



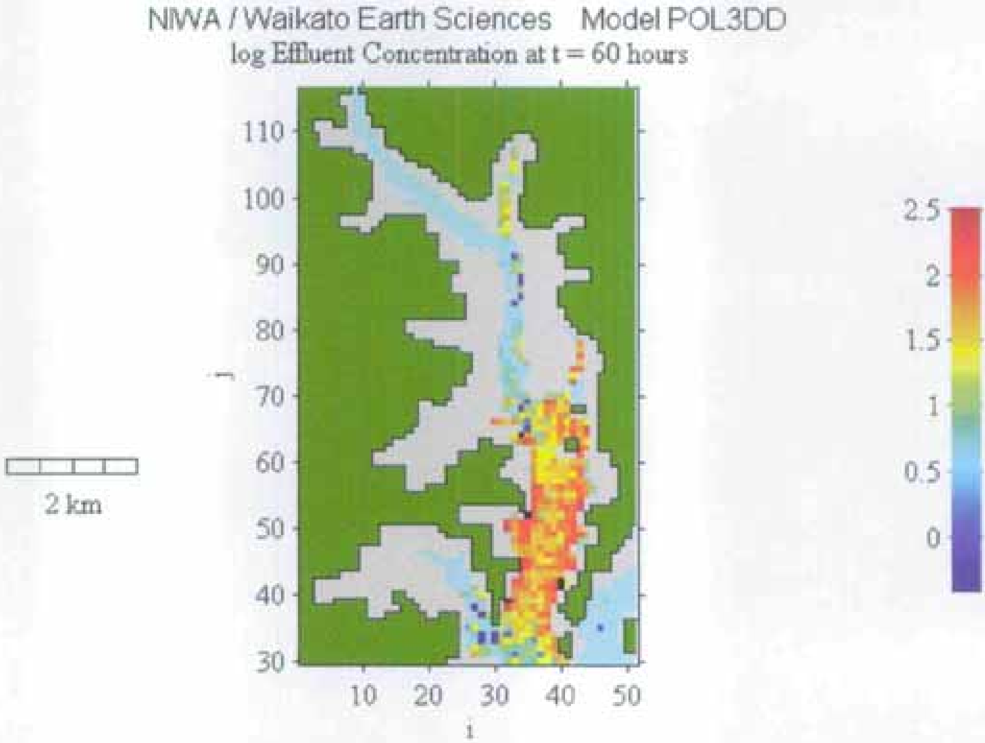


Figure 11n. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary for the 5th high and low waters after the start of a two hour overflow event with 35 cumecs freshwater inflows. (Examples: $2=10^2$ FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)

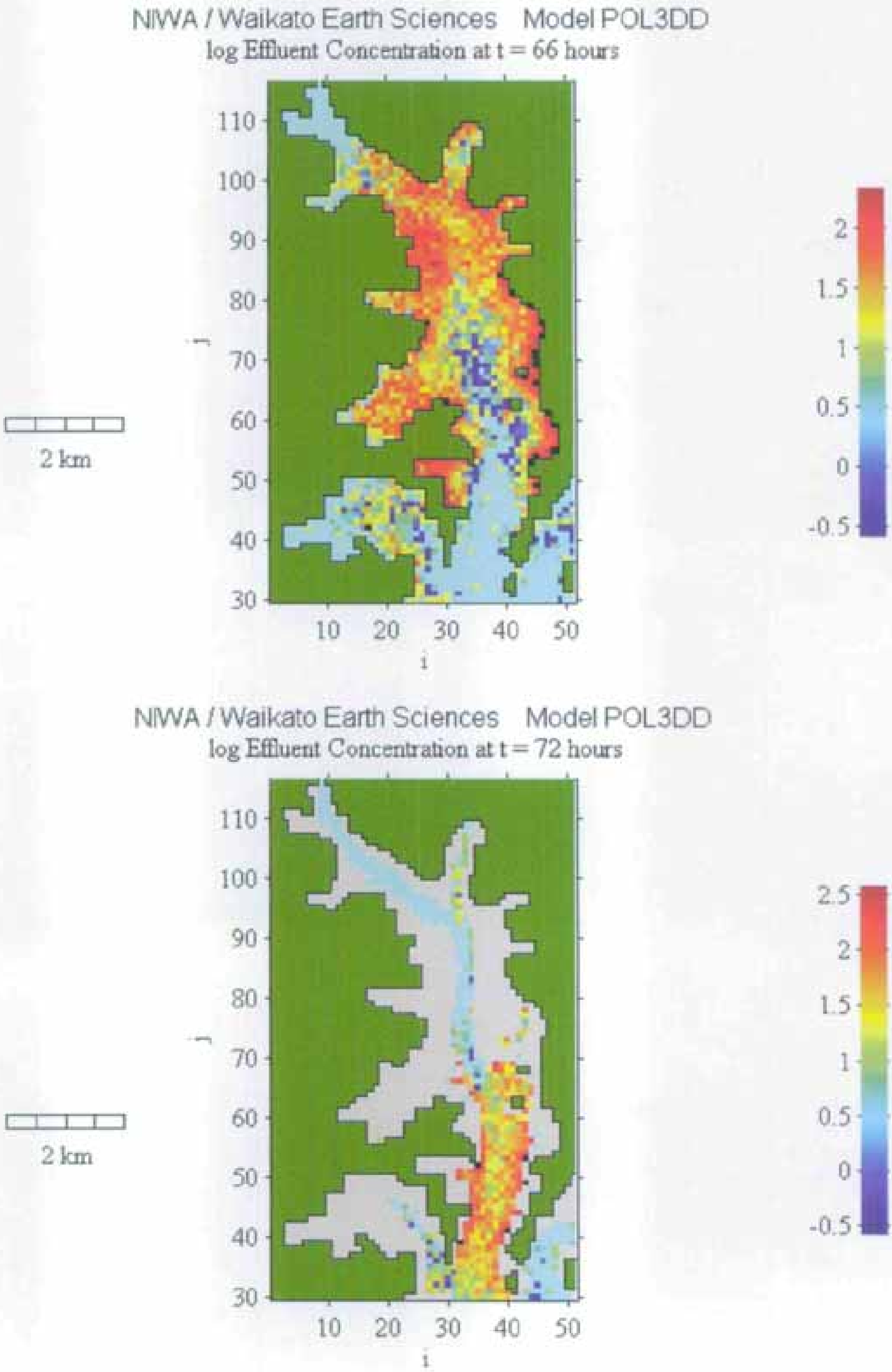


Figure 11o. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary for the 6th high and low waters after the start of a two hour overflow event with 35 cumecs freshwater inflows. (Examples: $2=10^2$ FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)

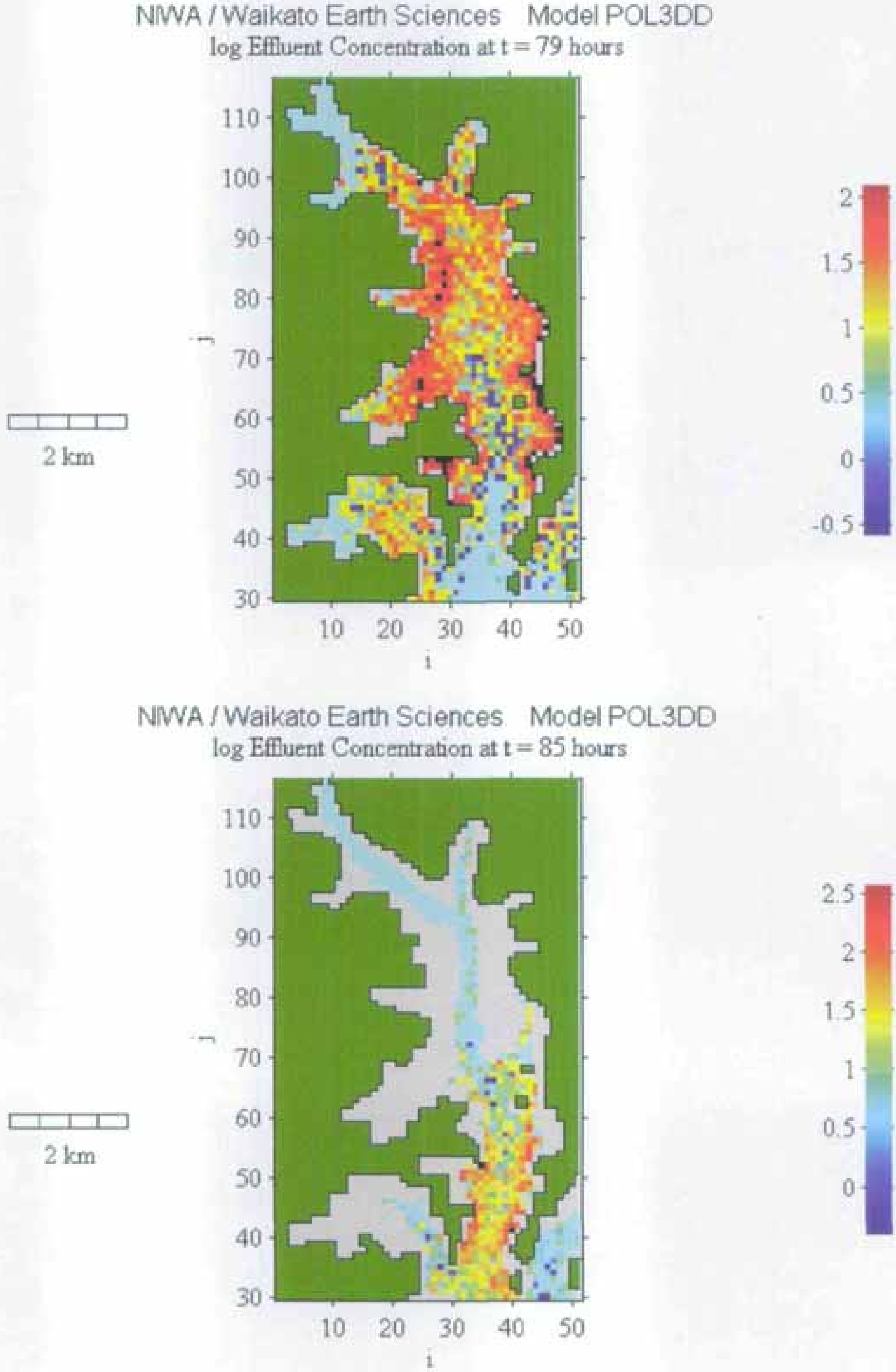


Figure 11p. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary for the 7th high and low waters after the start of a two hour overflow event with 35 cumecs freshwater inflows. (Examples: $2=10^2$ FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)

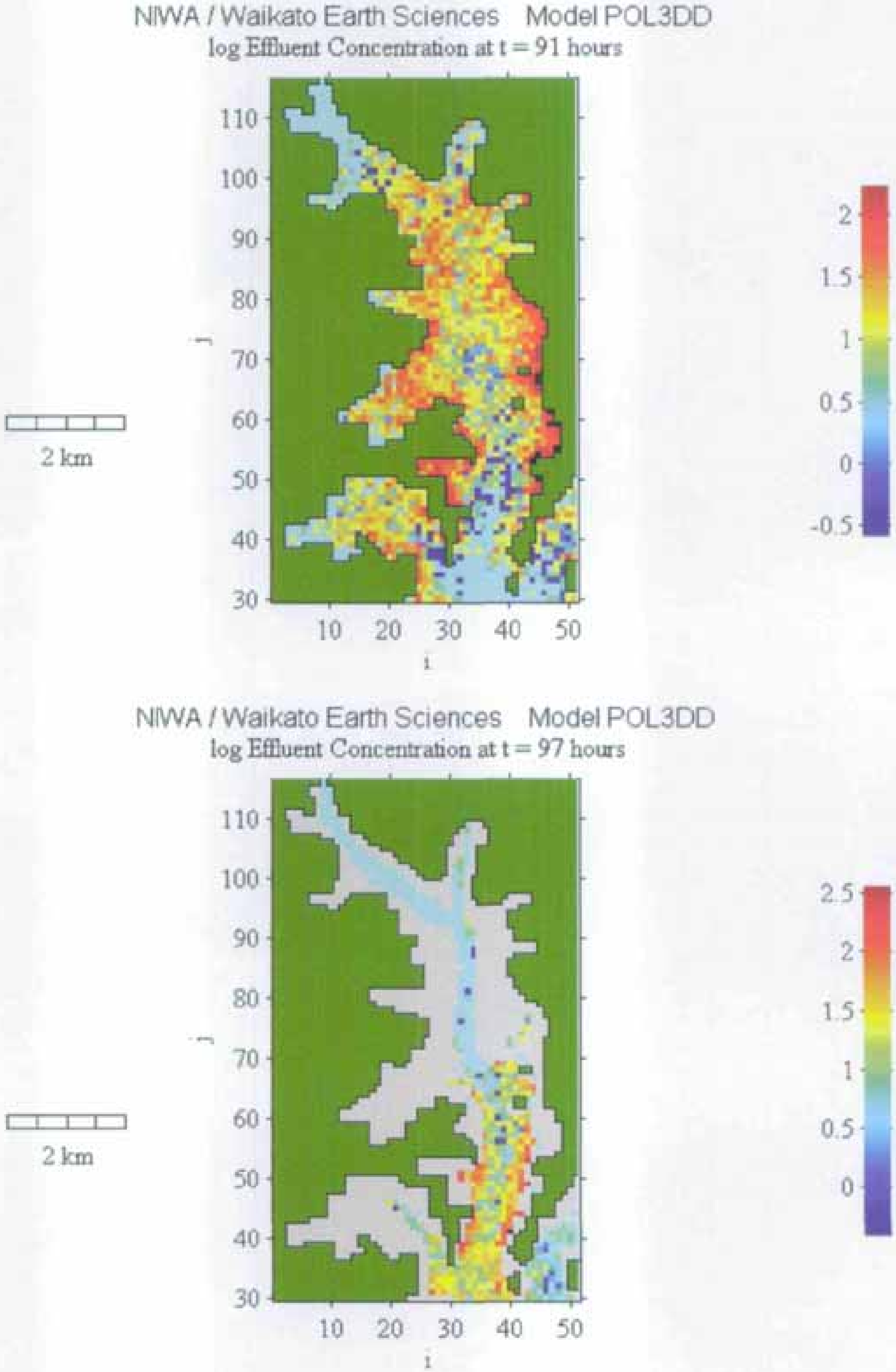


Figure 11q. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary for the 8th high and low waters after the start of a two hour overflow event with 35 cumecs freshwater inflows. (Examples: $2=10^2$ FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)

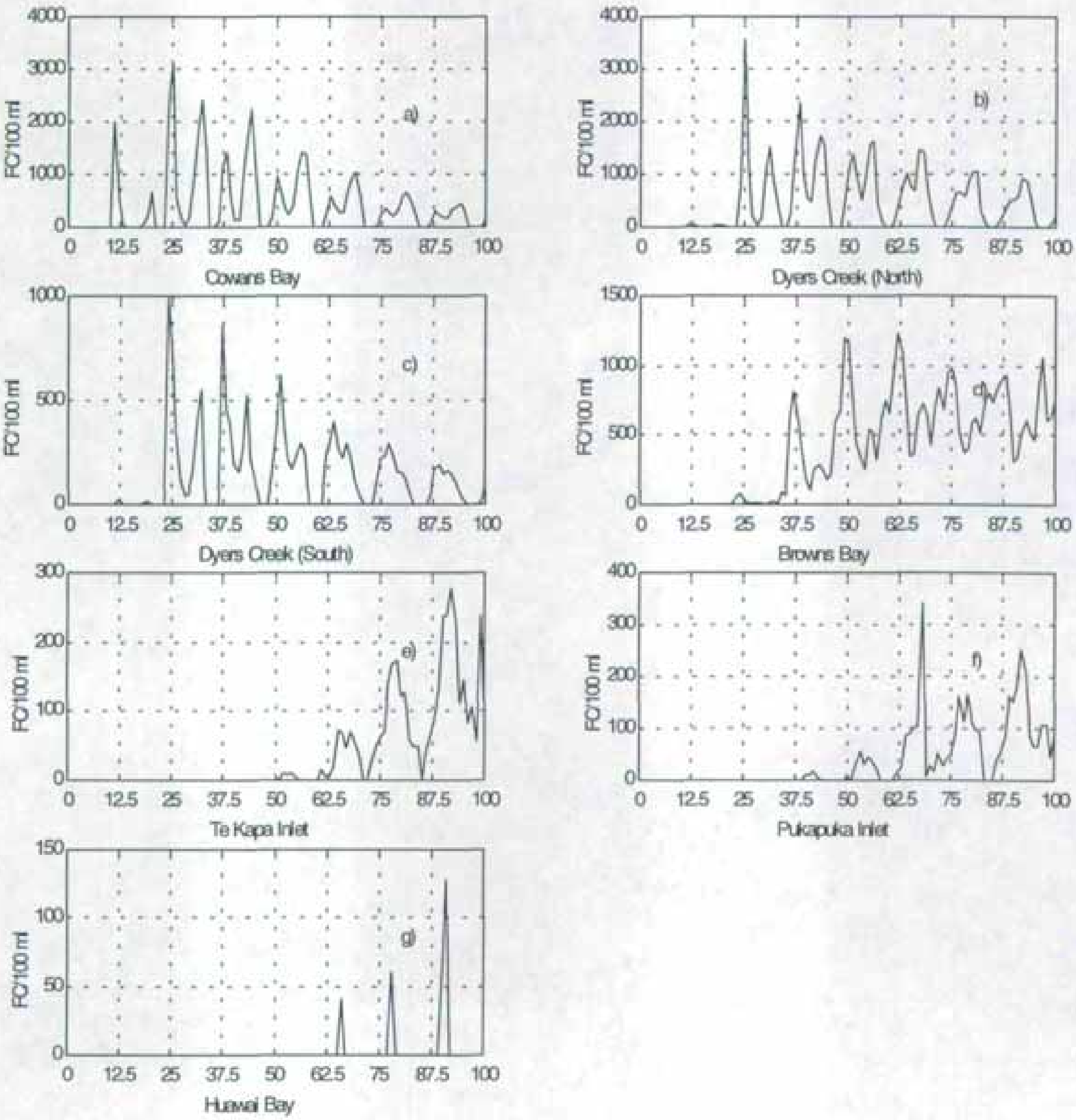


Figure 12. Predicted Faecal Coliform concentrations within the oyster farms for a four hour overflow event with 35 cumec freshwater inflows. (Horizontal axis is time in elapsed hours from the model start. Note: each tidal cycle = 12.5 hours).

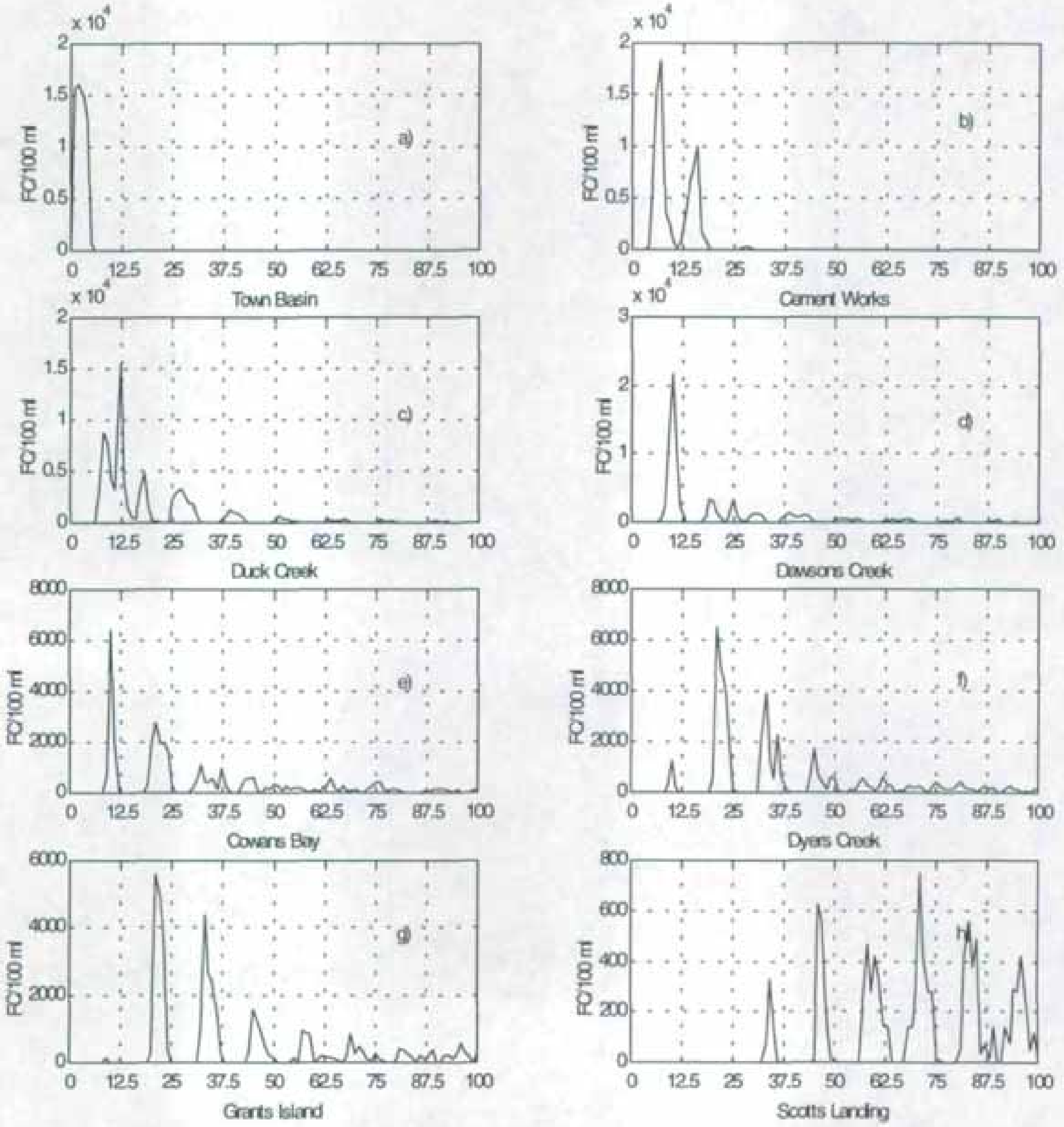


Figure 13. Predicted Faecal Coliform concentrations within the main channel for a four hour overflow event with 35 cumec freshwater inflows. (Horizontal axis is time in elapsed hours from the model start. Note: each tidal cycle = 12.5 hours)

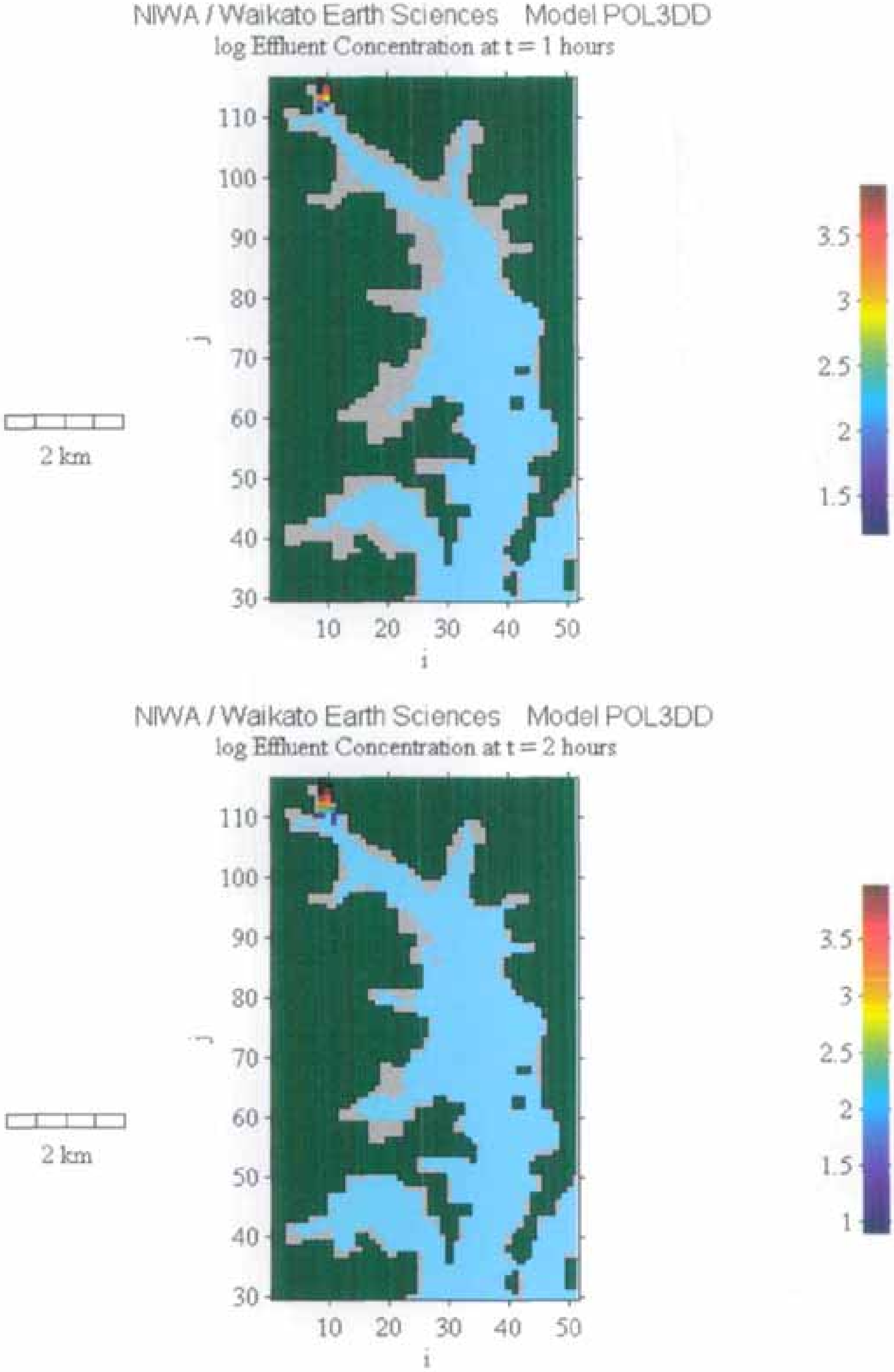


Figure 14a. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary at 1 hour and 2 hours after the start of a four hour overflow event with 35 cumecs freshwater inflows. (Examples: $2=10^2$ FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)

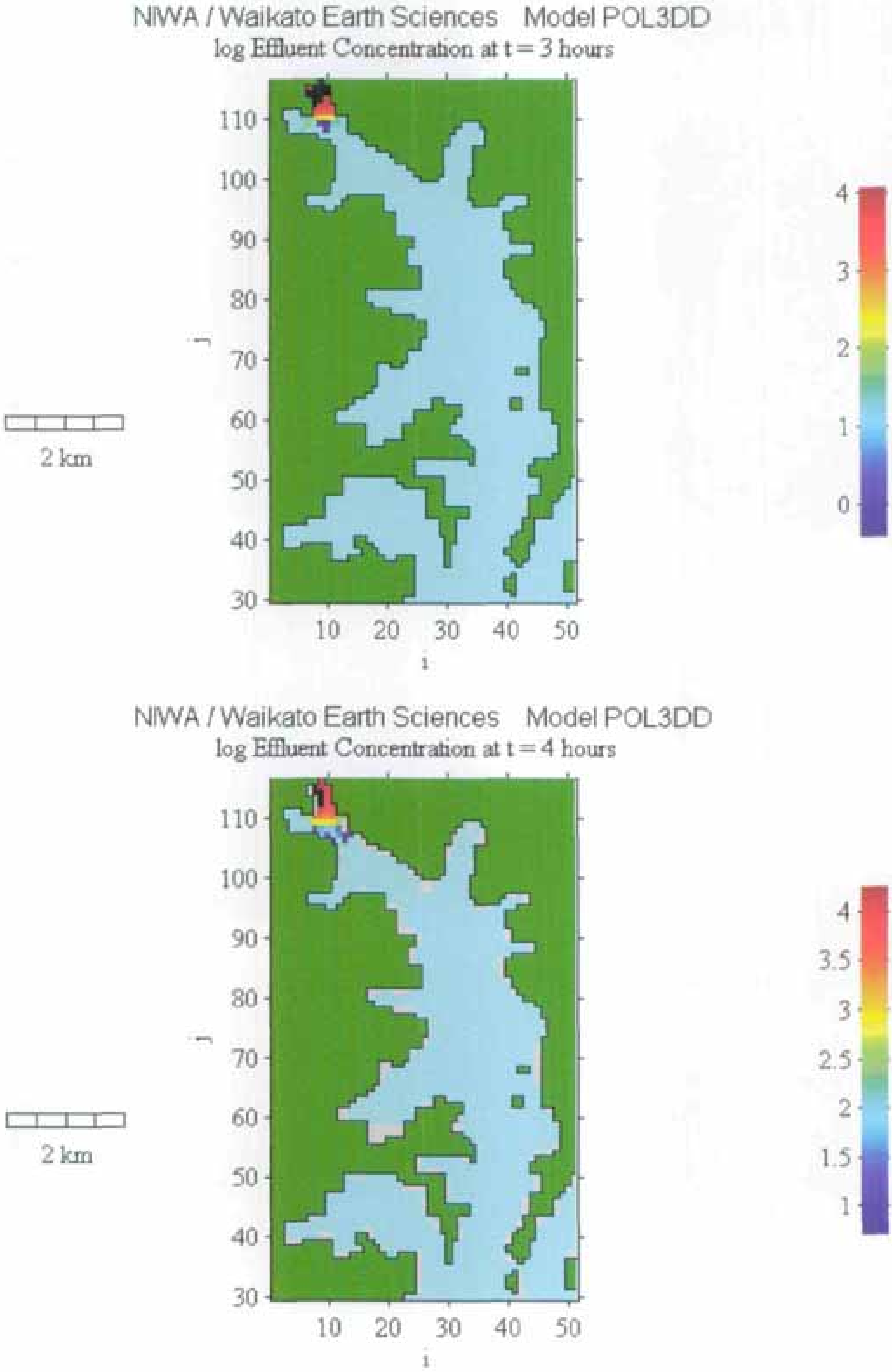


Figure 14b. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary at 3 hours and 4 hours after the start of a four hour overflow event with 35 cumecs freshwater inflows. (Examples: $2=10^2$ FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)

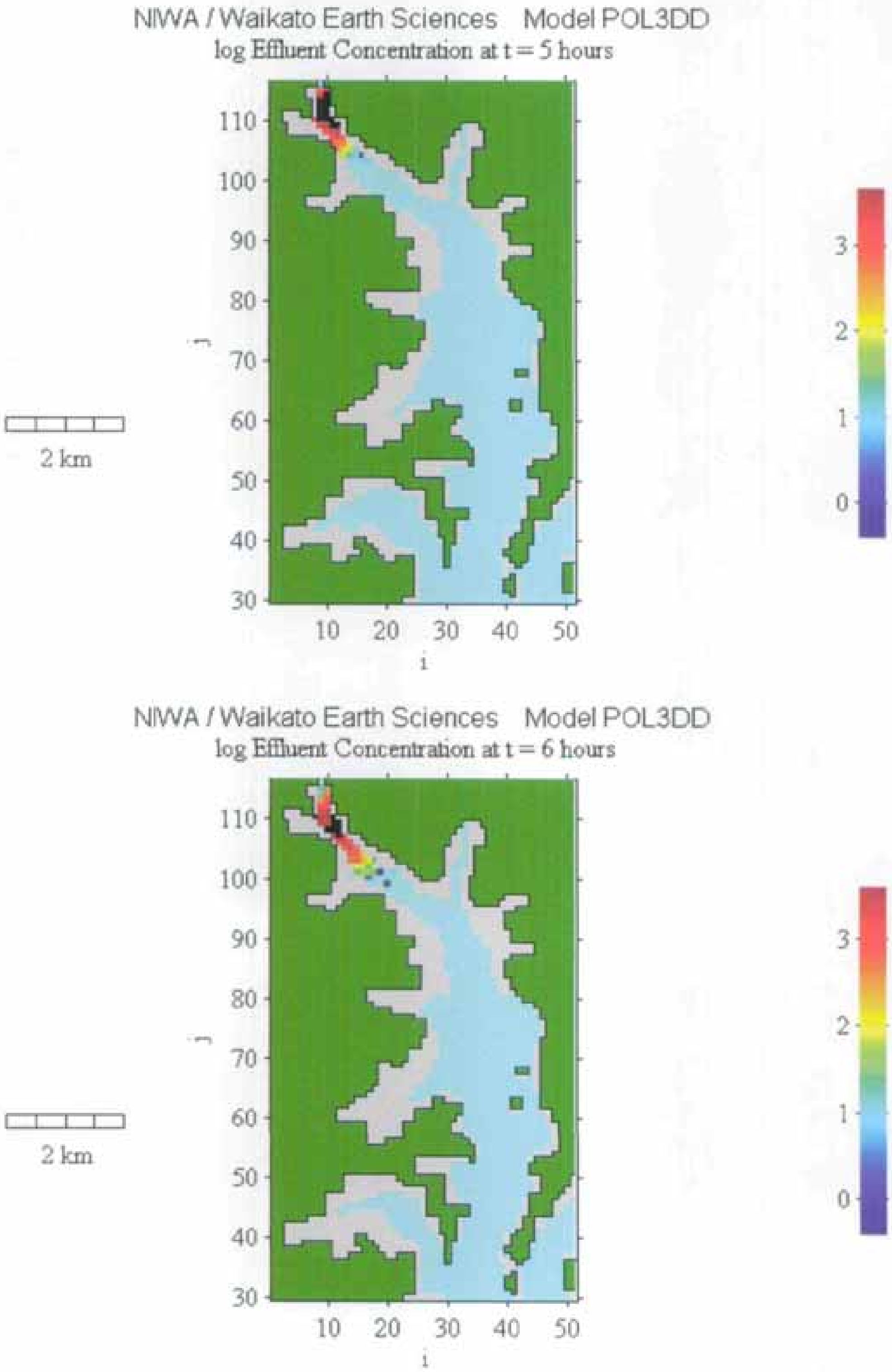


Figure 14c. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary at 5 hours and 6 hours after the start of a four hour overflow event with 35 cumecs freshwater inflows. (Examples: $2=10^2$ FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)

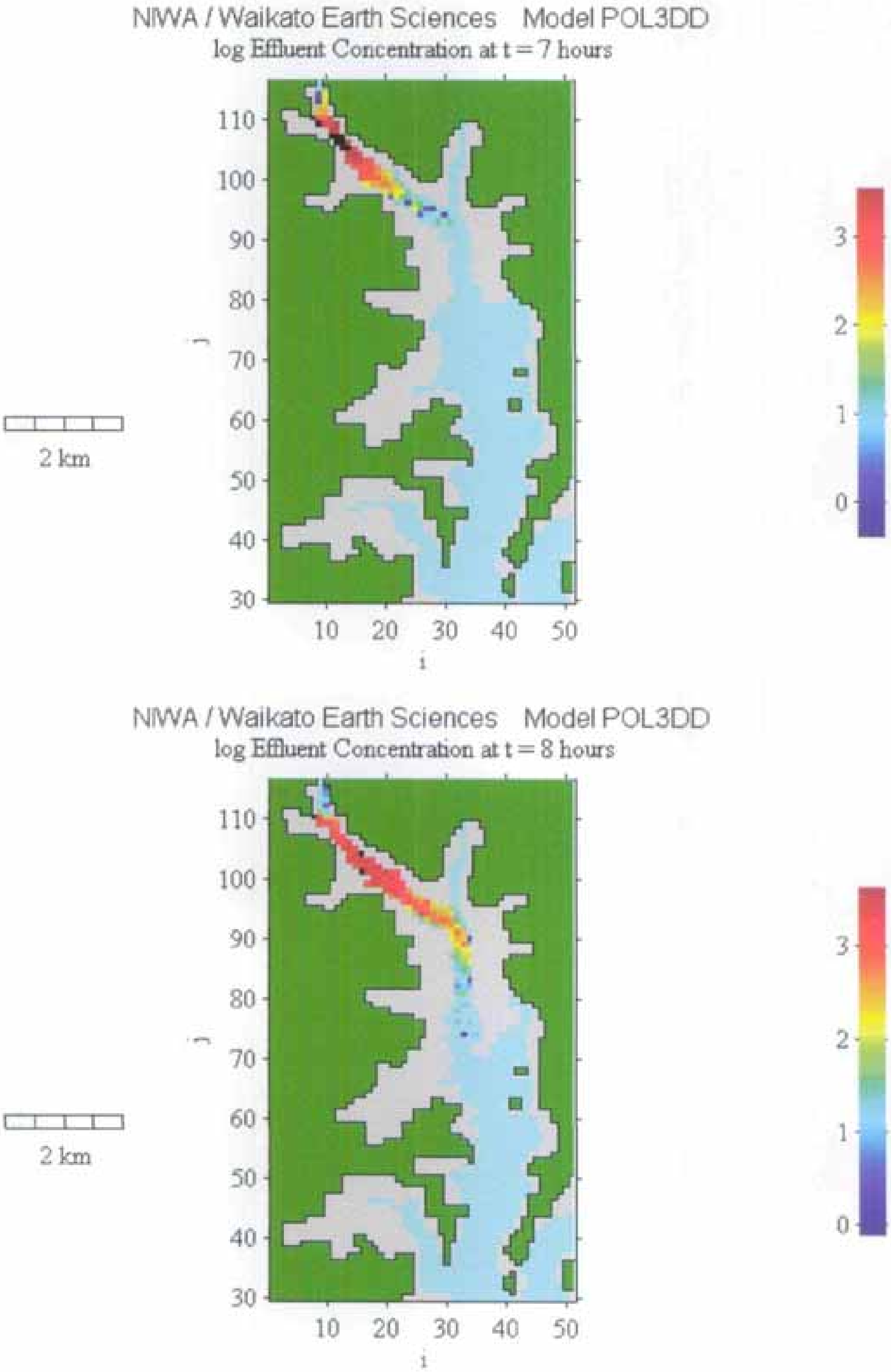


Figure 14d. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary at 7 hours and 8 hours after the start of a four hour overflow event with 35 cumecs freshwater inflows. (Examples: $2=10^2$ FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)

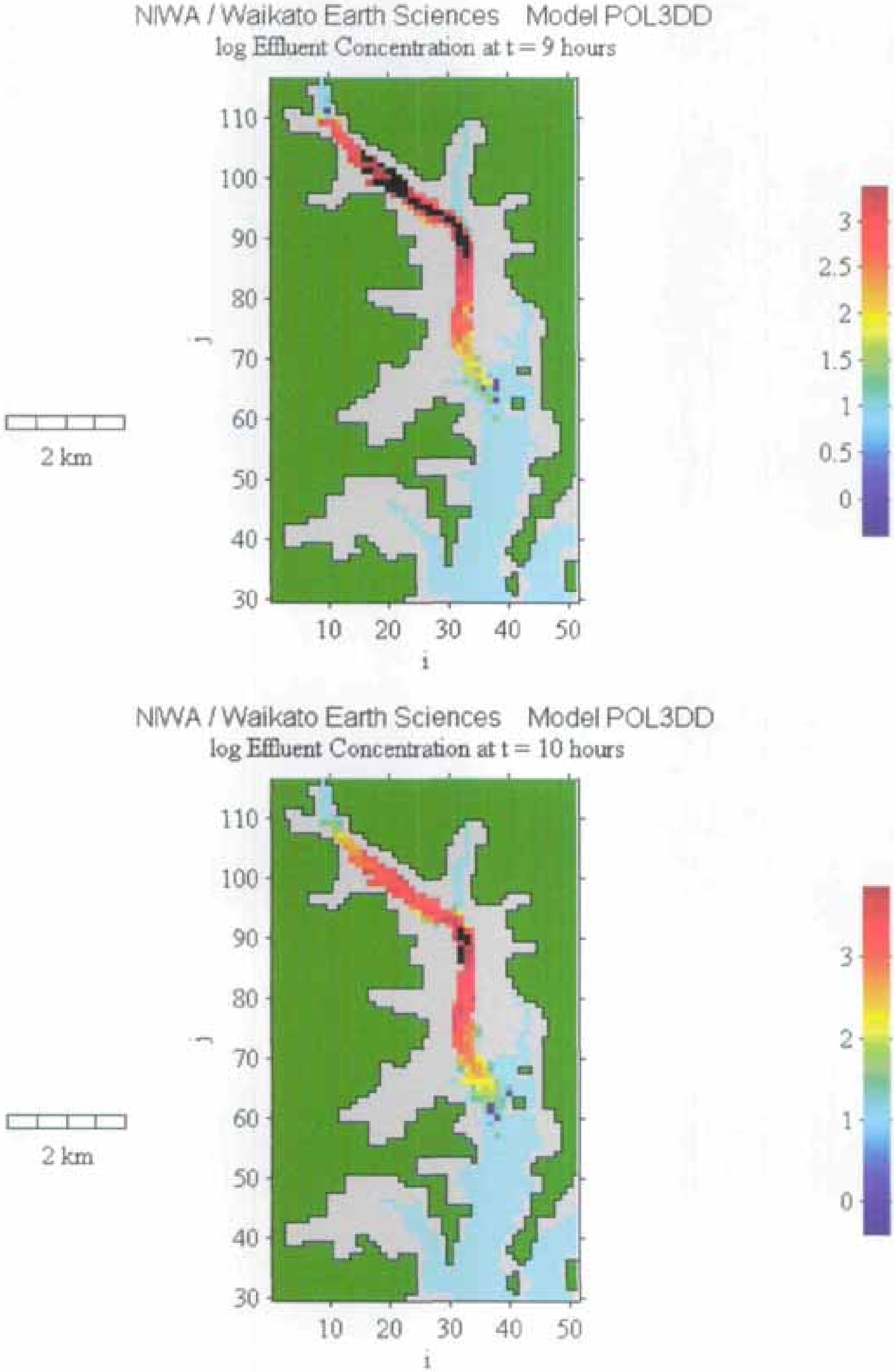


Figure 14e. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary at 9 hours and 10 hours after the start of a four hour overflow event with 35 cumecs freshwater inflows. (Examples: $2=10^2$ FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)

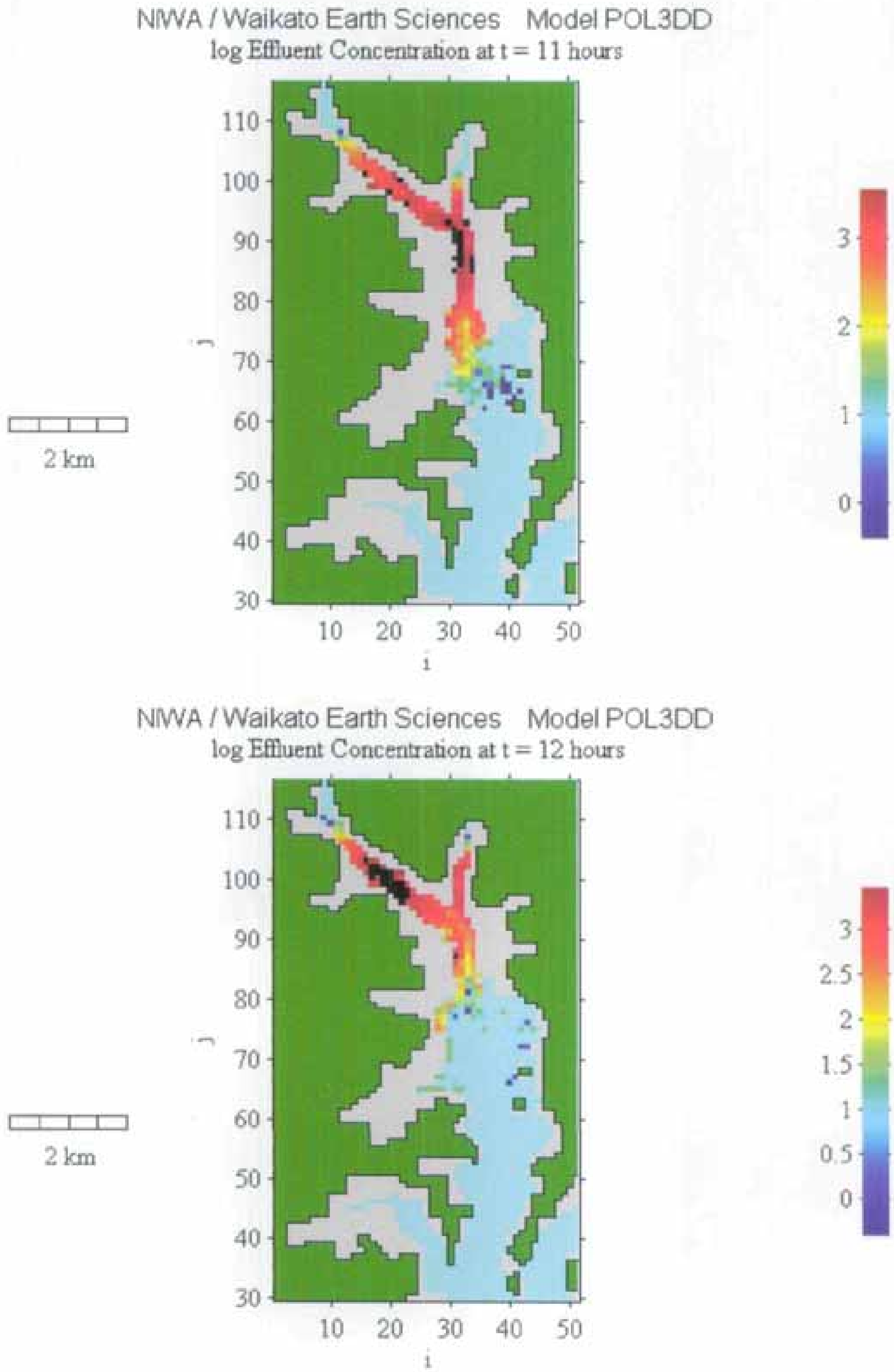


Figure 14f. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary at 11 hours and 12 hours after the start of a four hour overflow event with 35 cumecs freshwater inflows. (Examples: $2=10^2$ FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)

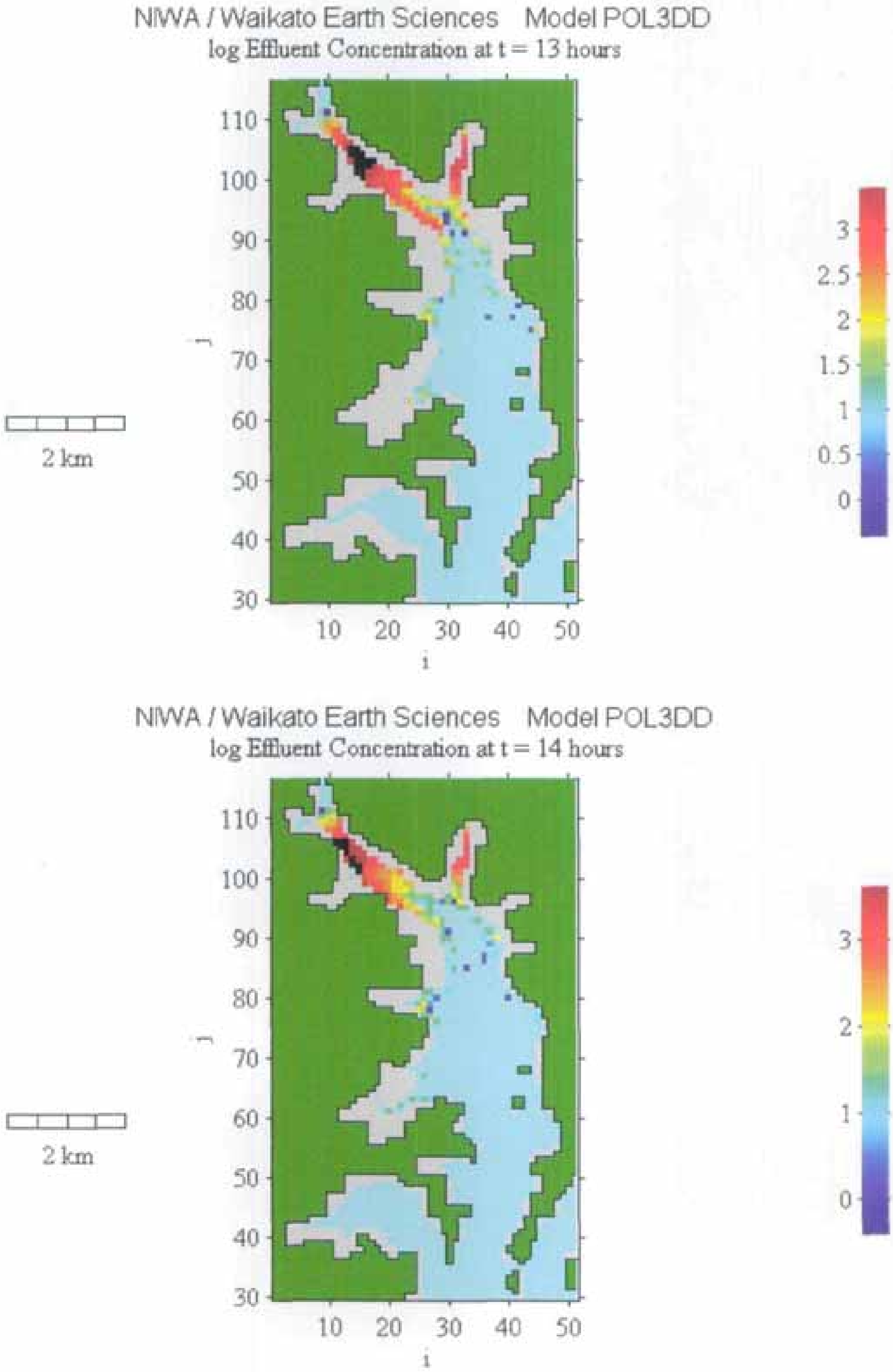


Figure 14g. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary at 13 hours and 14 hours after the start of a four hour overflow event with 35 cumecs freshwater inflows. (Examples: $2=10^2$ FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)

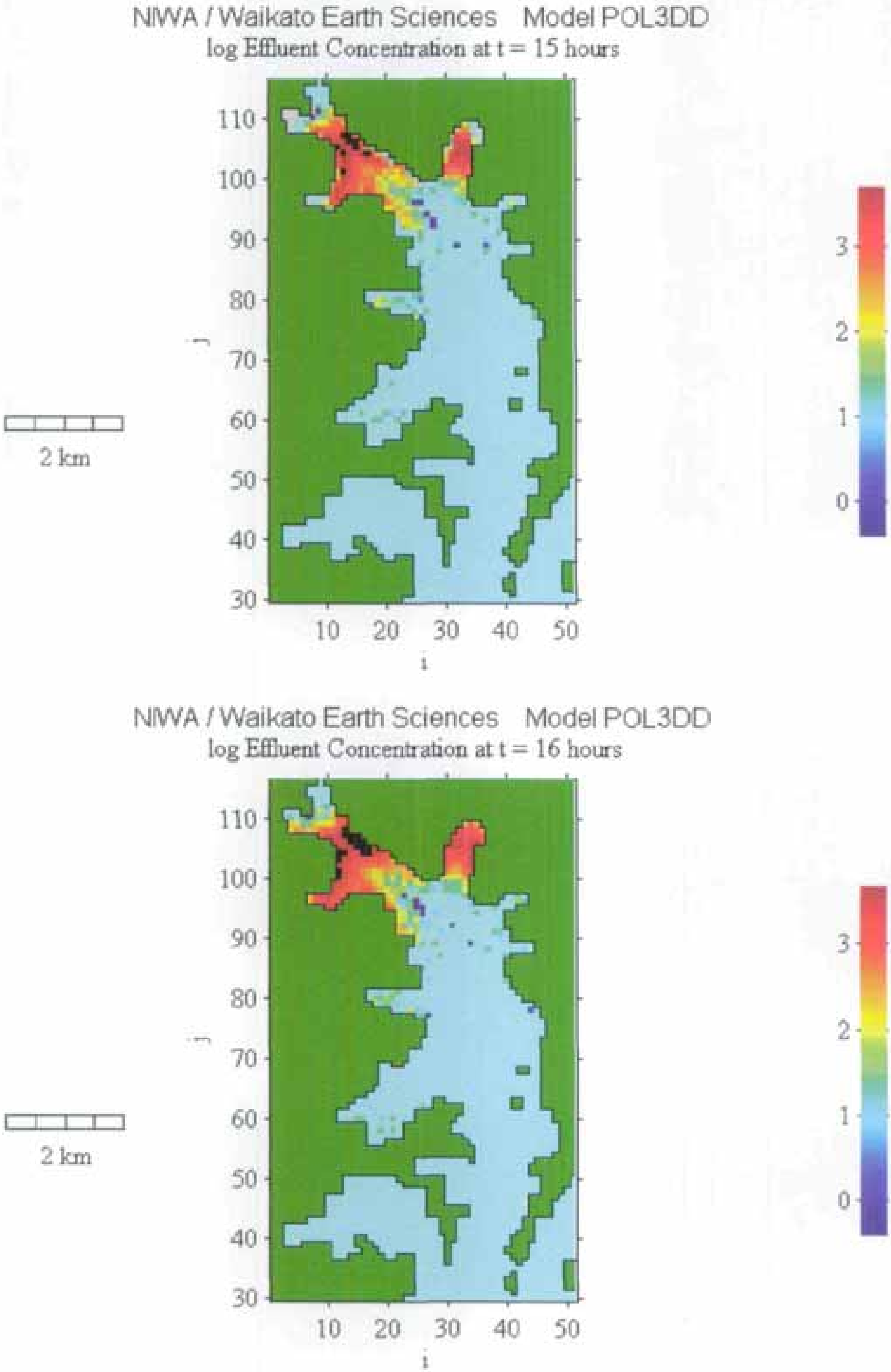


Figure 14h. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary at 15 hours and 16 hours after the start of a four hour overflow event with 35 cumecs freshwater inflows. (Examples: $2=10^2$ FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)

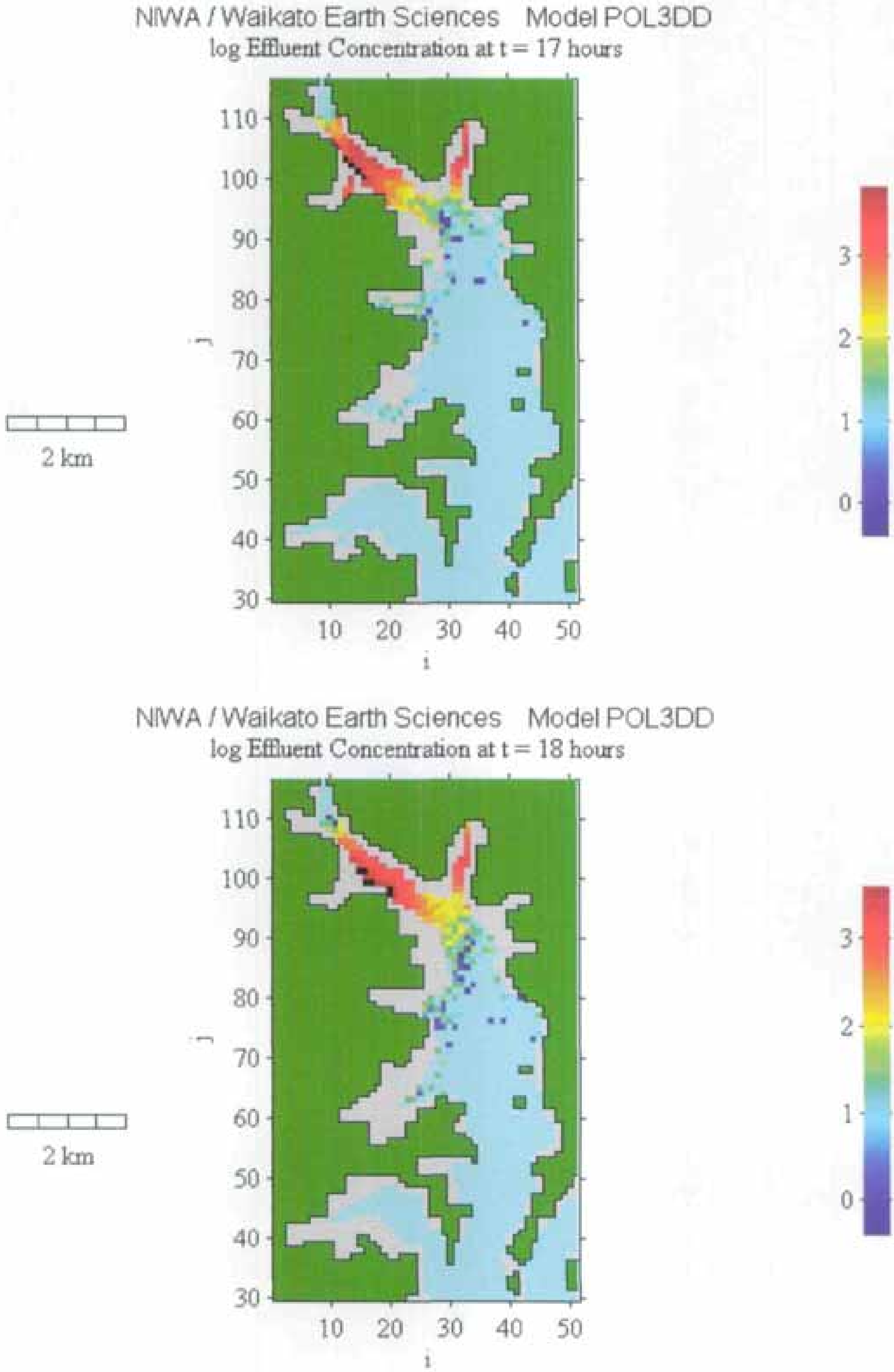


Figure 14i. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary at 17 hours and 18 hours after the start of a four hour overflow event with 35 cumecs freshwater inflows. (Examples: 2=10^2 FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)

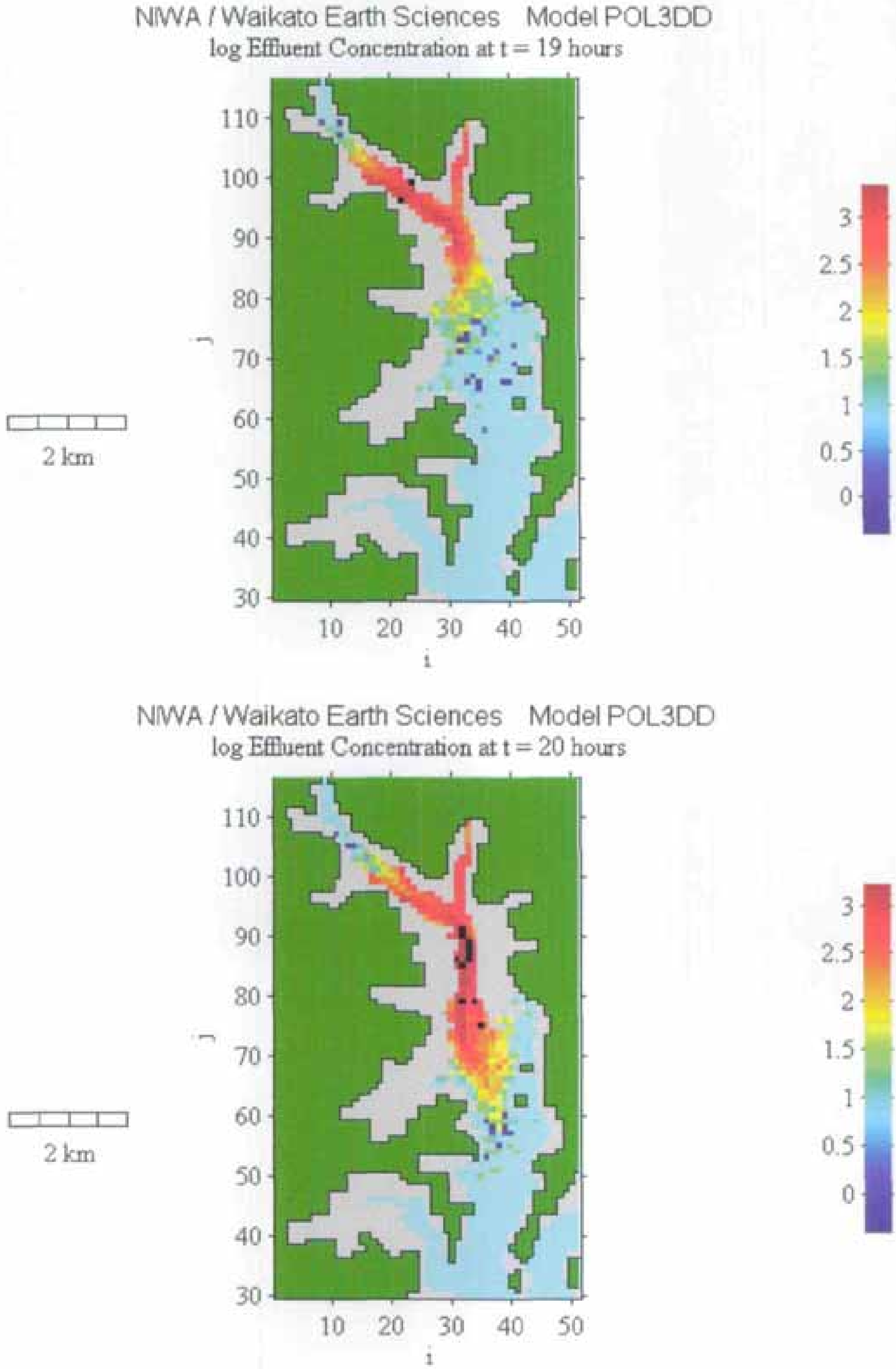


Figure 14j. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary at 19 hours and 20 hours after the start of a four hour overflow event with 35 cumecs freshwater inflows. (Examples: 2=10^2 FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)

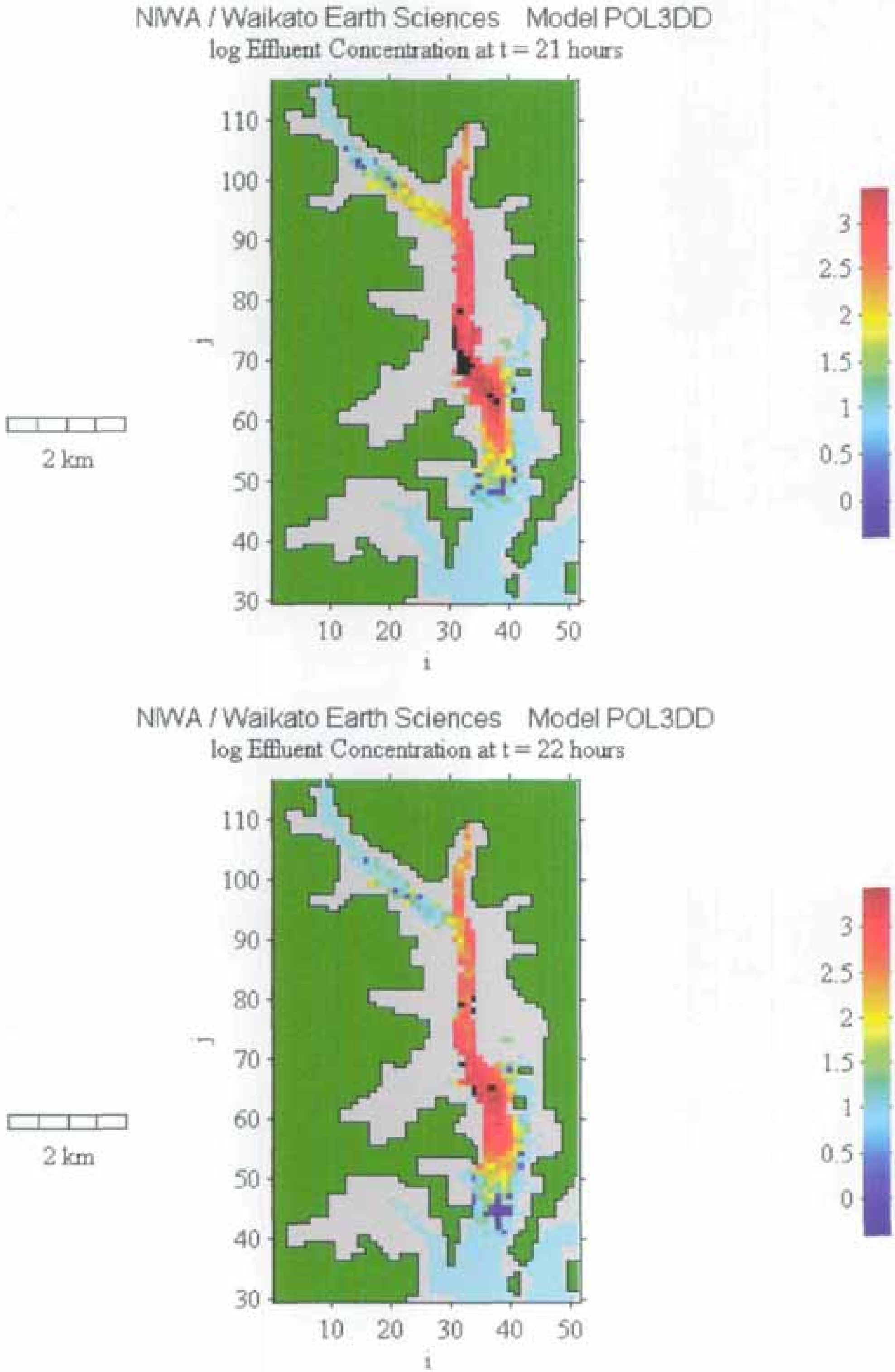


Figure 14k. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary at 21 hours and 22 hours after the start of a four hour overflow event with 35 cumecs freshwater inflows. (Examples: $2=10^2$ FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)

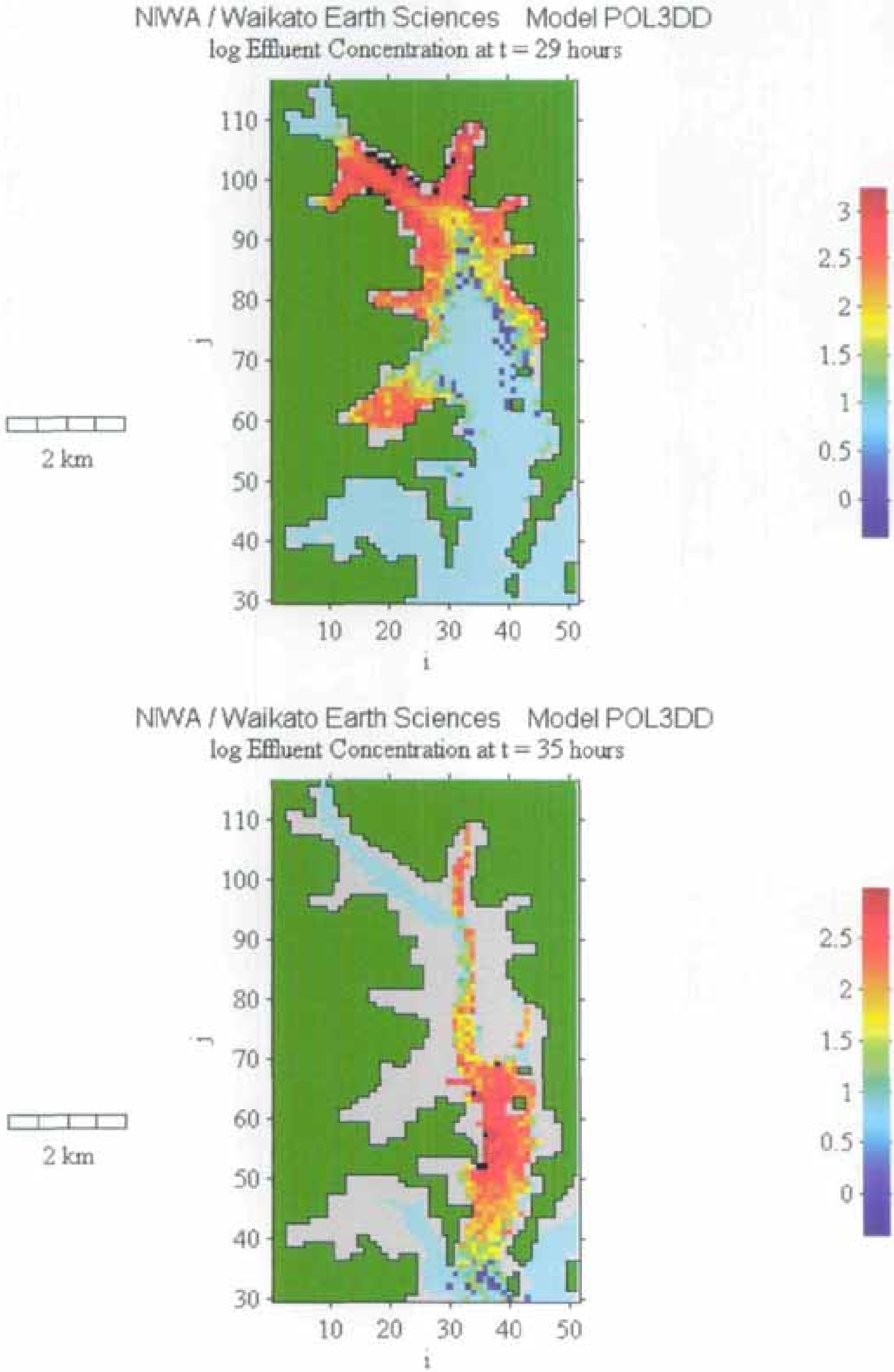


Figure 14l. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary for the 3rd high and low waters after the start of a four hour overflow event with 35 cumecs freshwater inflows. (Examples: $2=10^2$ FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)

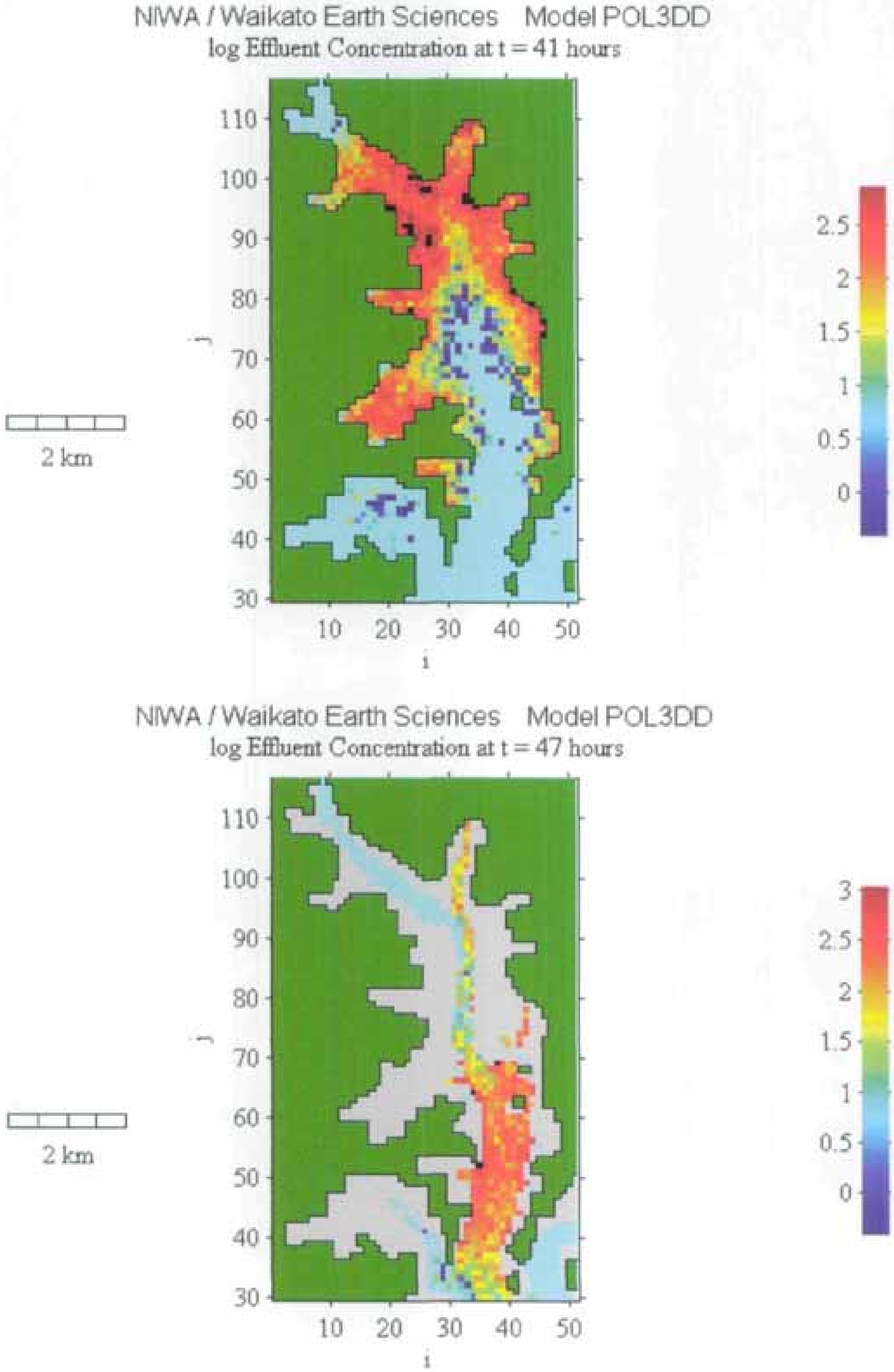


Figure 14m. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary for the 4th high and low waters after the start of a four hour overflow event with 35 cumecs freshwater inflows. (Examples: $2=10^2$ FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)

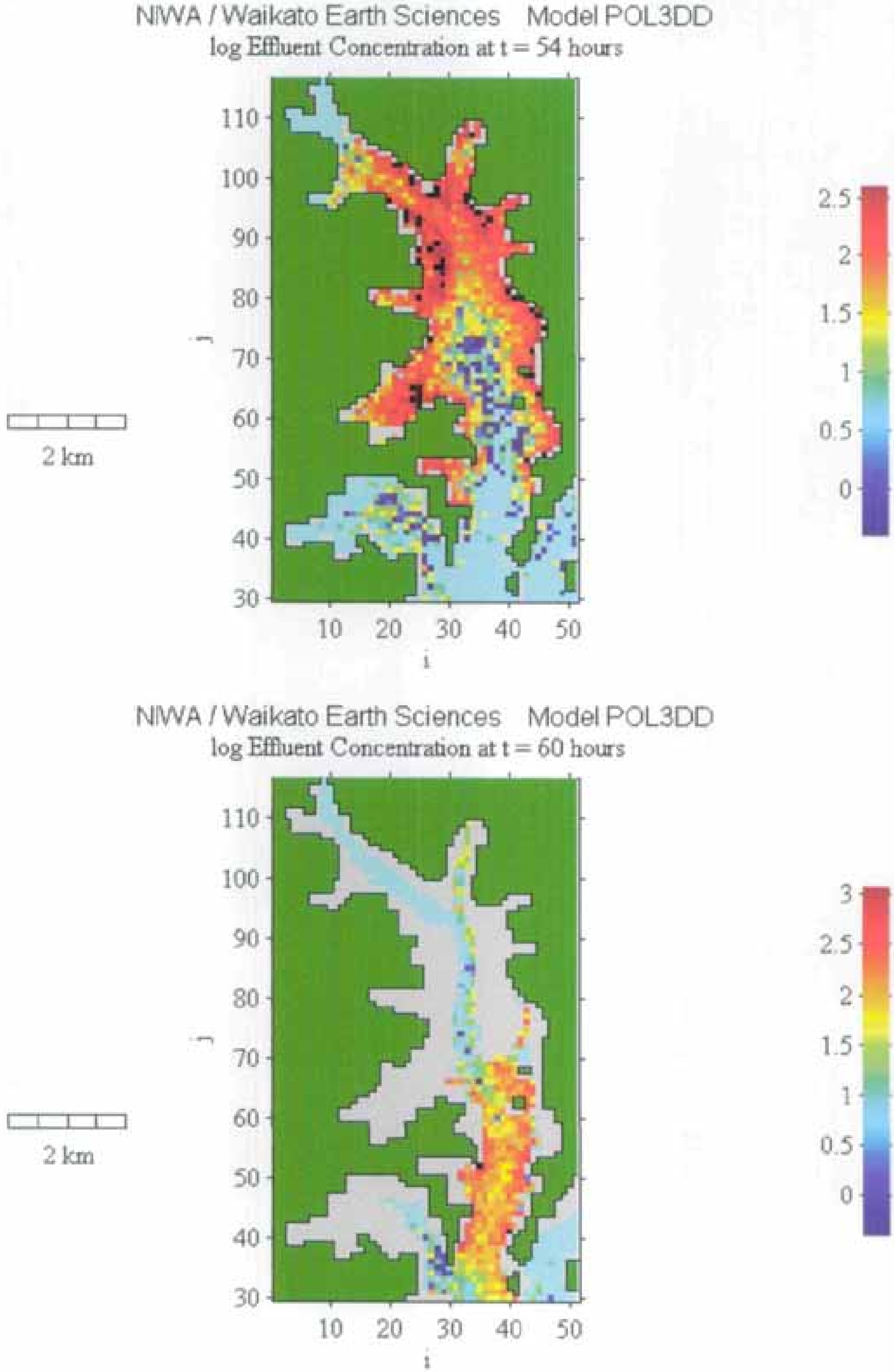


Figure 14n. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary for the 5th high and low waters after the start of a four hour overflow event with 35 cumecs freshwater inflows. (Examples: $2=10^2$ FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)

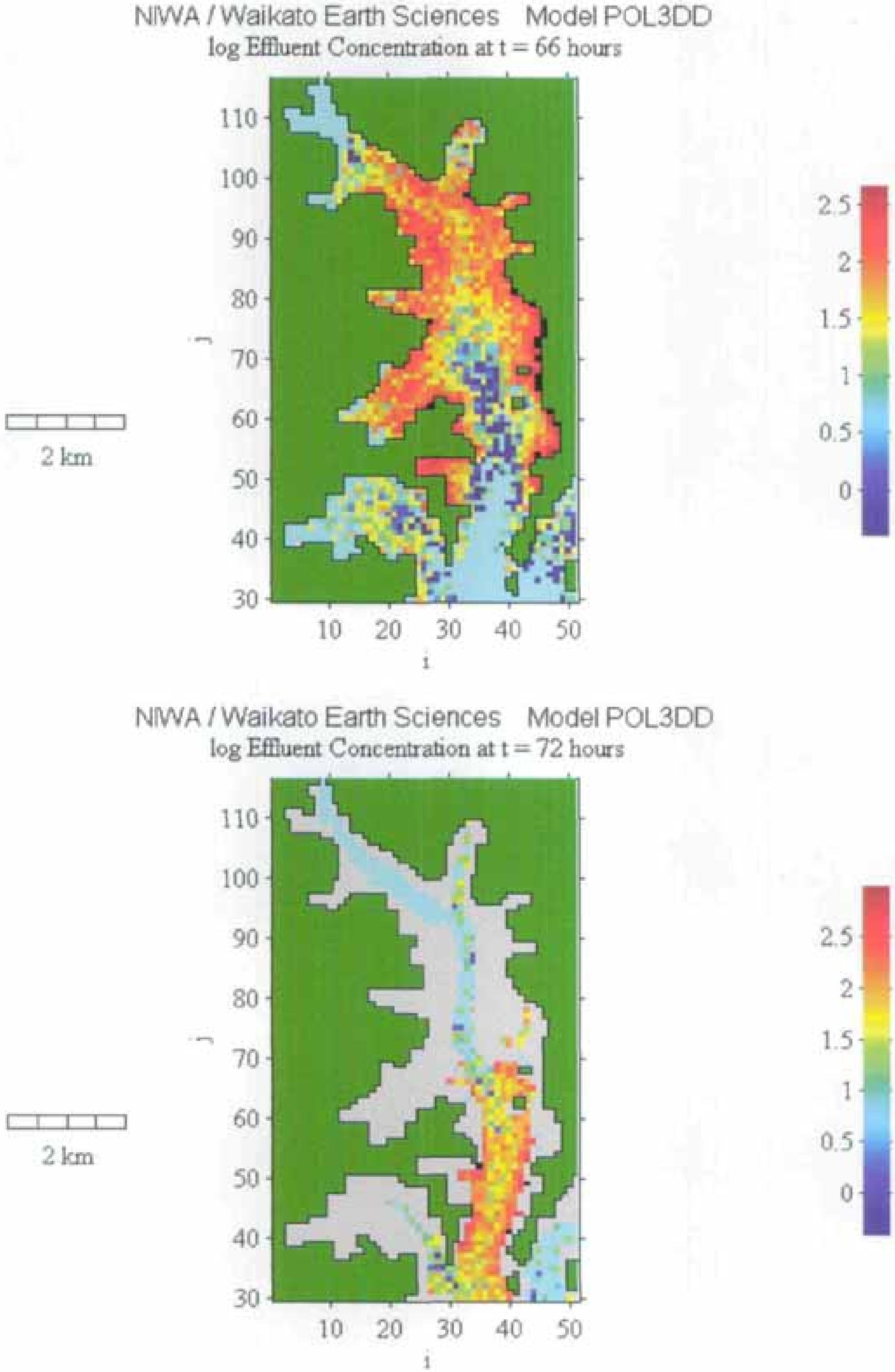


Figure 14o. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary for the 6th high and low waters after the start of a four hour overflow event with 35 cumecs freshwater inflows. (Examples: $2=10^2$ FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)

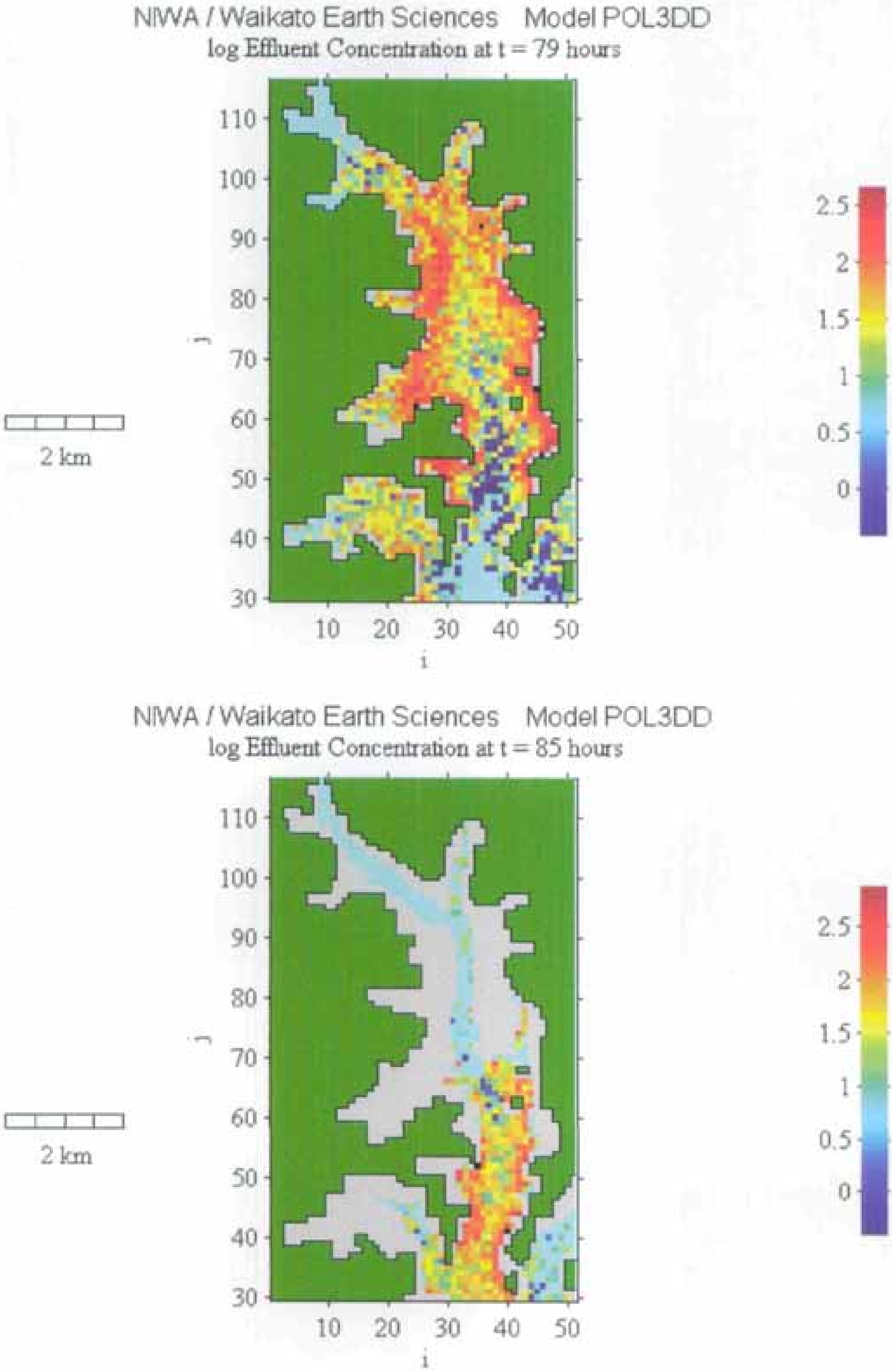


Figure 14p. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary for the 7th high and low waters after the start of a four hour overflow event with 35 cumecs freshwater inflows. (Examples: $2=10^2$ FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)

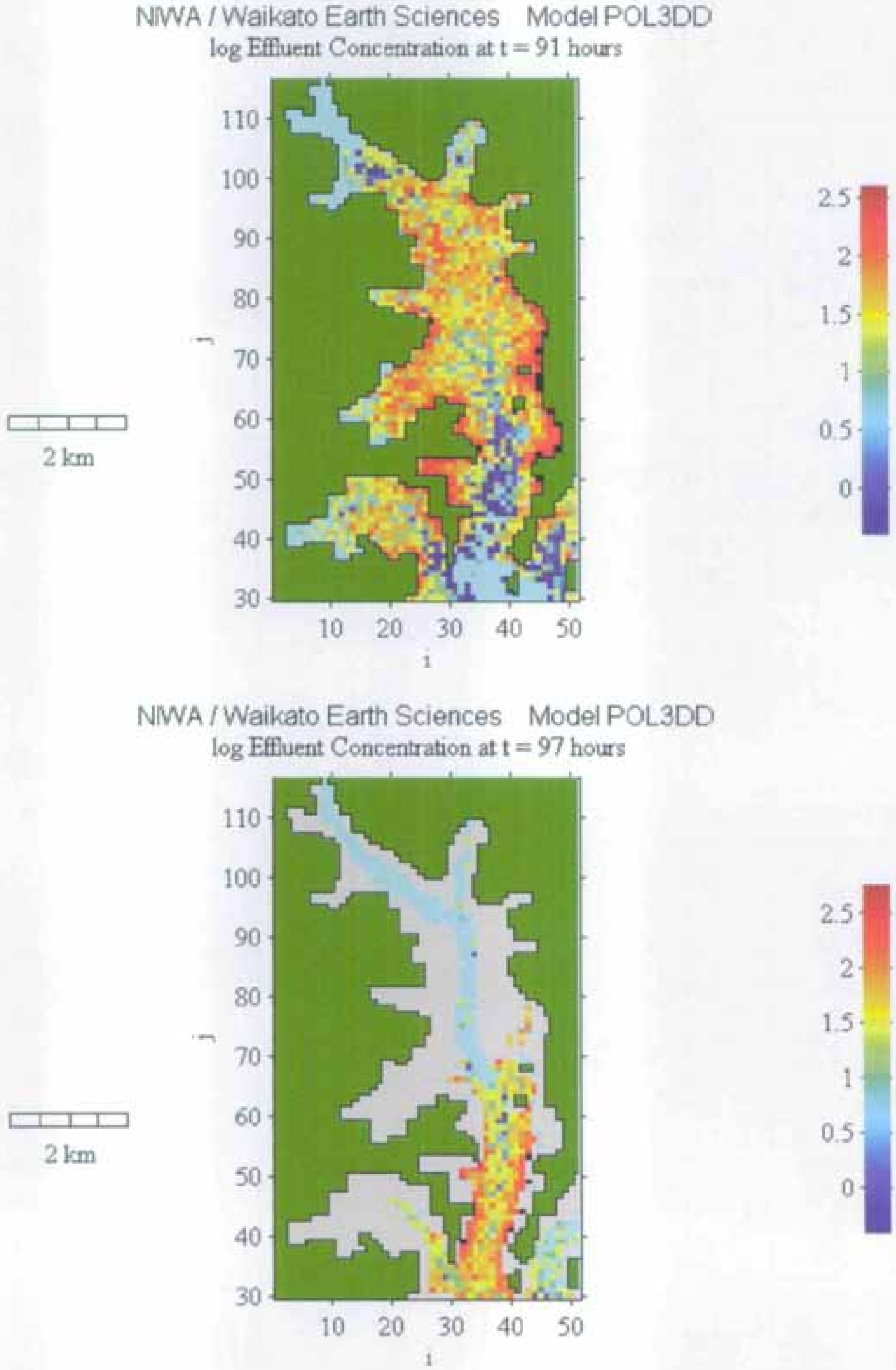


Figure 14q. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary for the 8th high and low waters after the start of a four hour overflow event with 35 cumecs freshwater inflows. (Examples: 2=10^2 FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)

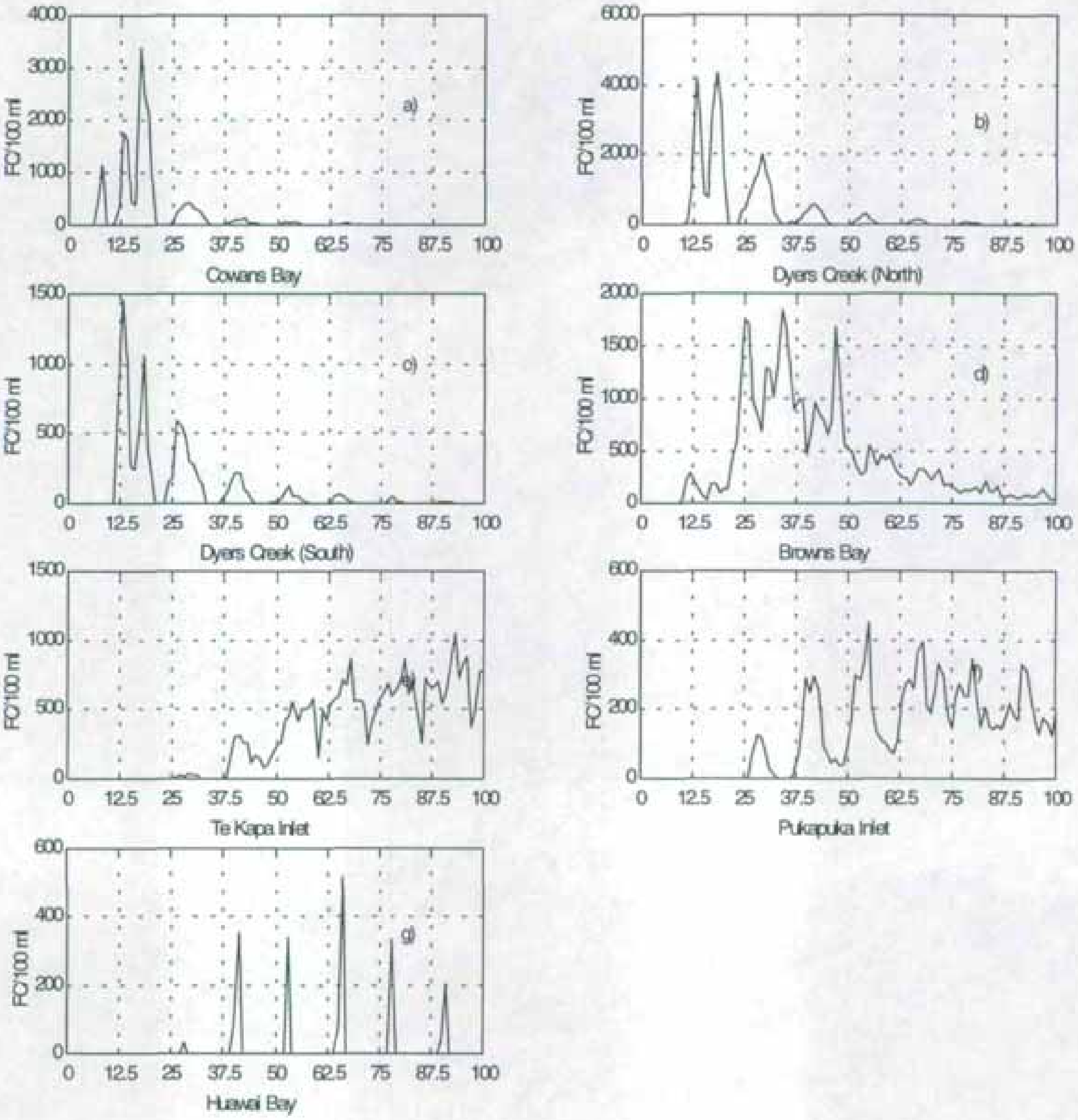


Figure 15. Predicted Faecal Coliform concentrations within the oyster farms for a four hour overflow event with 140 cumec freshwater inflows. (Horizontal axis is time in elapsed hours from the model start. Note: each tidal cycle = 12.5 hours).

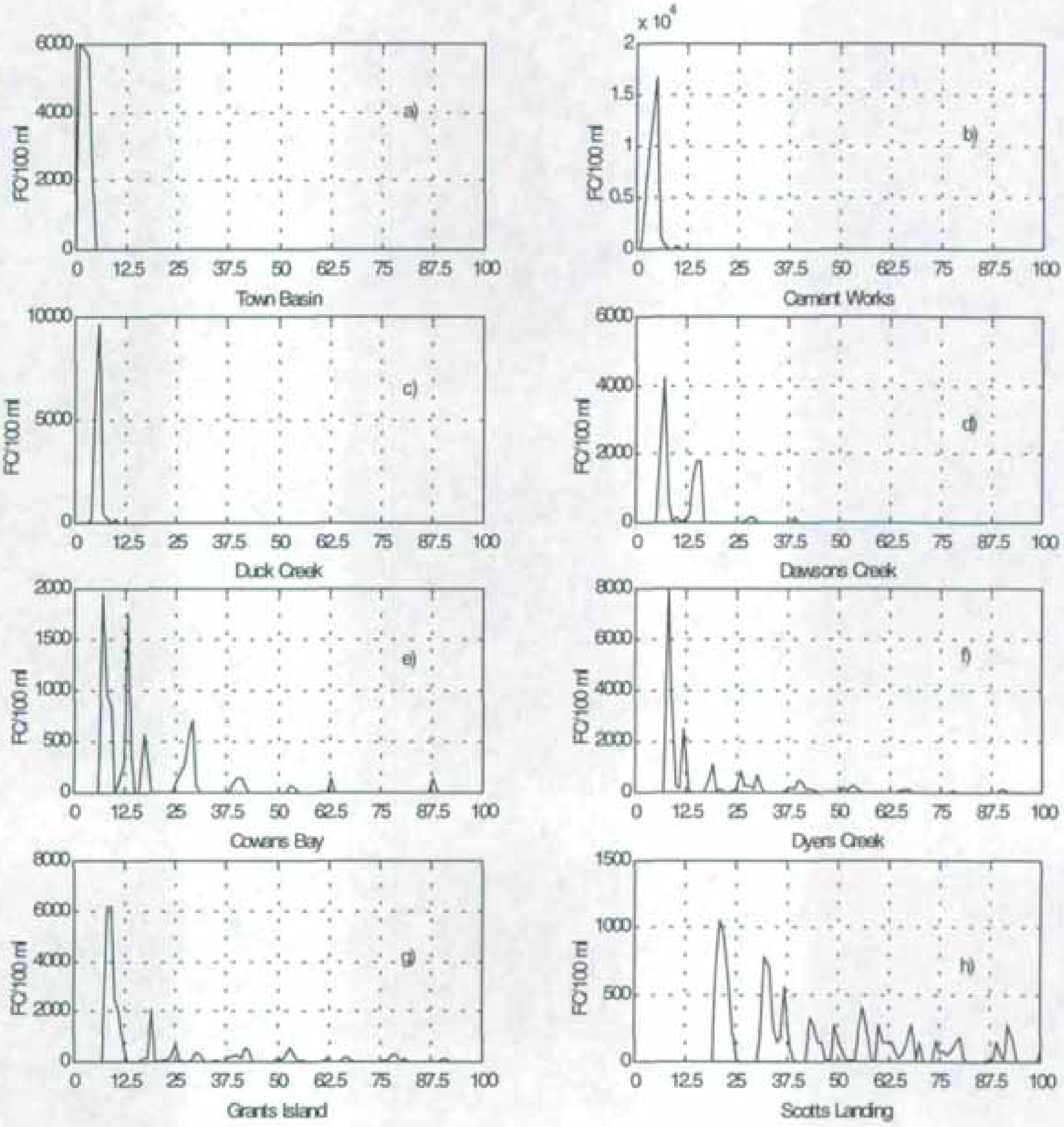
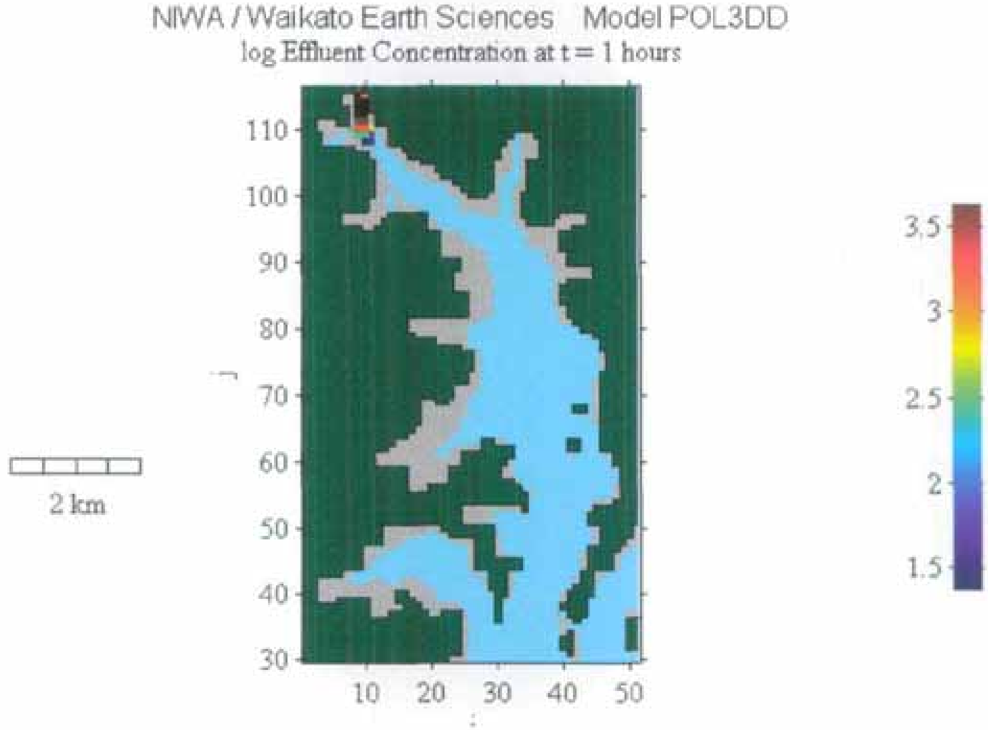


Figure 16. Predicted Faecal Coliform concentrations within the main channel for a four hour overflow event with 140 cumec freshwater inflows. (Horizontal axis is time in elapsed hours from the model start. Note: each tidal cycle = 12.5 hours).



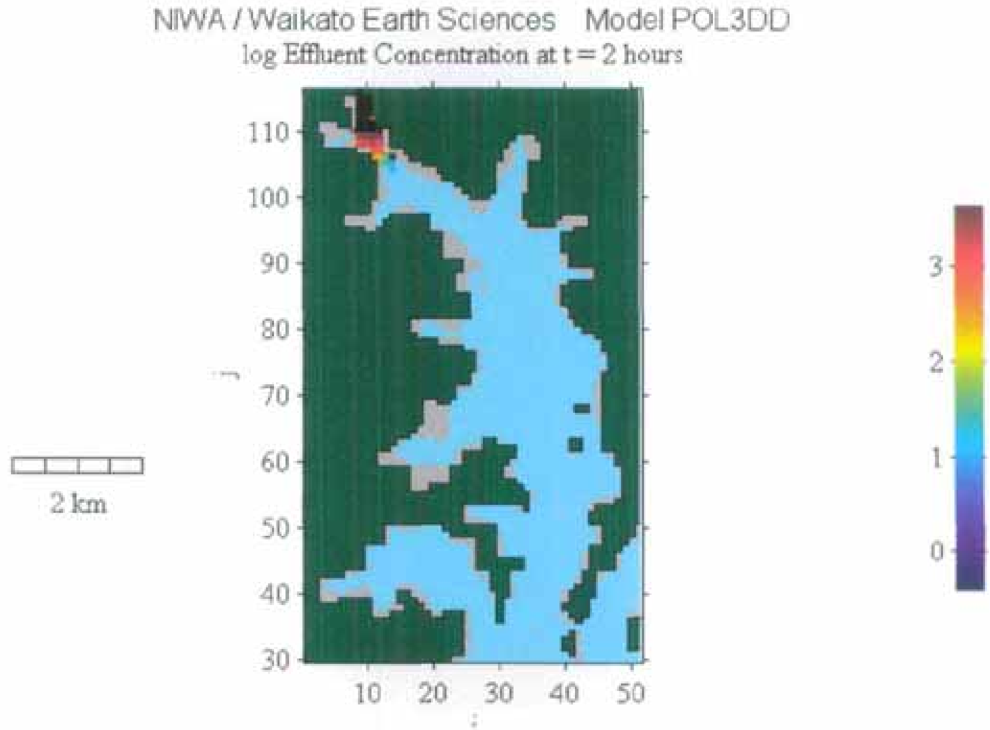
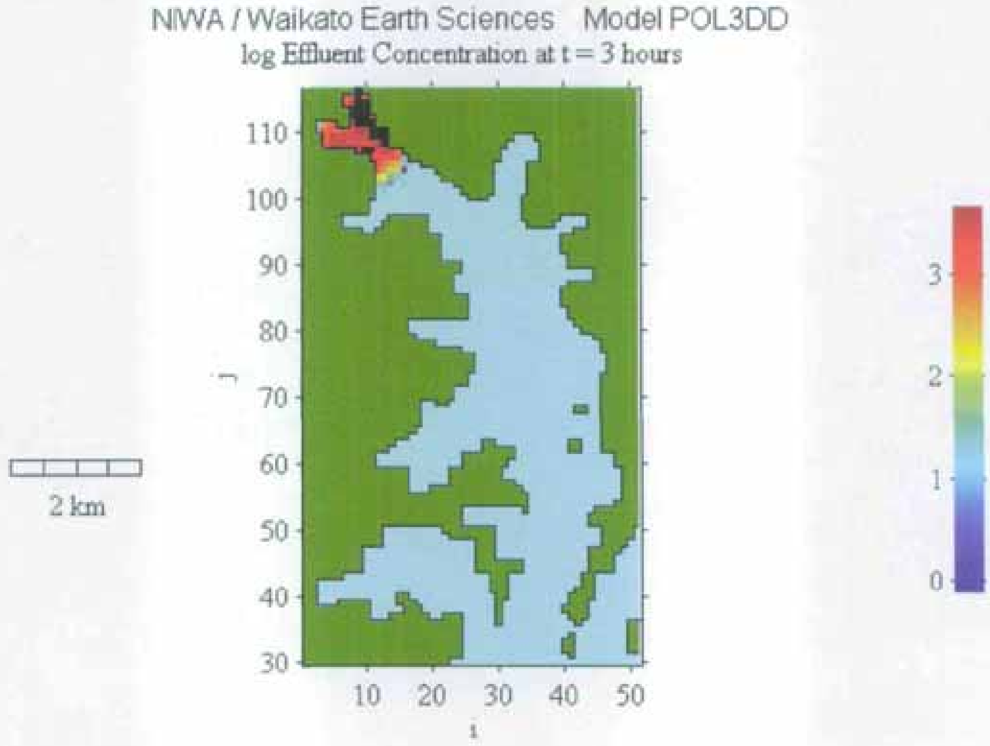


Figure 17a. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary at 1 hour and 2 hours after the start of a four hour overflow event with 140 cumecs freshwater inflows. (Examples: 2=10^2 FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour).



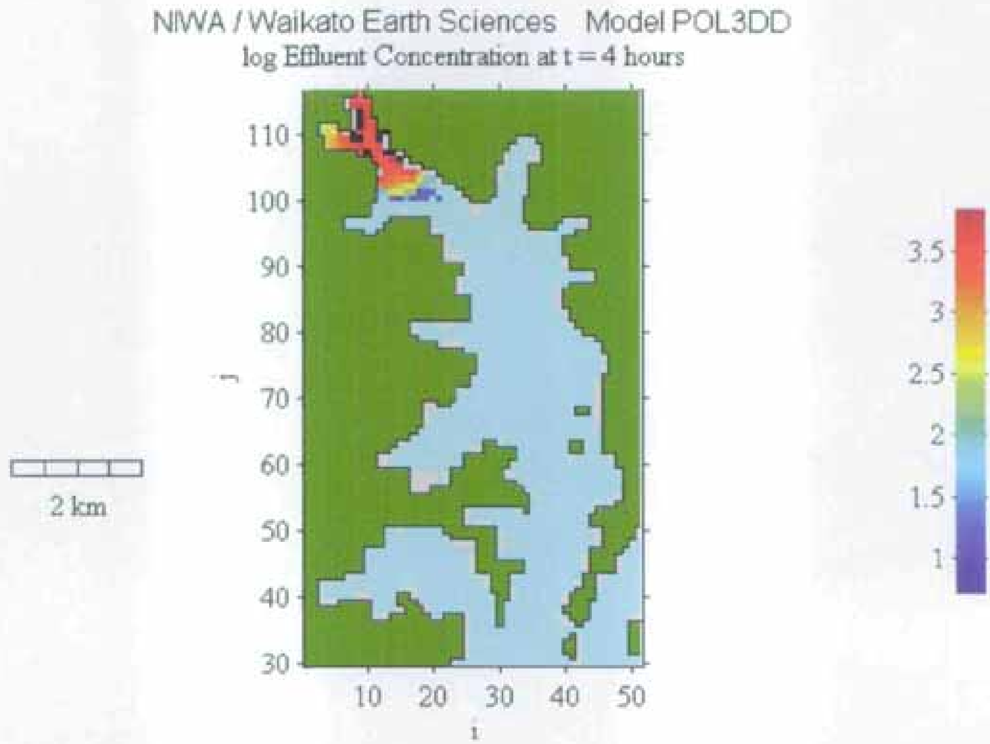
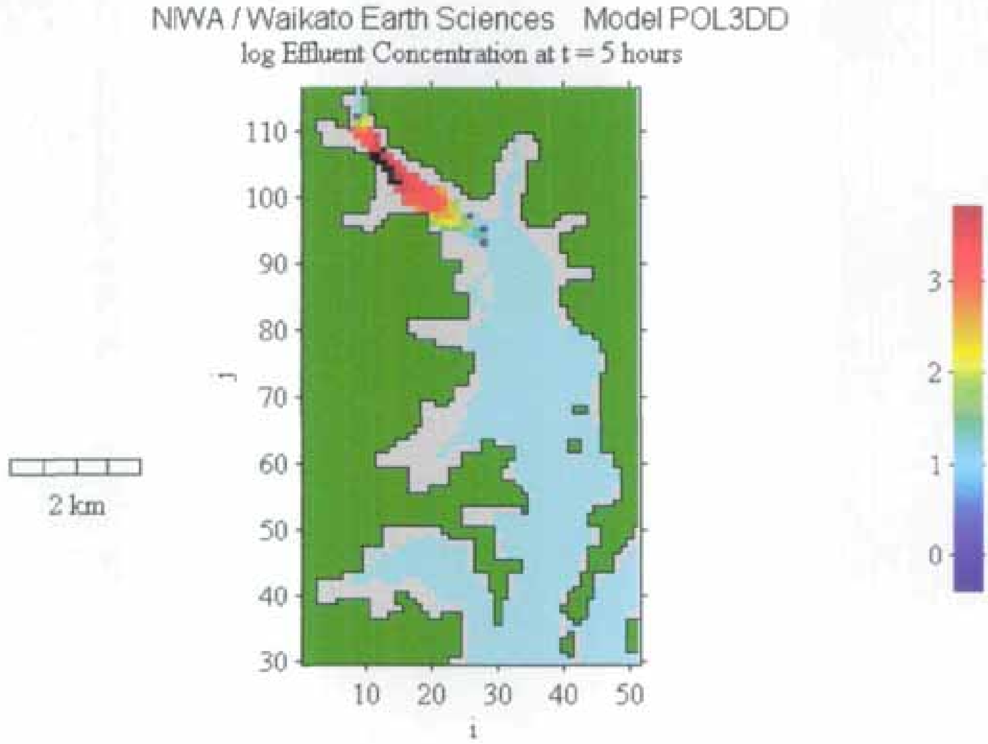


Figure 17b. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary at 3 hours and 4 hours after the start of a four hour overflow event with 140 cumecs freshwater inflows. (Examples: $2=10^2$ FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)



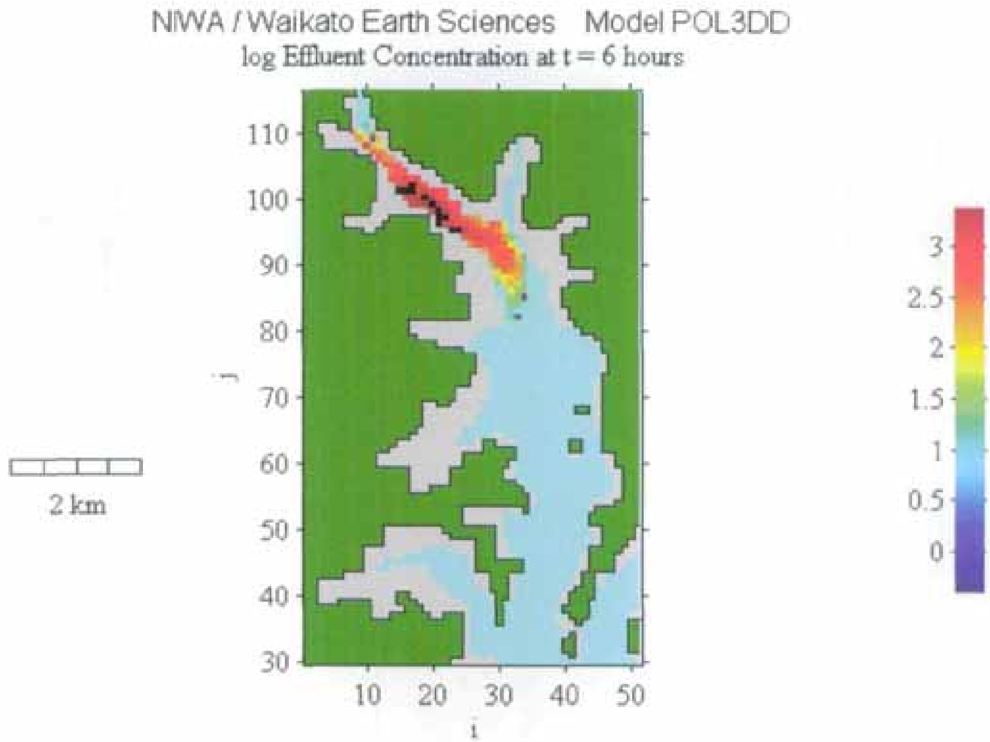


Figure 17c. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary at 5 hours and 6 hours after the start of a four hour overflow event with 140 cumecs freshwater inflows. (Examples: $2=10^2$ FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)

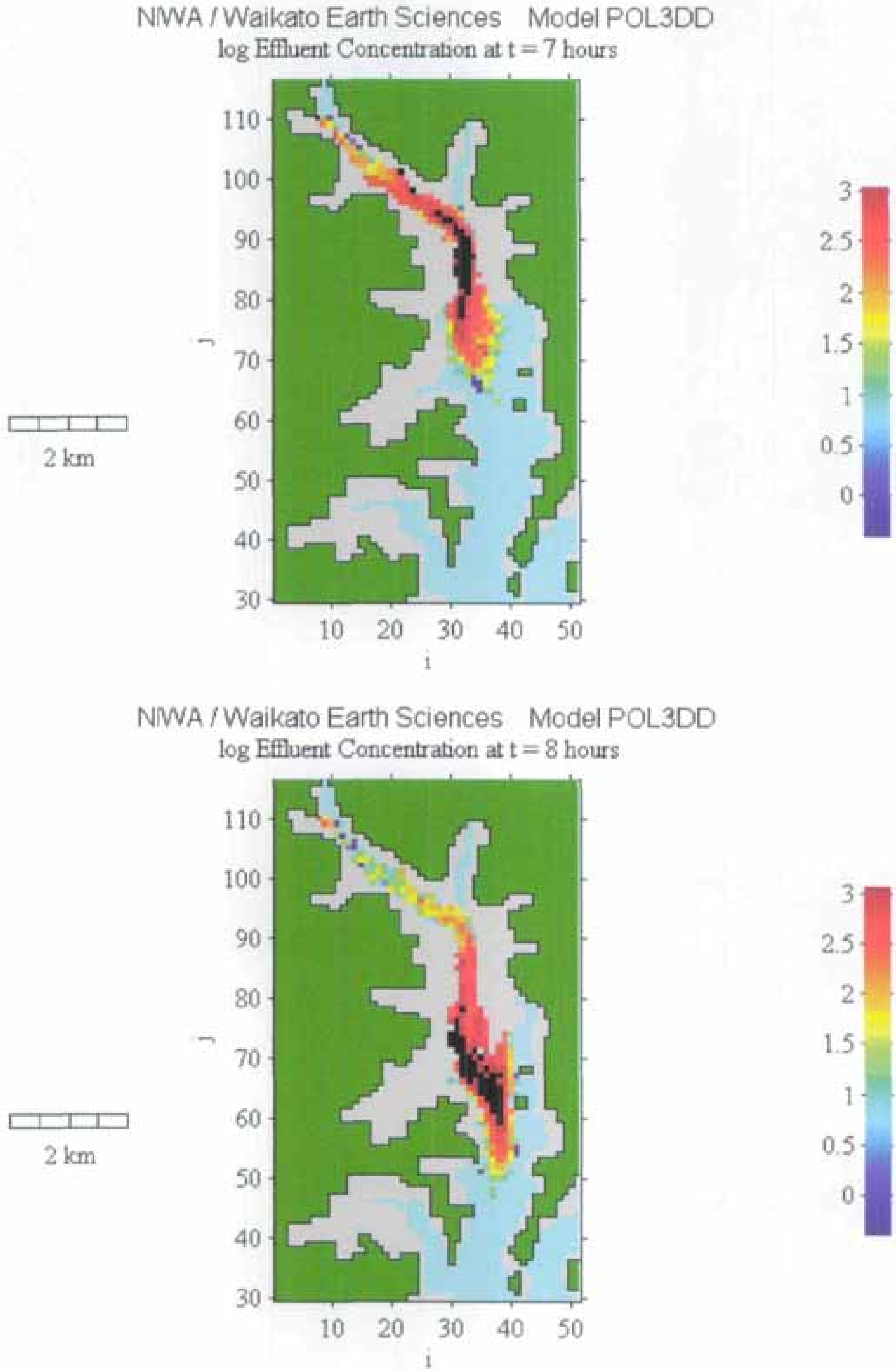


Figure 17d. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary at 7 hours and 8 hours after the start of a four hour overflow event with 140 cumecs freshwater inflows. (Examples: $2=10^2$ FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)

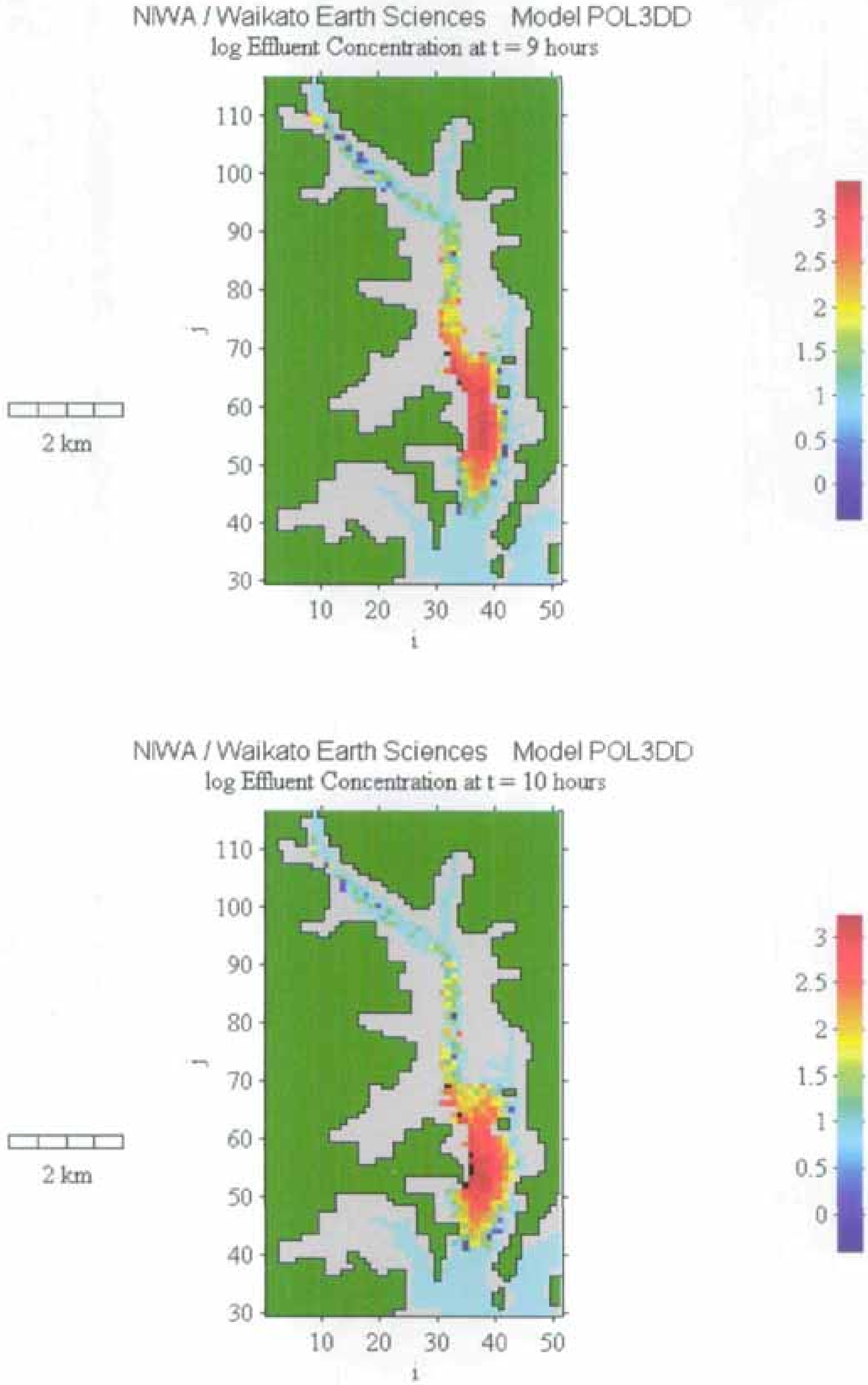


Figure 17e. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary at 9 hours and 10 hours after the start of a four hour overflow event with 140 cumecs freshwater inflows. (Examples: $2=10^2$ FC/100 ml and $0=1$ FC/100 ml. Intertidal areas are shaded a grey colour)

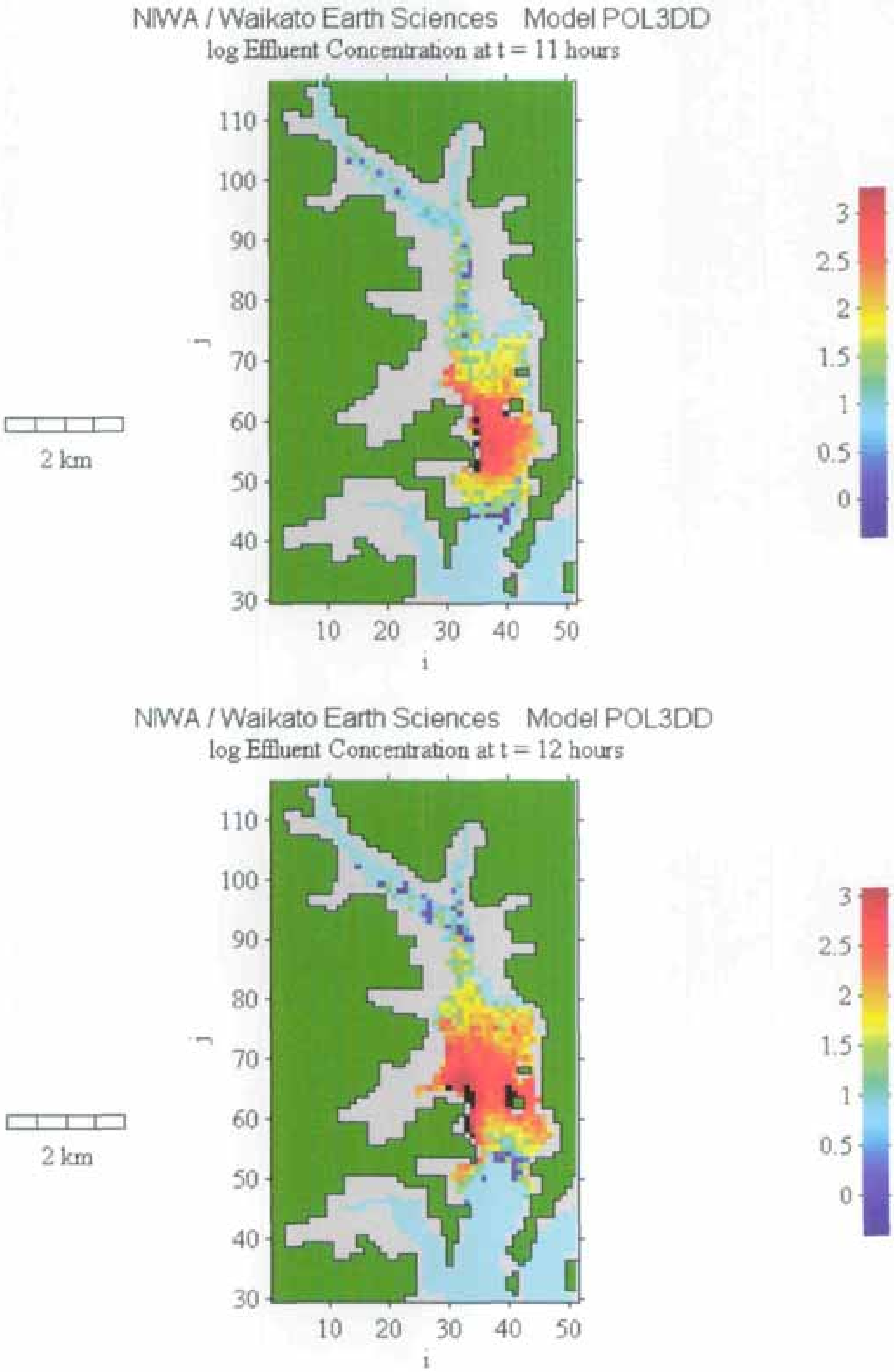


Figure 17f. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary at 11 hours and 12 hours after the start of a four hour overflow event with 140 cumecs freshwater inflows. (Examples: $2=10^2$ FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)

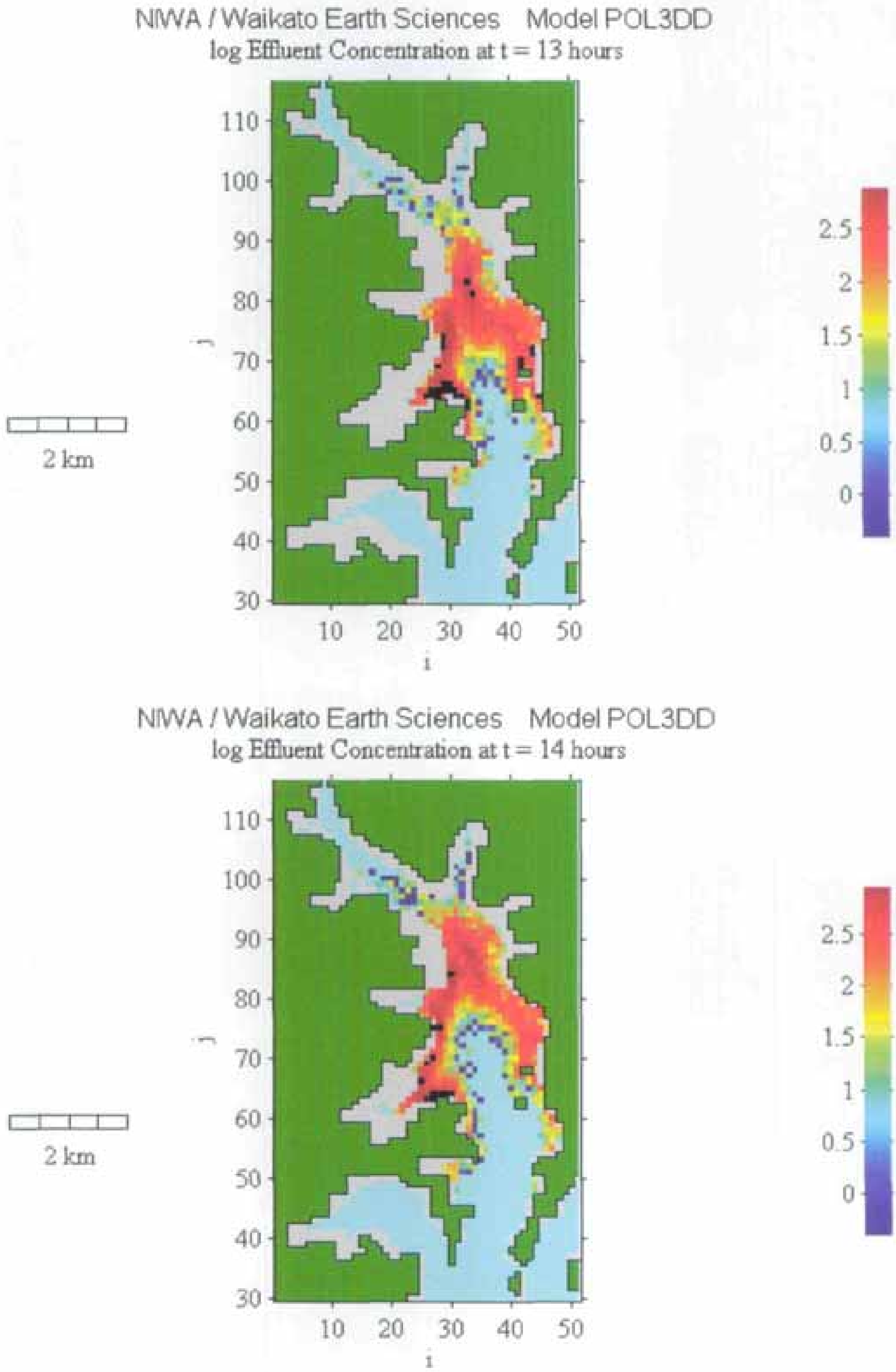


Figure 17g. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary at 13 hours and 14 hours after the start of a four hour overflow event with 140 cumecs freshwater inflows. (Examples: $2=10^2$ FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)

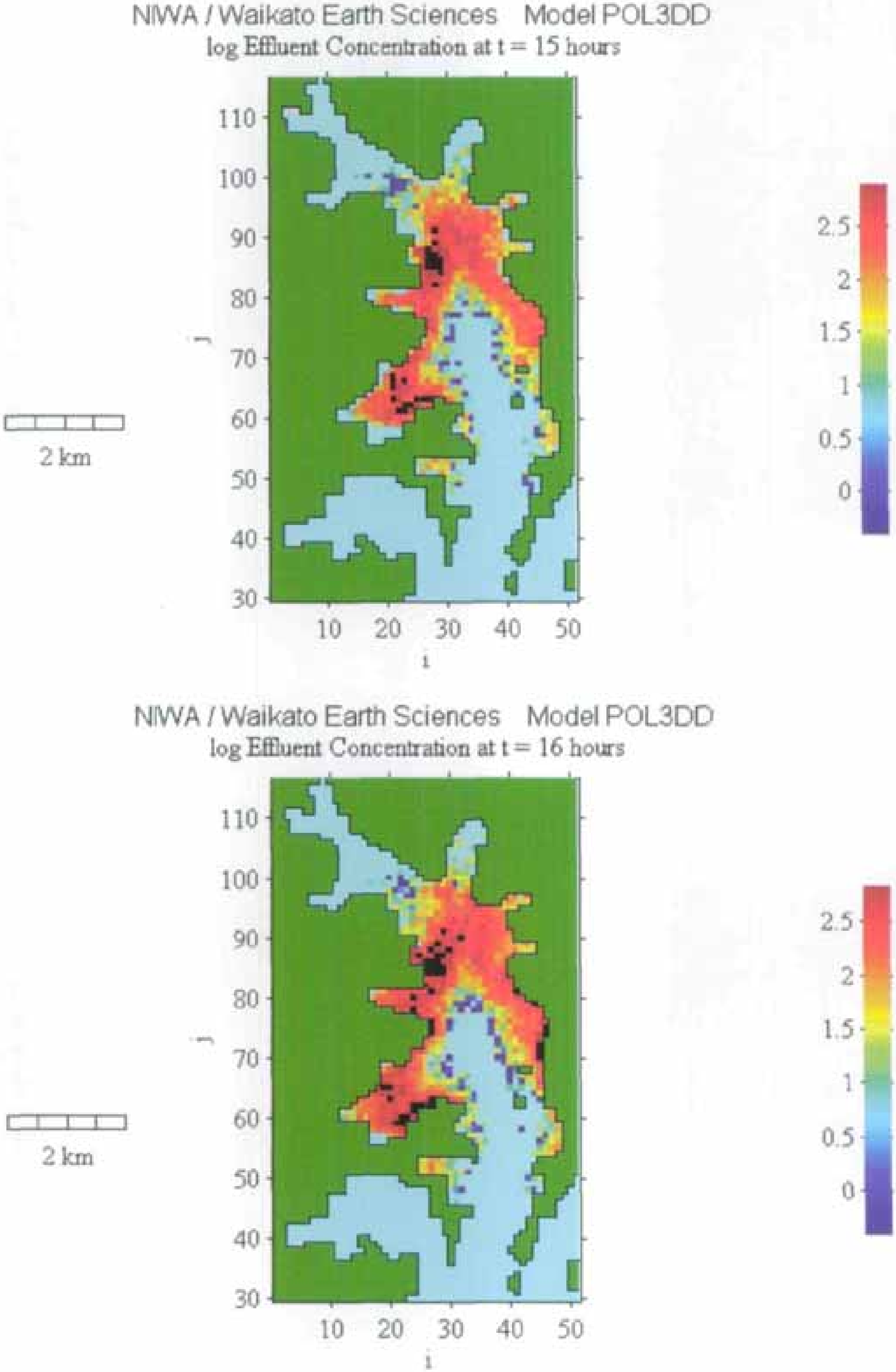


Figure 17h. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary at 15 hours and 16 hours after the start of a four hour overflow event with 140 cumecs freshwater inflows. (Examples: $2=10^2$ FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)

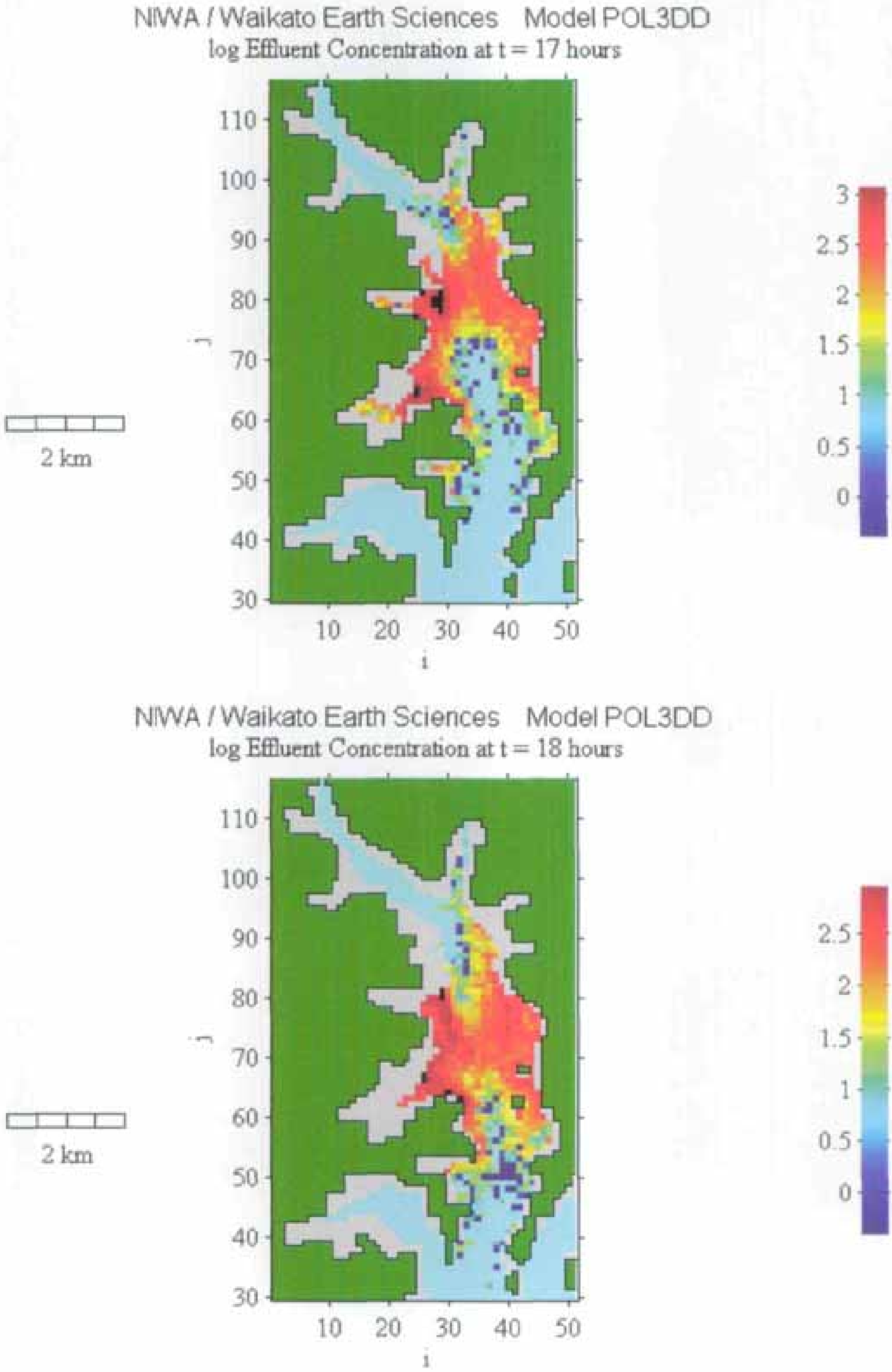


Figure 17i. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary at 17 hours and 18 hours after the start of a four hour overflow event with 140 cumecs freshwater inflows. (Examples: $2=10^2$ FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)

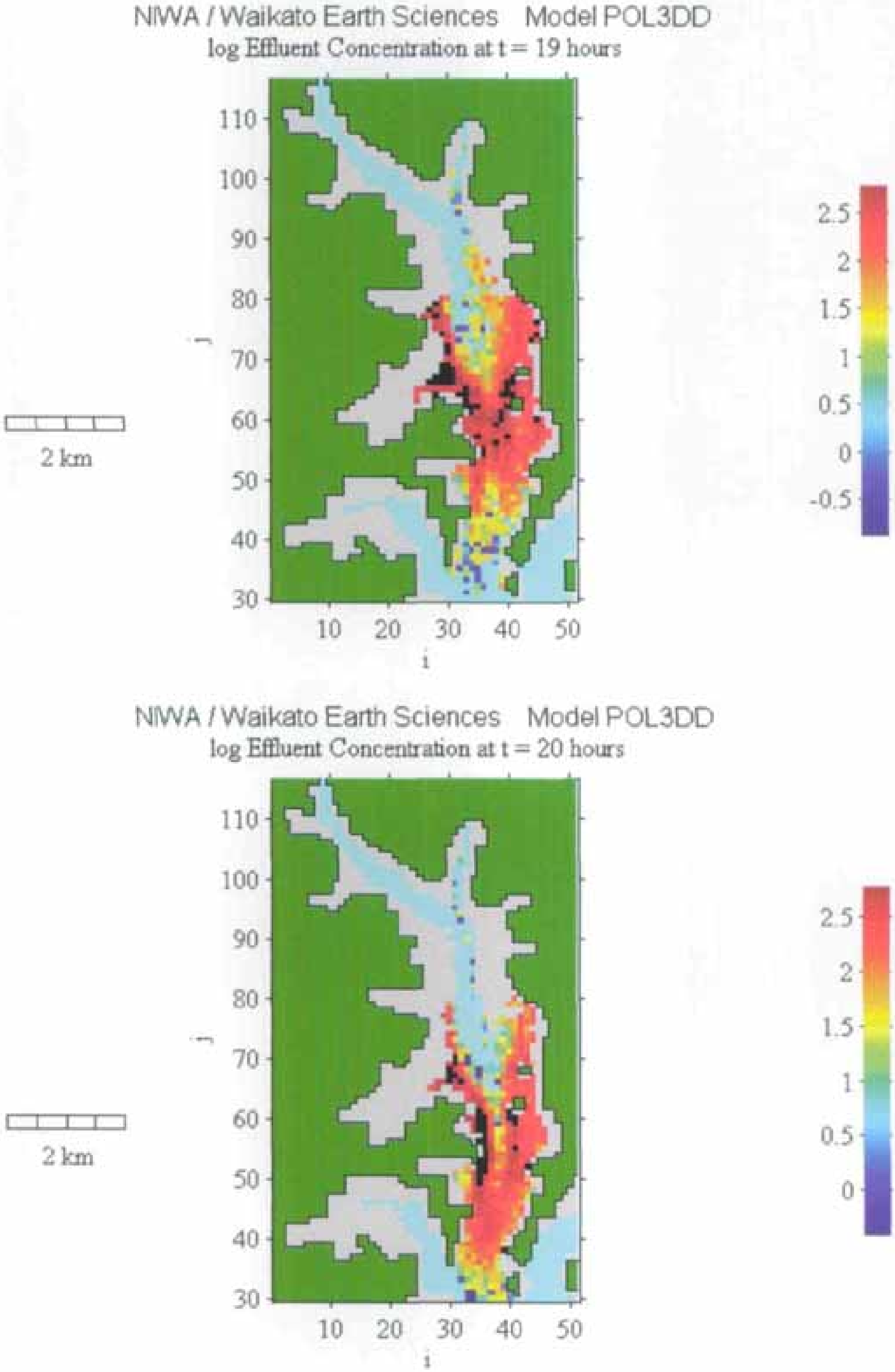


Figure 17j. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary at 19 hours and 20 hours after the start of a four hour overflow event with 140 cumecs freshwater inflows. (Examples: $2=10^2$ FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)

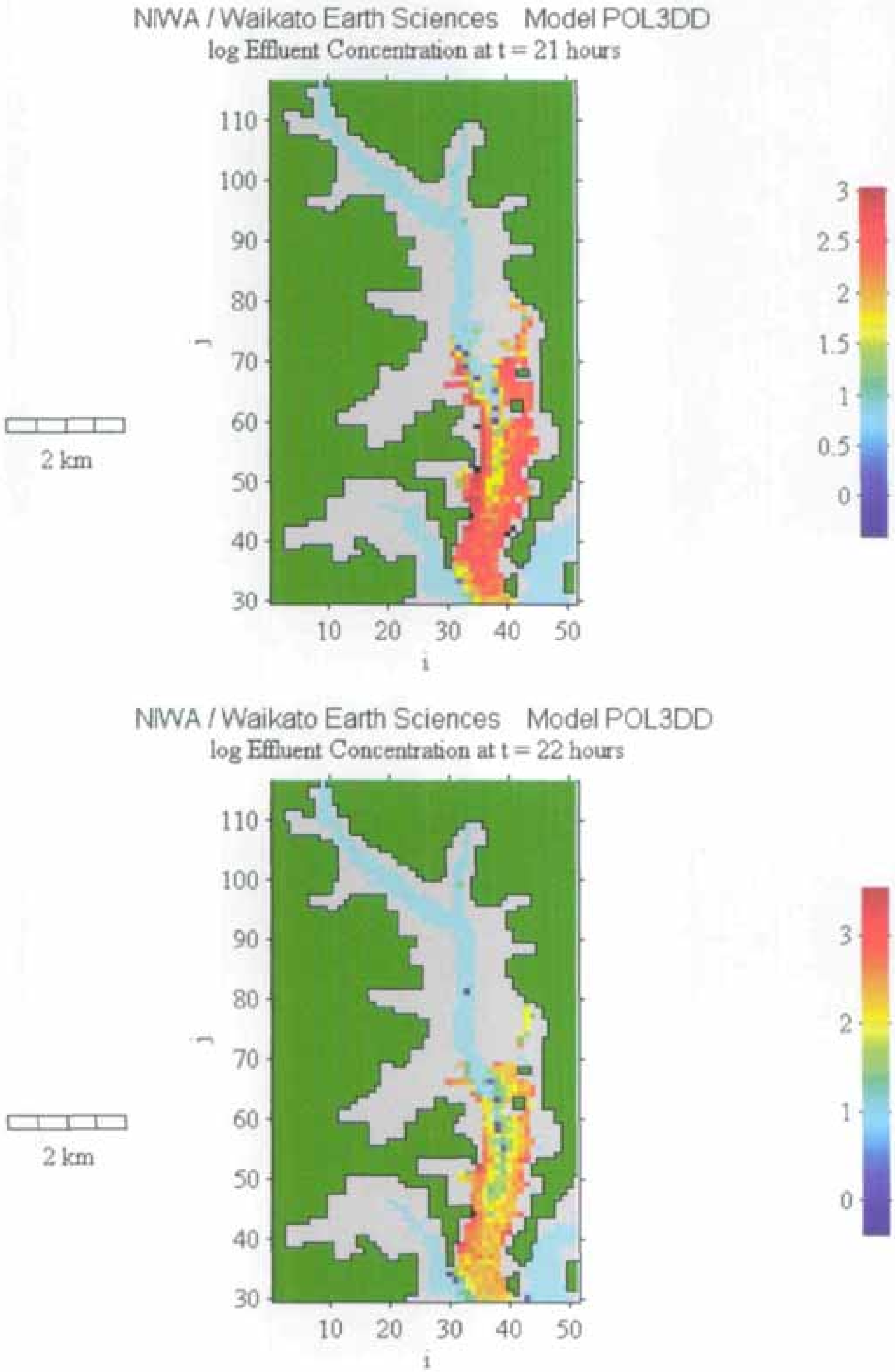


Figure 17k. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary at 21 hours and 22 hours after the start of a four hour overflow event with 140 cumecs freshwater inflows. (Examples: $2=10^2$ FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)

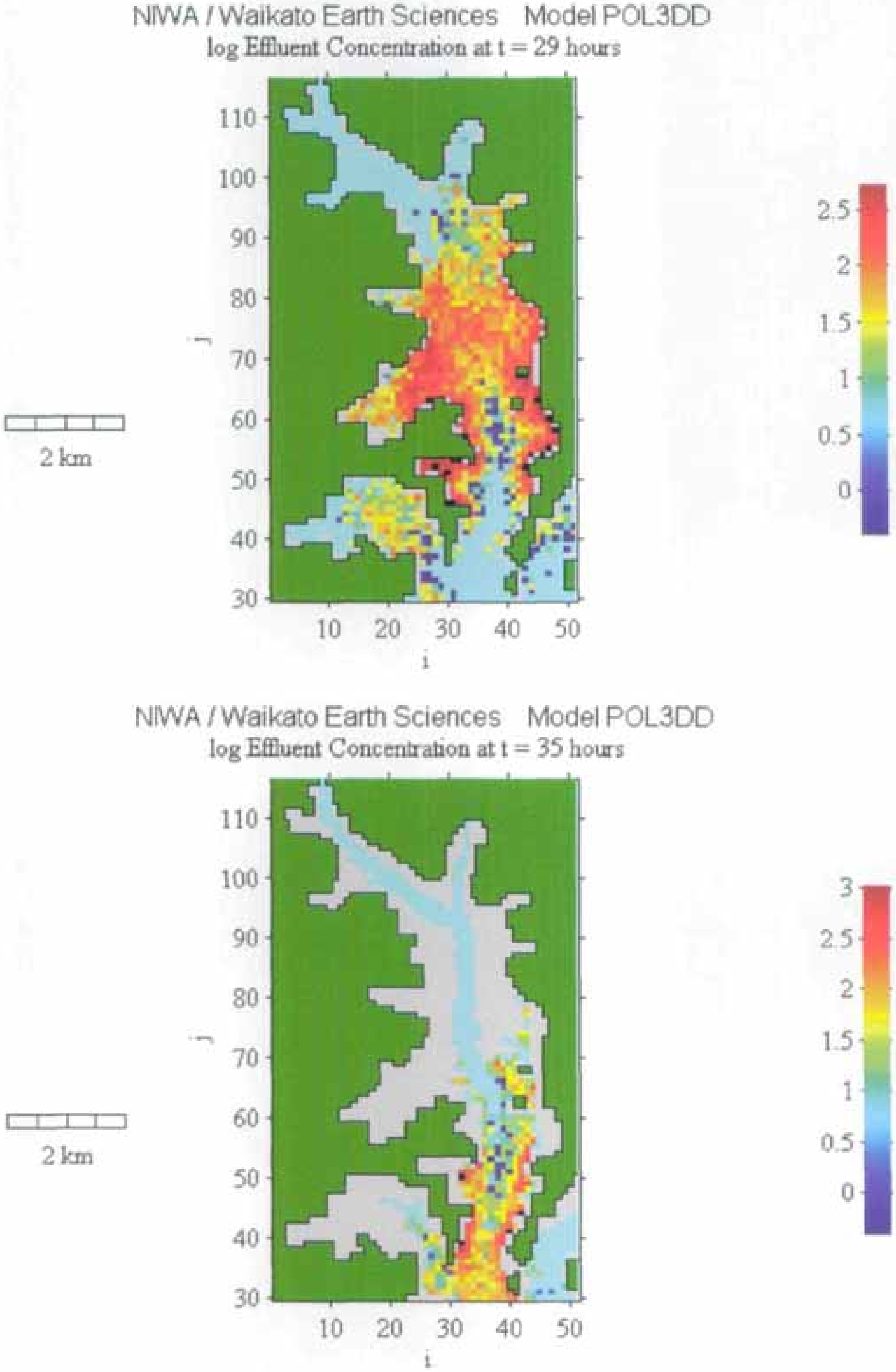
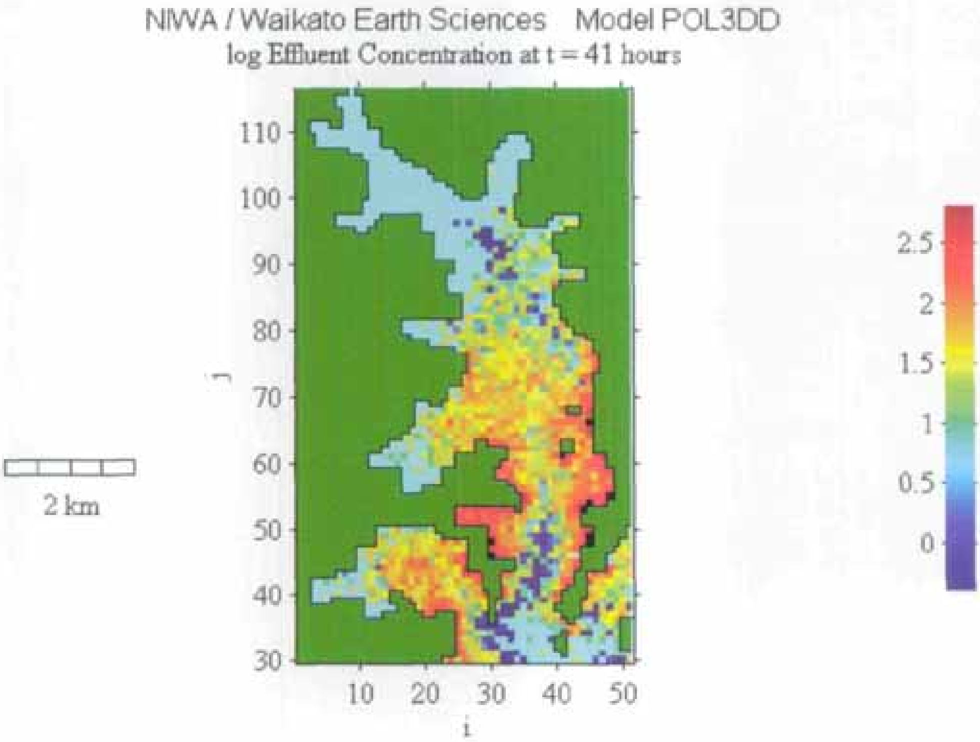


Figure 17l. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary for the 3rd high and low waters after the start of a four hour overflow event with 140 cumecs freshwater inflows. (Examples: $2=10^2$ FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)



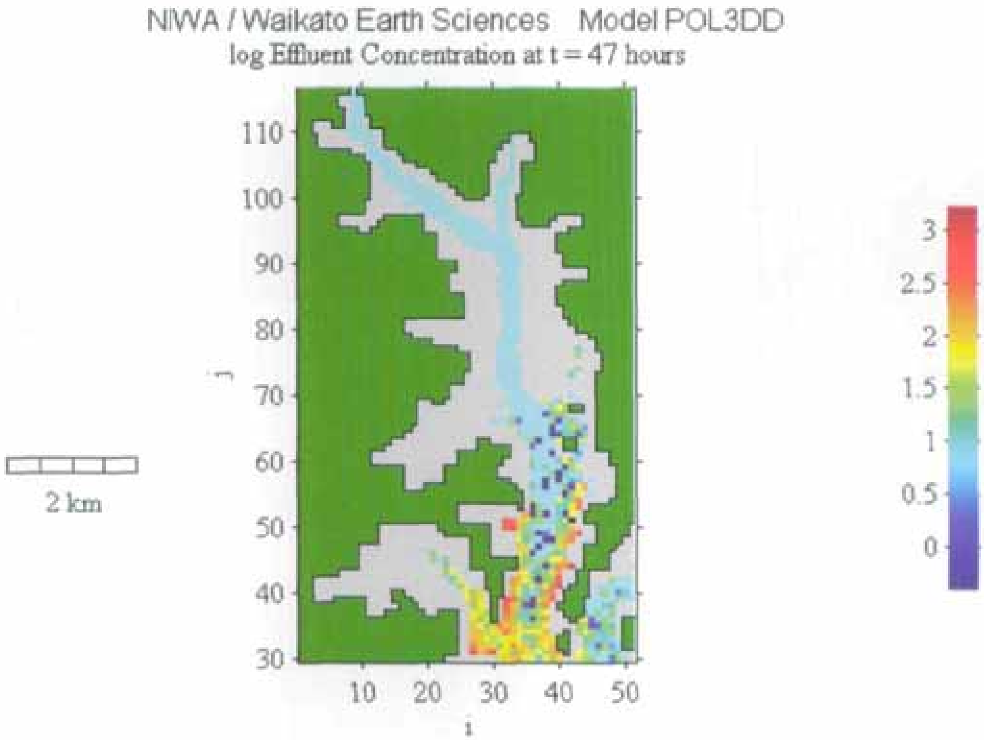


Figure 17m. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary for the 4th high and low waters after the start of a four hour overflow event with 140 cumecs freshwater inflows. (Examples: $2=10^2$ FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)

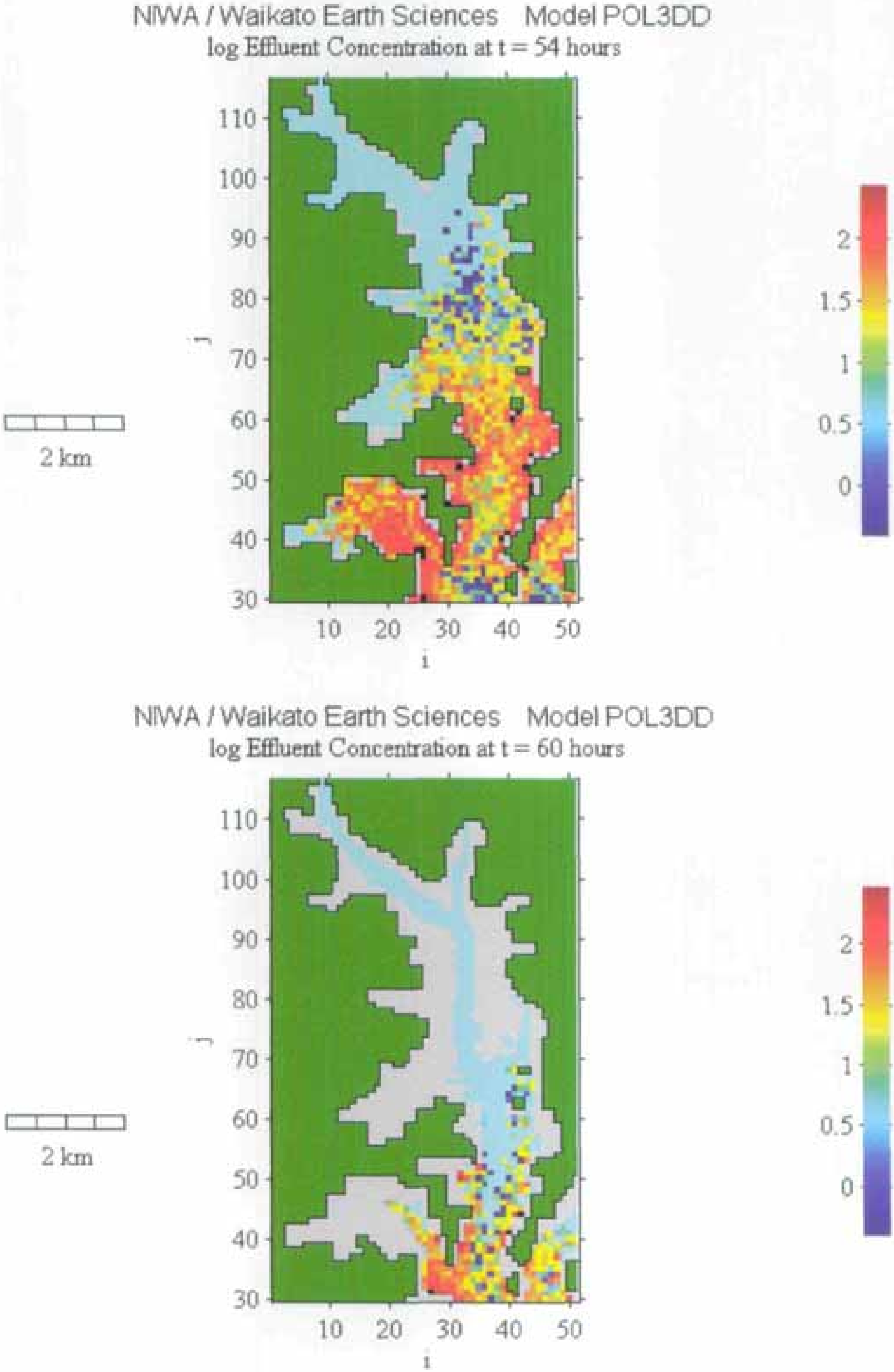


Figure 17n. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary for the 5th high and low waters after the start of a four hour overflow event with 140 cumecs freshwater inflows. (Examples: $2=10^2$ FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)

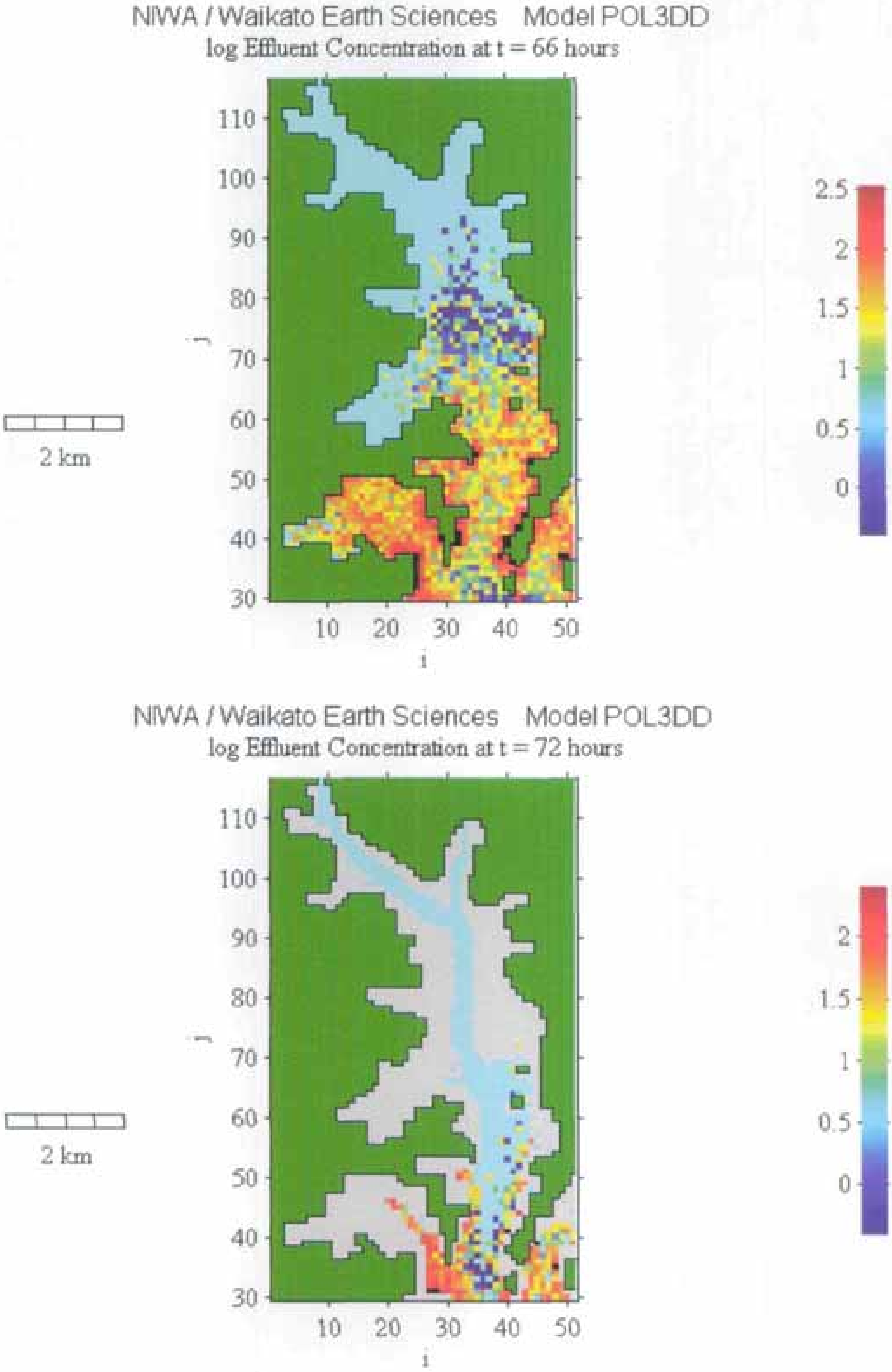


Figure 17o. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary for the 6th high and low waters after the start of a four hour overflow event with 140 cumecs freshwater inflows. (Examples: $2=10^2$ FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)

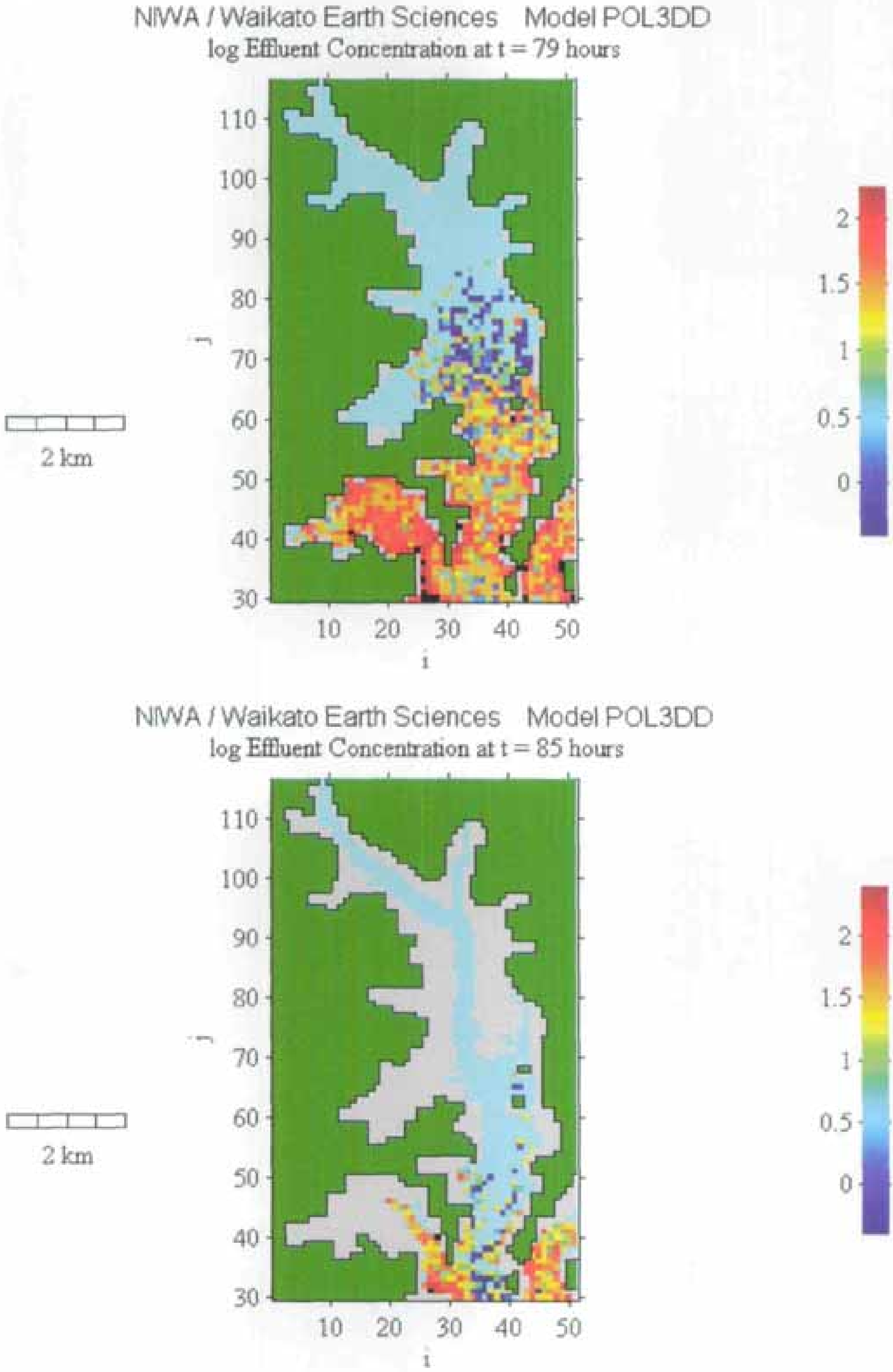
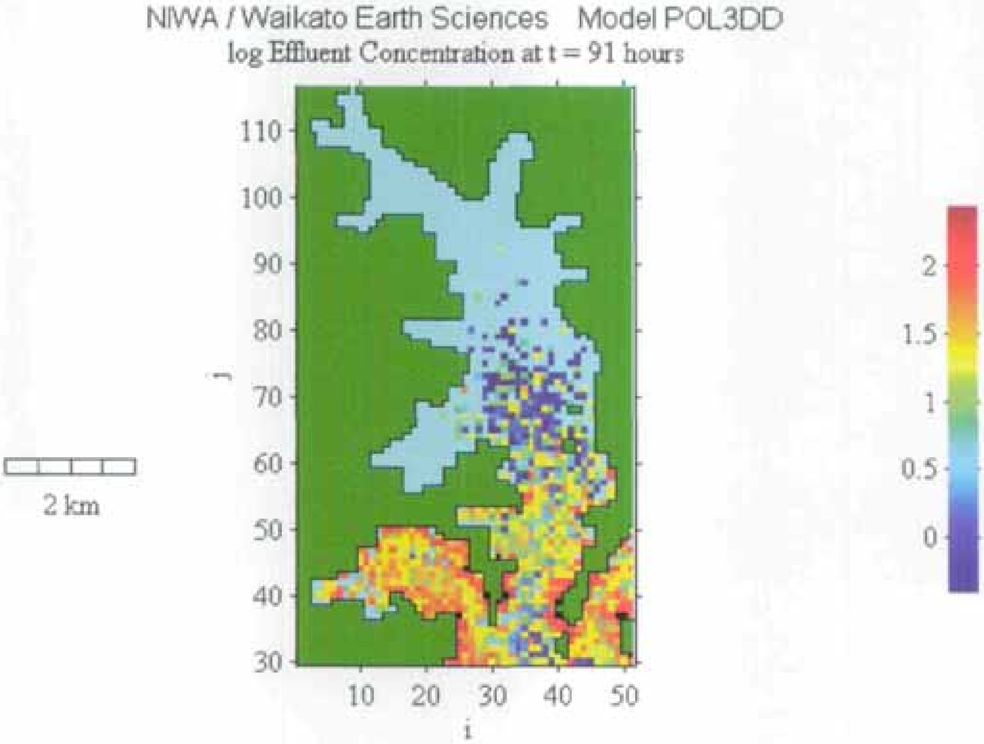


Figure 17p. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary for the 7th high and low waters after the start of a four hour overflow event with 140 cumecs freshwater inflows. (Examples: $2=10^2$ FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)



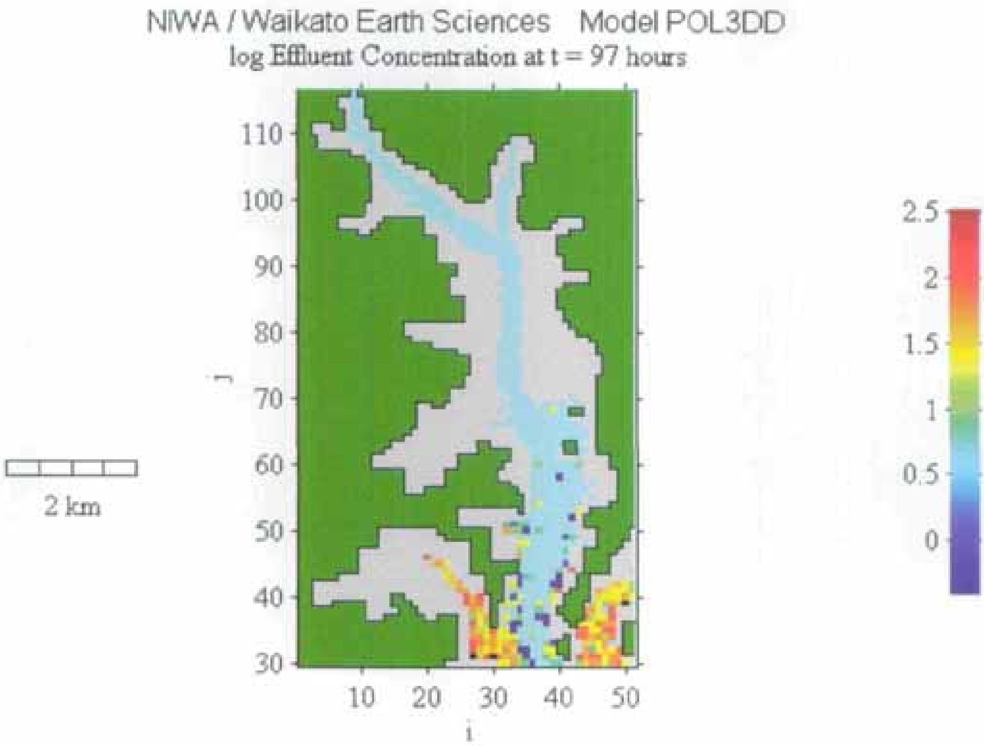


Figure 17q. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary for the 8th high and low waters after the start of a four hour overflow event with 140 cumecs freshwater inflows. (Examples: $2=10^2$ FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)

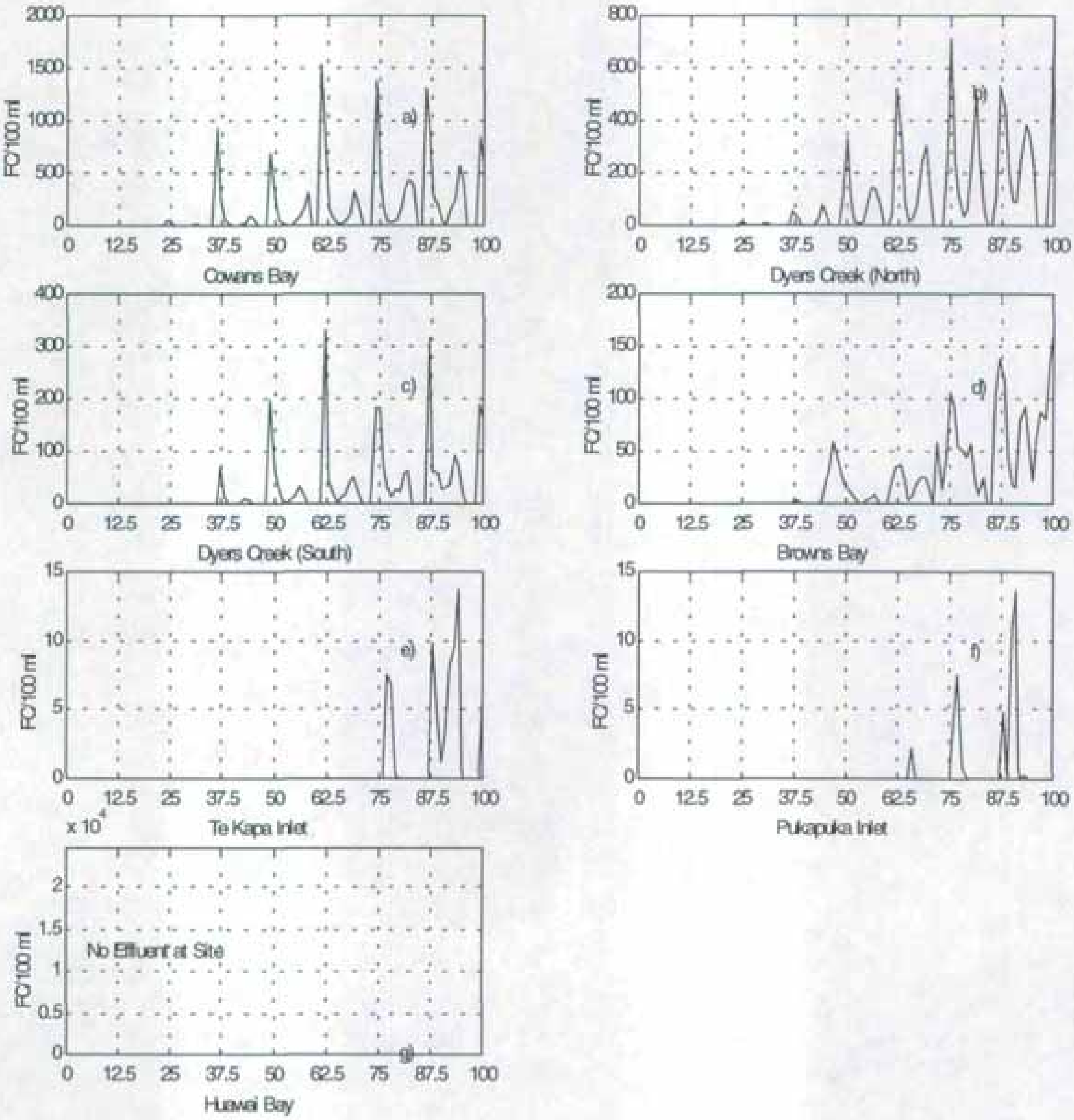


Figure 18. Predicted Faecal Coliform concentrations within the oyster farms for a four hour overflow event with 5 cumec freshwater inflows. (Horizontal axis is time in elapsed hours from the model start. Note: each tidal cycle = 12.5 hours).

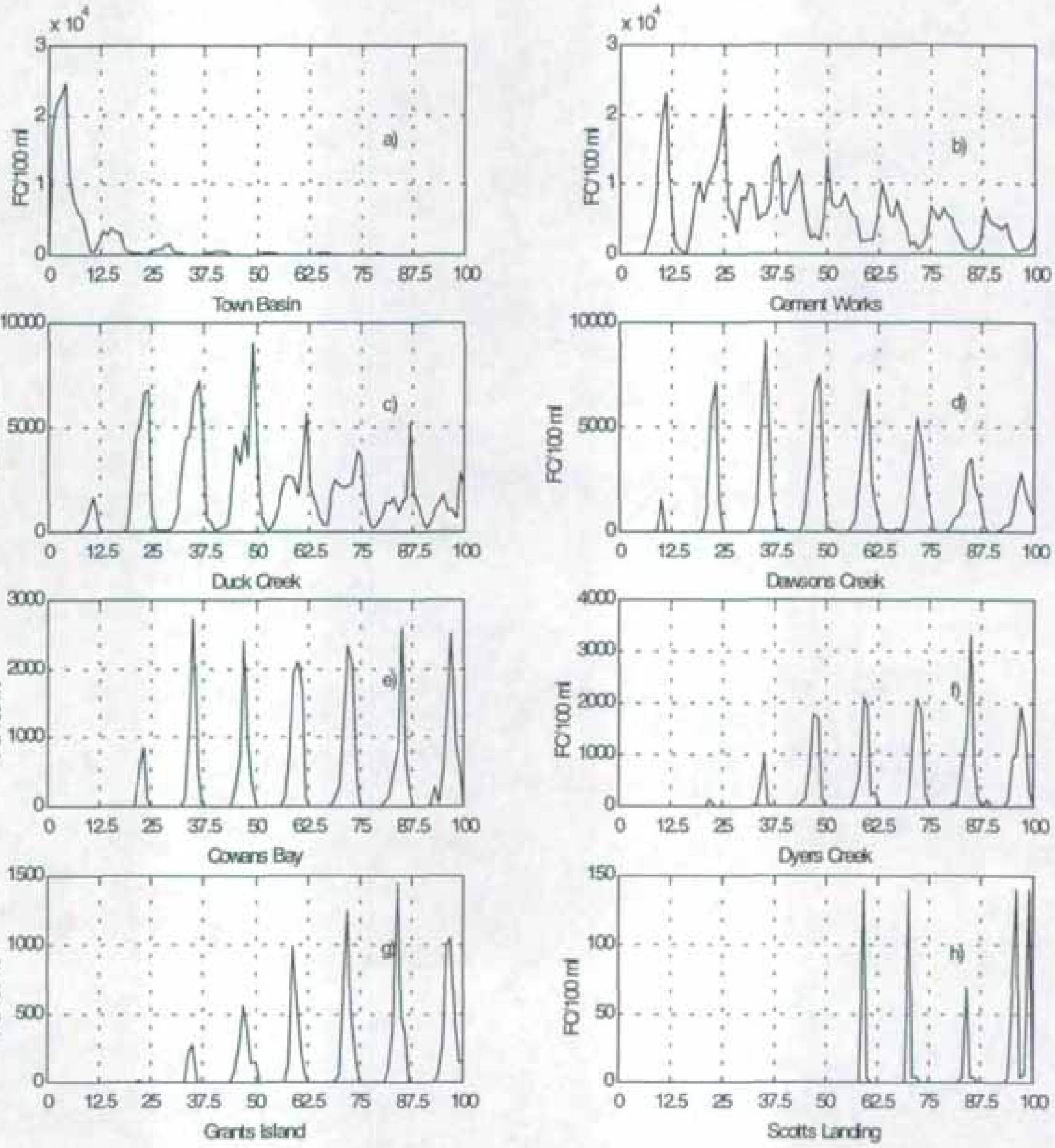


Figure 19. Predicted Faecal Coliform concentrations within the main channel for a four hour overflow event with 5 cumec freshwater inflows. (Horizontal axis is time in elapsed hours from the model start. Note: each tidal cycle = 12.5 hours).

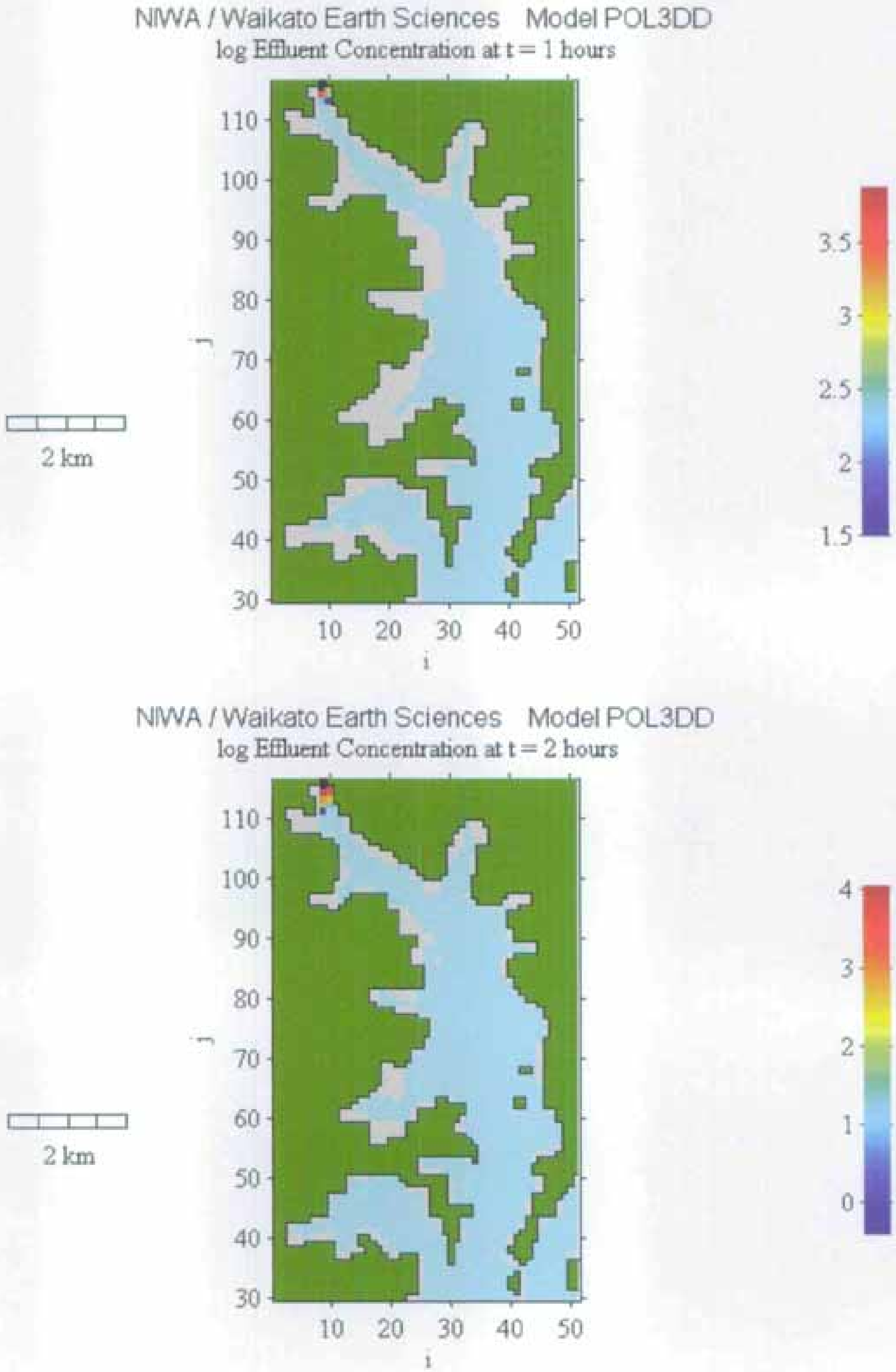


Figure 20a. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary at 1 hour and 2 hours after the start of a four hour overflow event with 5 cumecs freshwater inflows. (Examples: $2=10^2$ FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)

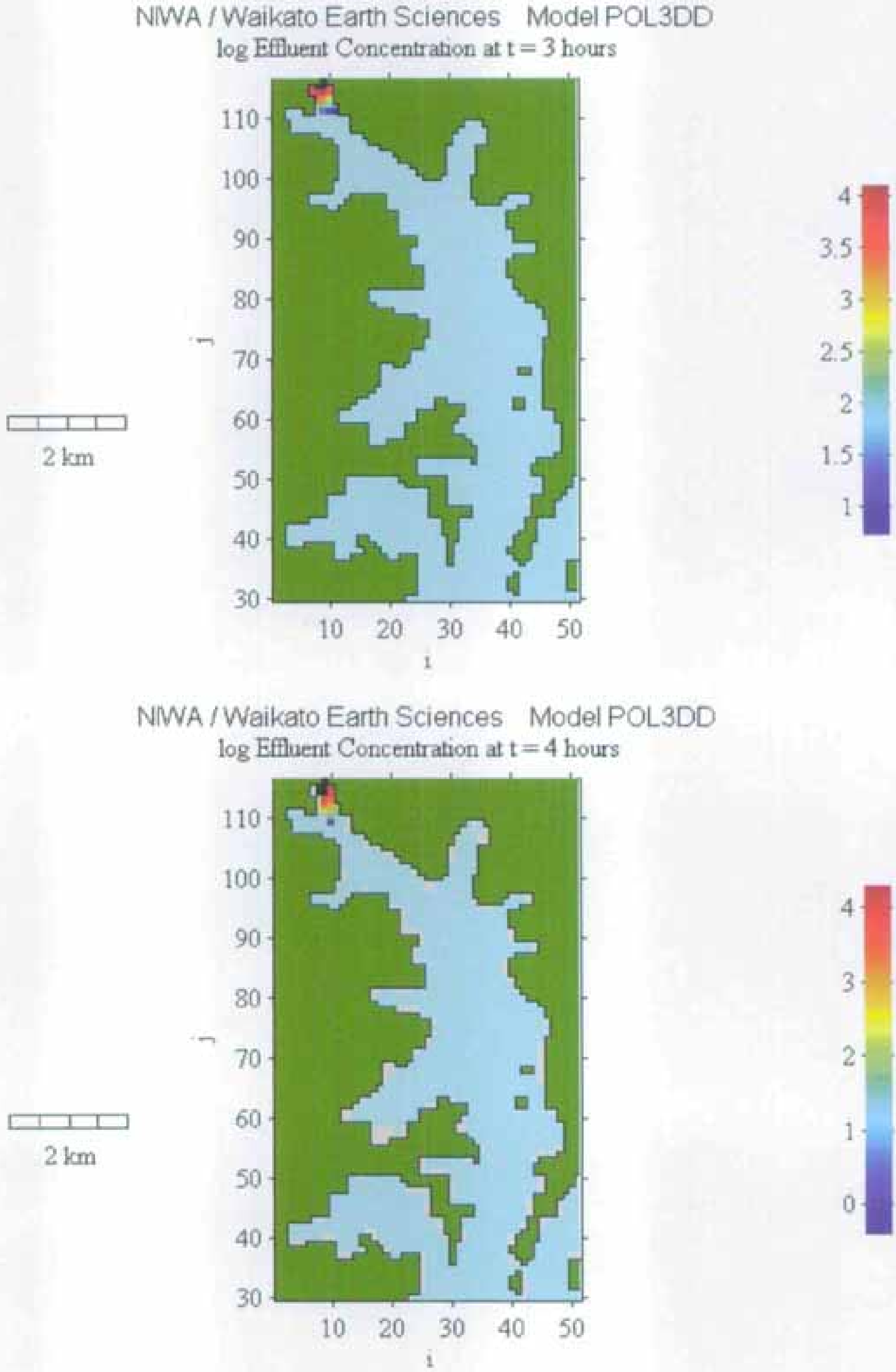
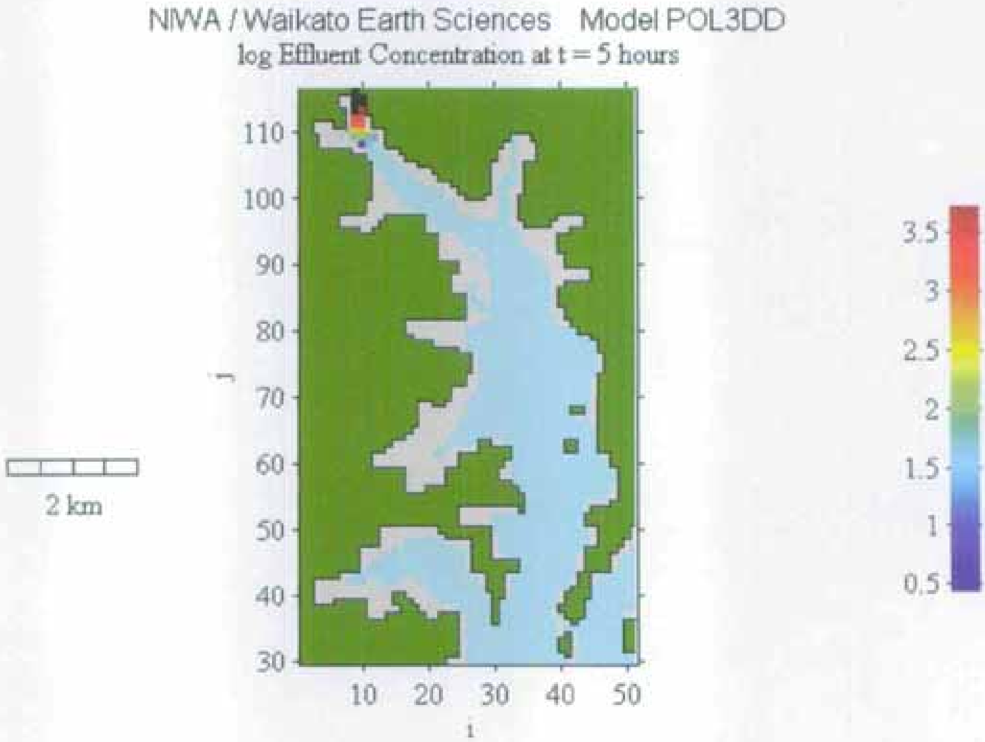


Figure 20b. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary at 3 hours and 4 hours after the start of a four hour overflow event with 5 cumecs freshwater inflows. (Examples: $2=10^2$ FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)



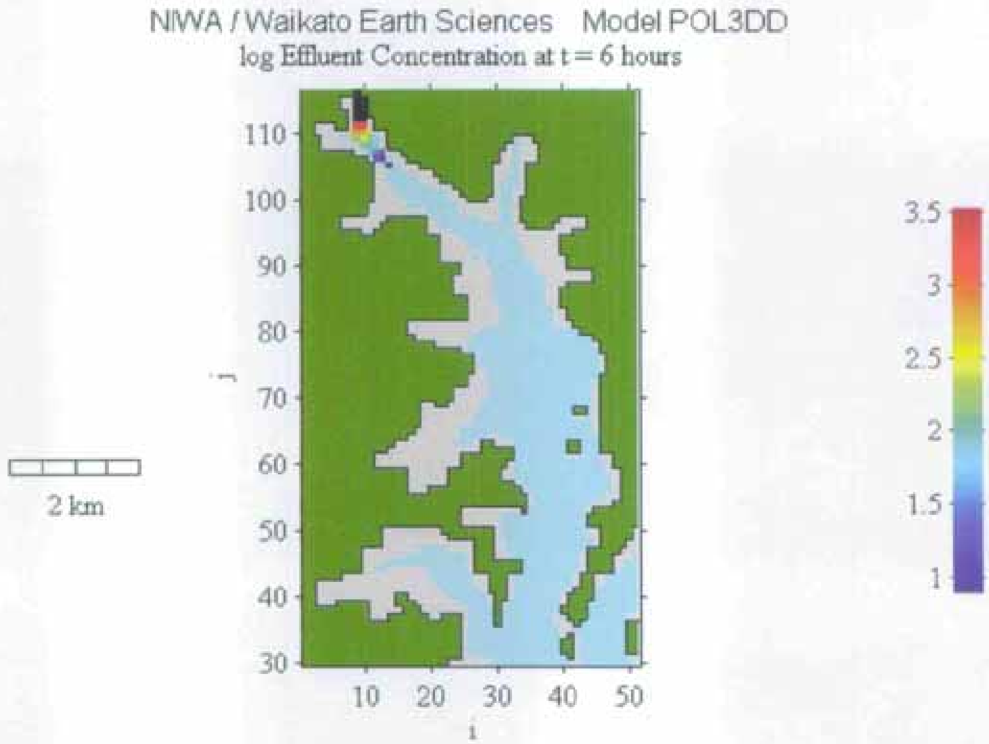
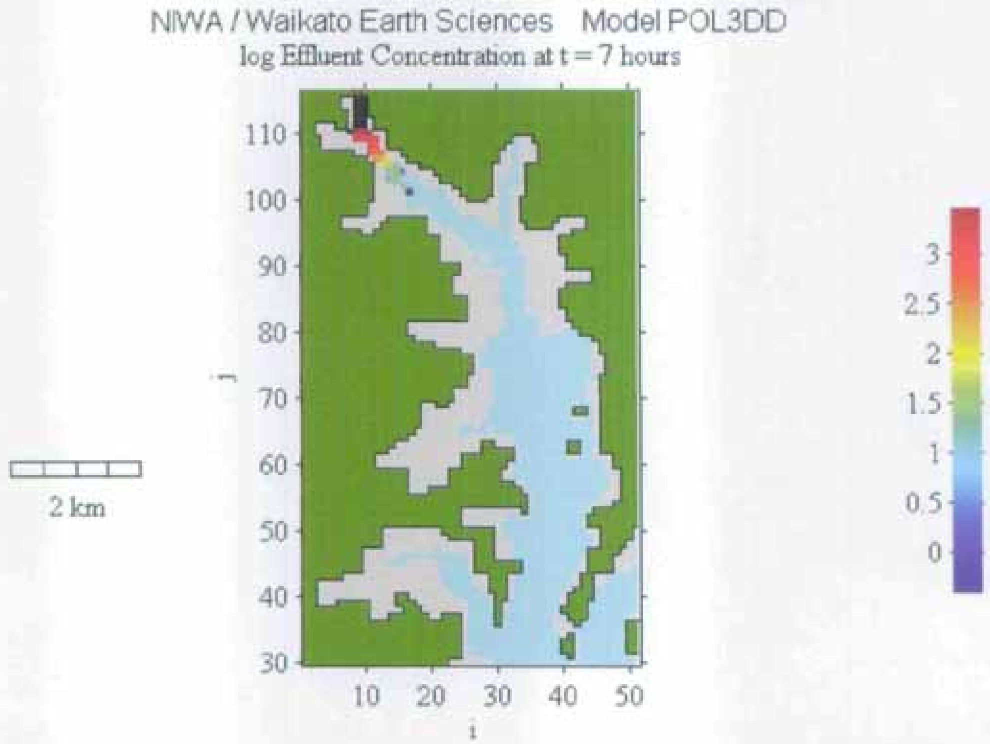


Figure 20c. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary at 5 hours and 6 hours after the start of a four hour overflow event with 5 cumecs freshwater inflows. (Examples: $2=10^2$ FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)



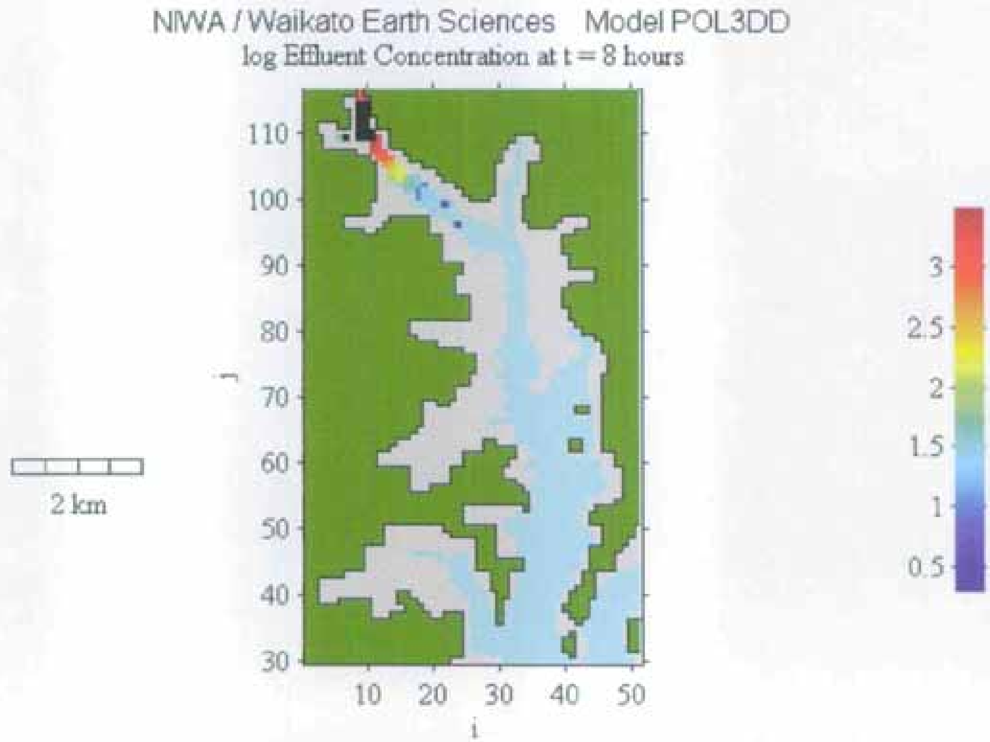


Figure 20d. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary at 7 hours and 8 hours after the start of a four hour overflow event with 5 cumecs freshwater inflows. (Examples: $2=10^2$ FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)

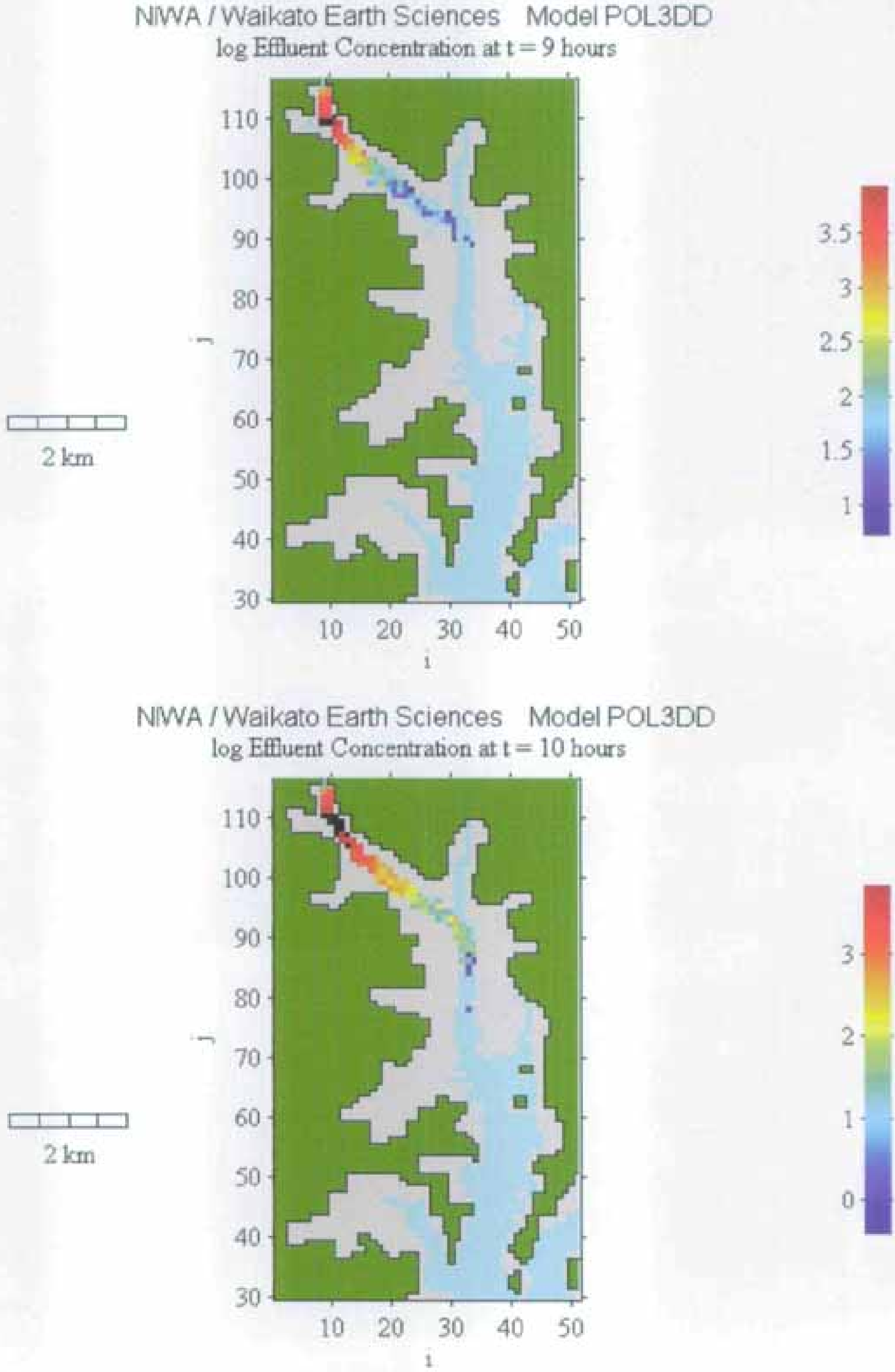


Figure 20e. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary at 9 hours and 10 hours after the start of a four hour overflow event with 5 cumecs freshwater inflows. (Examples: $2=10^2$ FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)

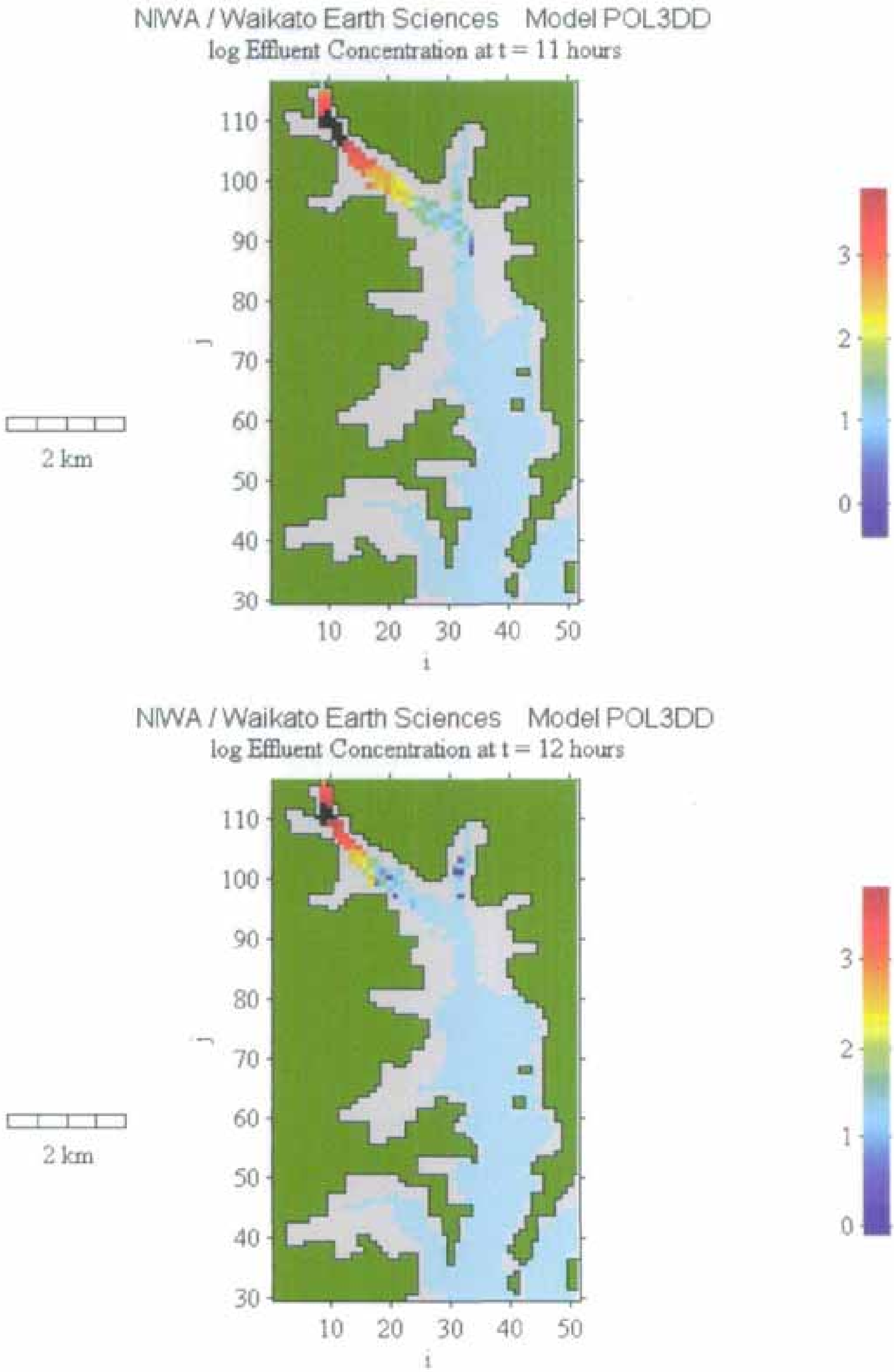


Figure 20f. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary at 11 hours and 12 hours after the start of a four hour overflow event with 5 cumecs freshwater inflows. (Examples: $2=10^2$ FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)

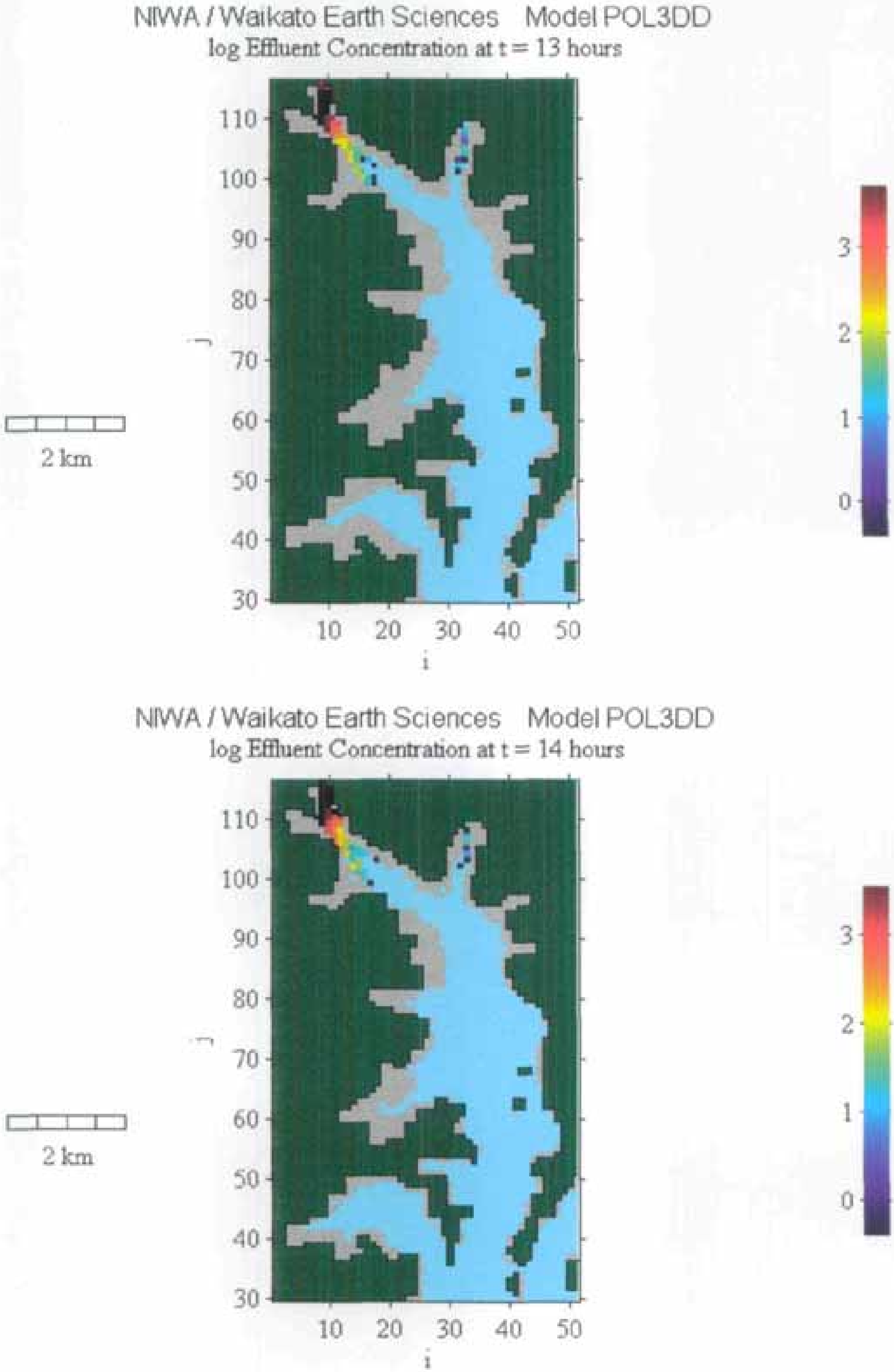


Figure 20g. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary at 13 hours and 14 hours after the start of a four hour overflow event with 5 cumecs freshwater inflows. (Examples: $2=10^2$ FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)

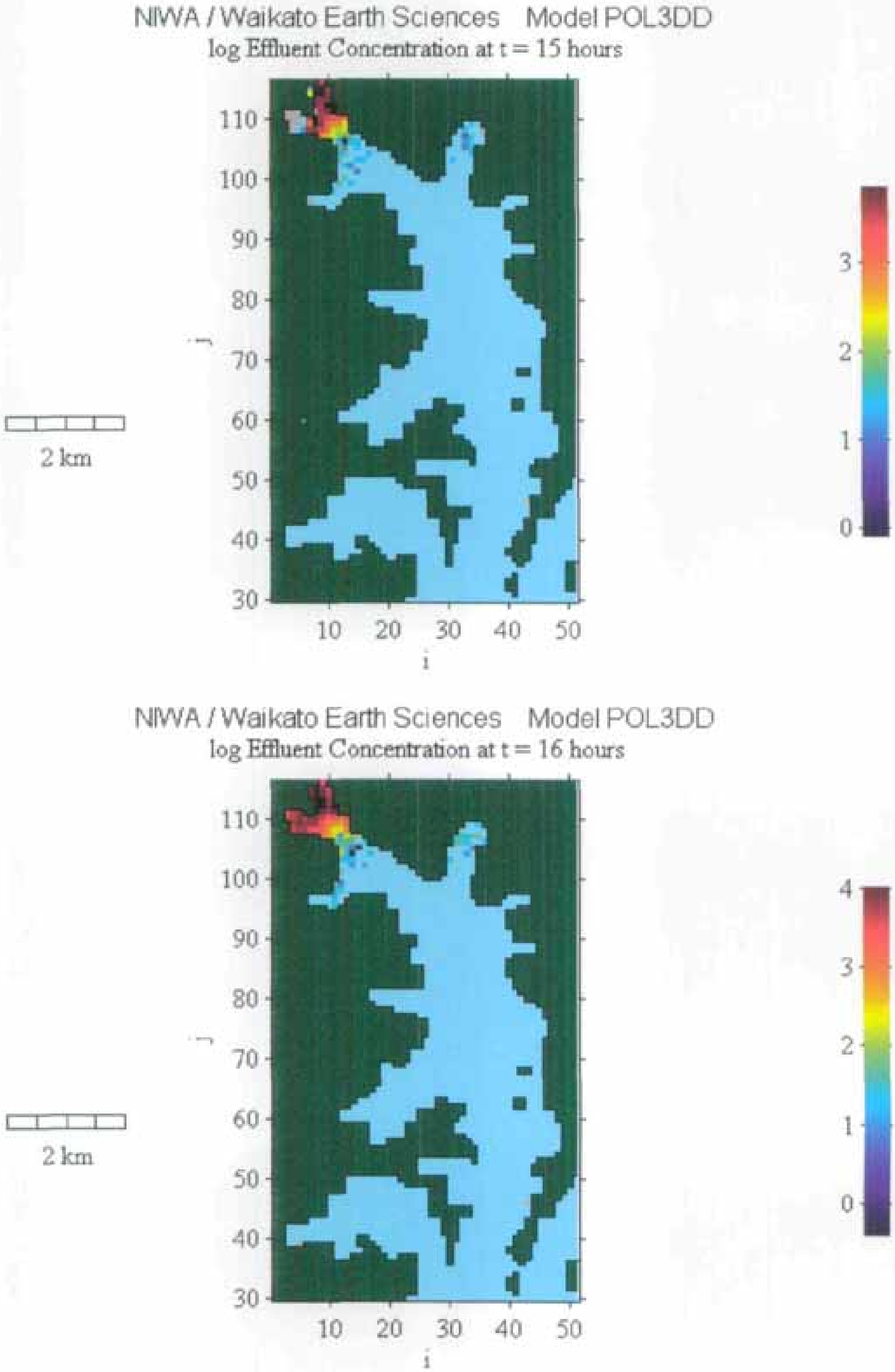
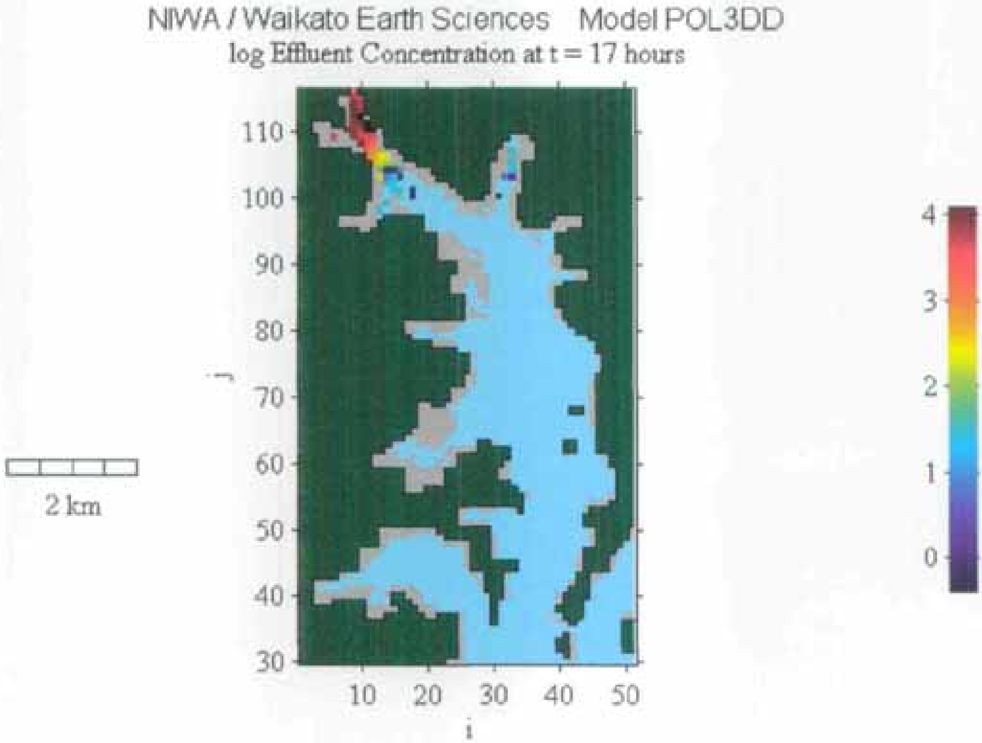


Figure 20h. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary at 15 hours and 16 hours after the start of a four hour overflow event with 5 cumecs freshwater inflows. (Examples: 2=10^2 FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)



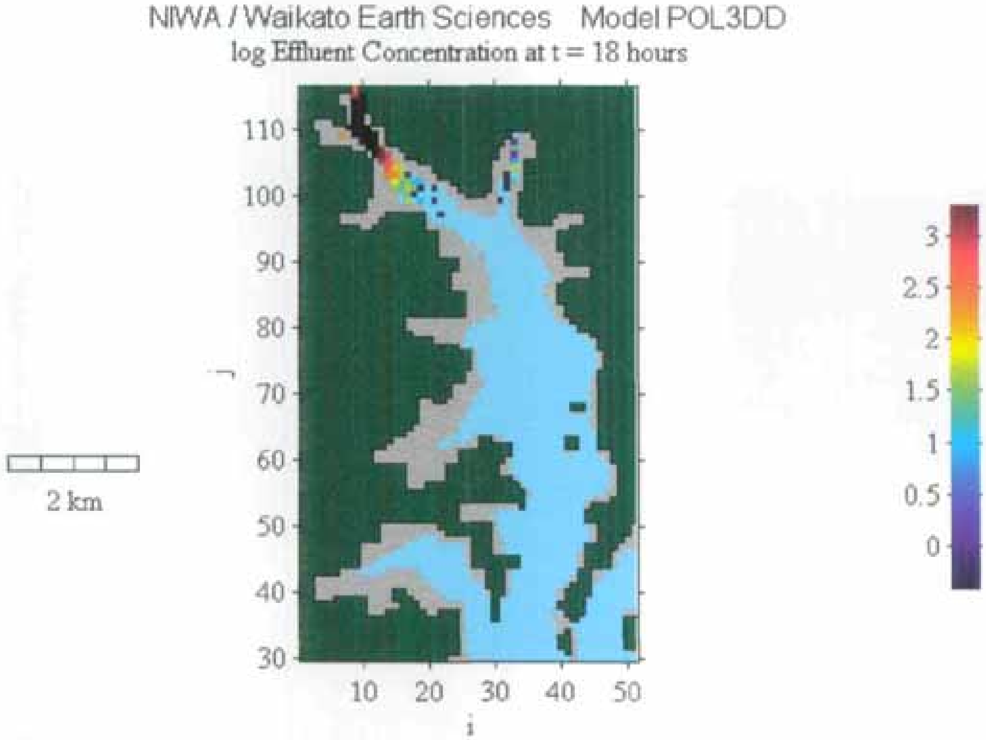


Figure 20i. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary at 17 hours and 18 hours after the start of a four hour overflow event with 5 cumecs freshwater inflows. (Examples: $2=10^2$ FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)

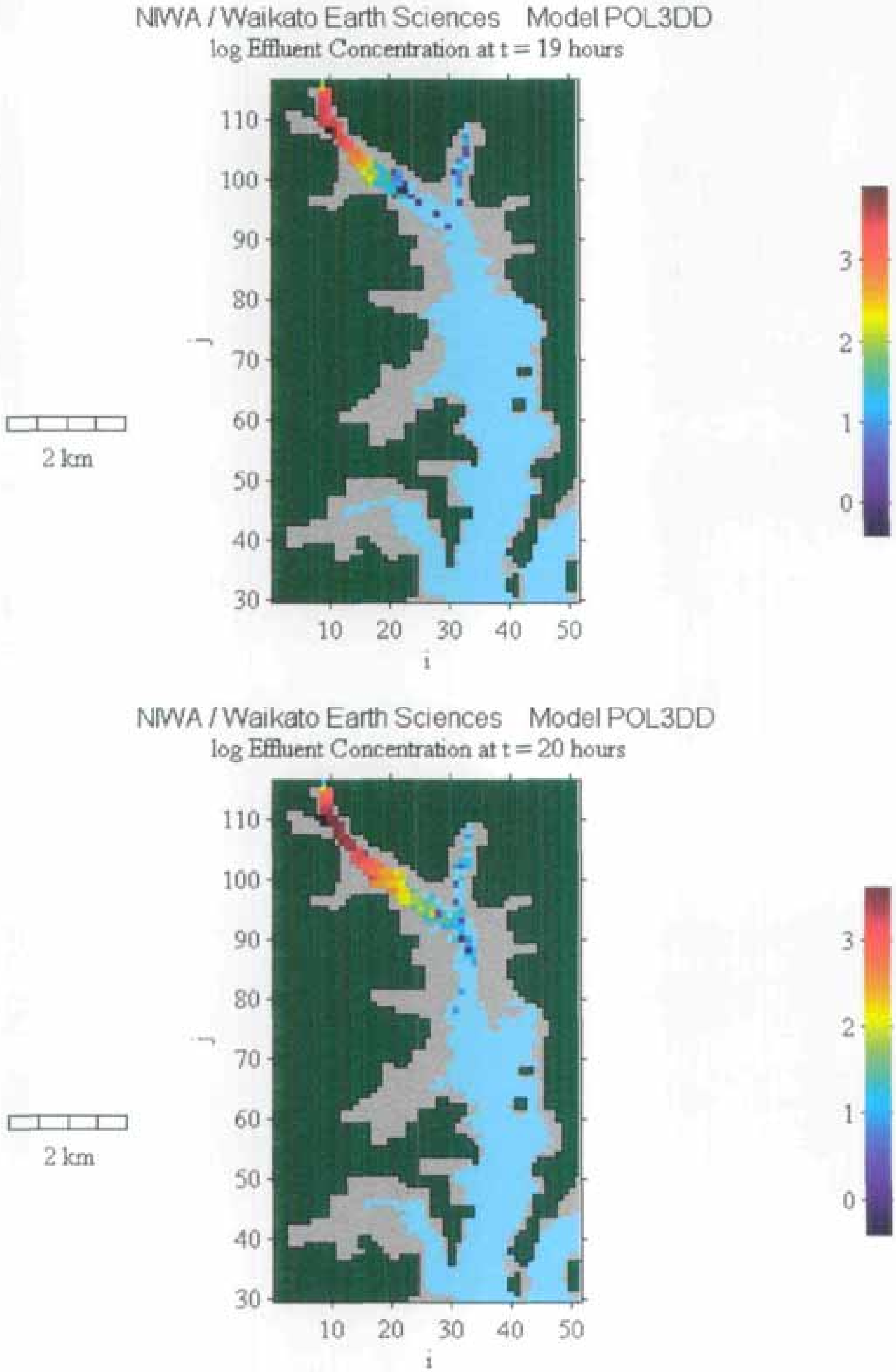


Figure 20j. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary at 19 hours and 20 hours after the start of a four hour overflow event with 5 cumecs freshwater inflows. (Examples: $2=10^2$ FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)

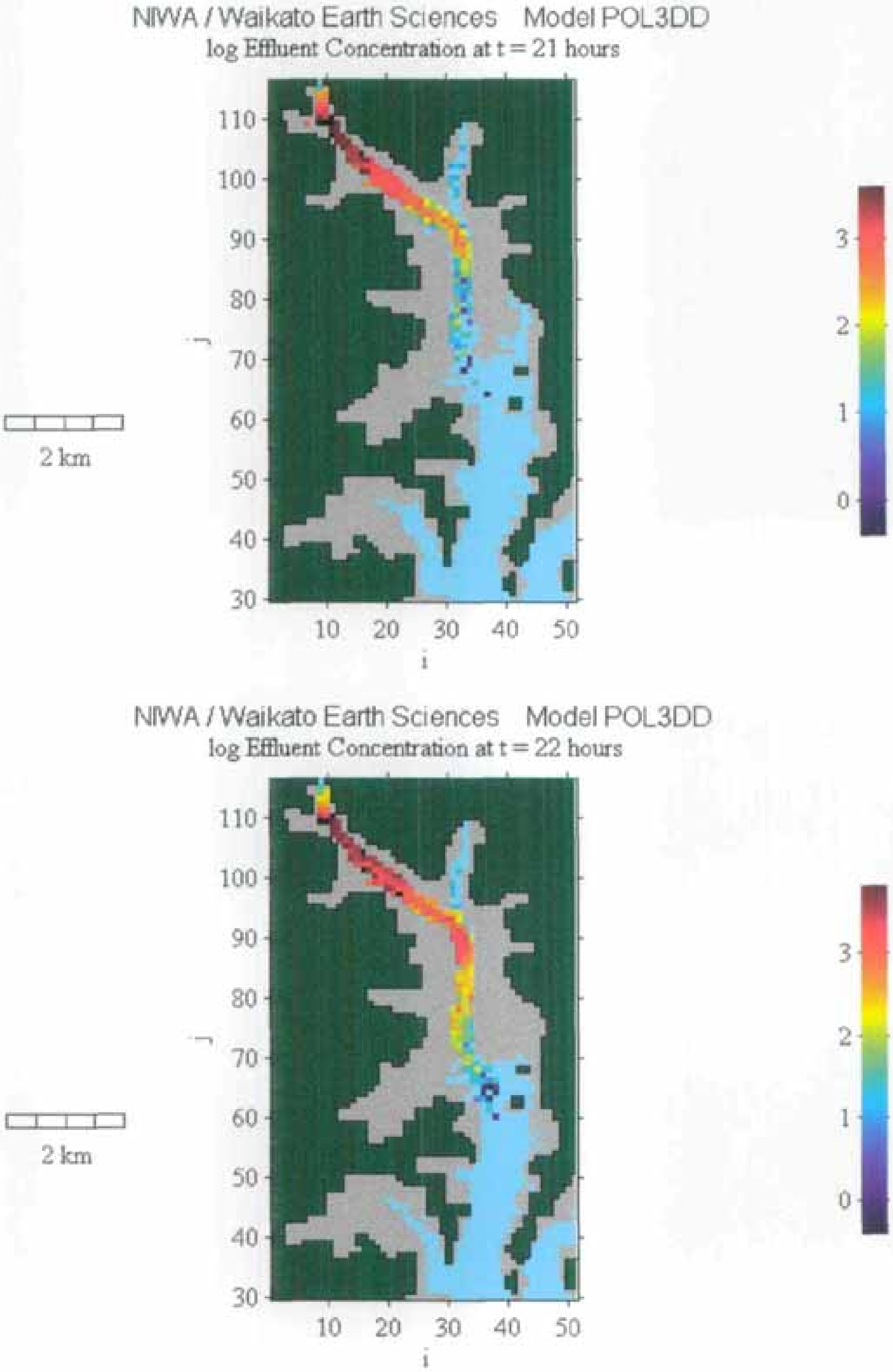


Figure 20k. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary at 21 hours and 22 hours after the start of a four hour overflow event with 5 cumecs freshwater inflows. (Examples: $2=10^2$ FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)

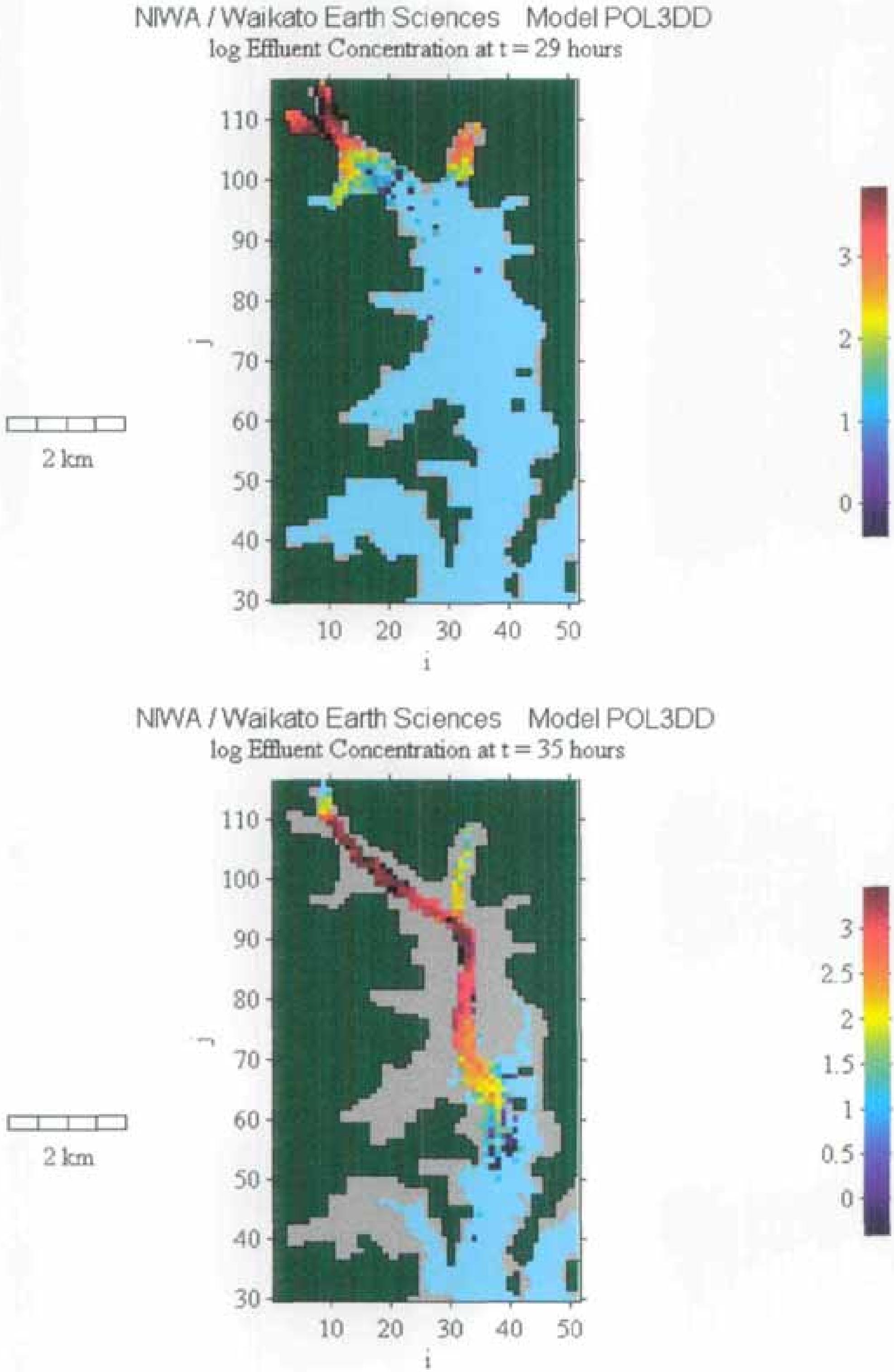


Figure 20l. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary for the 3rd high and low waters after the start of a four hour overflow event with 5 cumecs freshwater inflows. (Examples: $2=10^2$ FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)

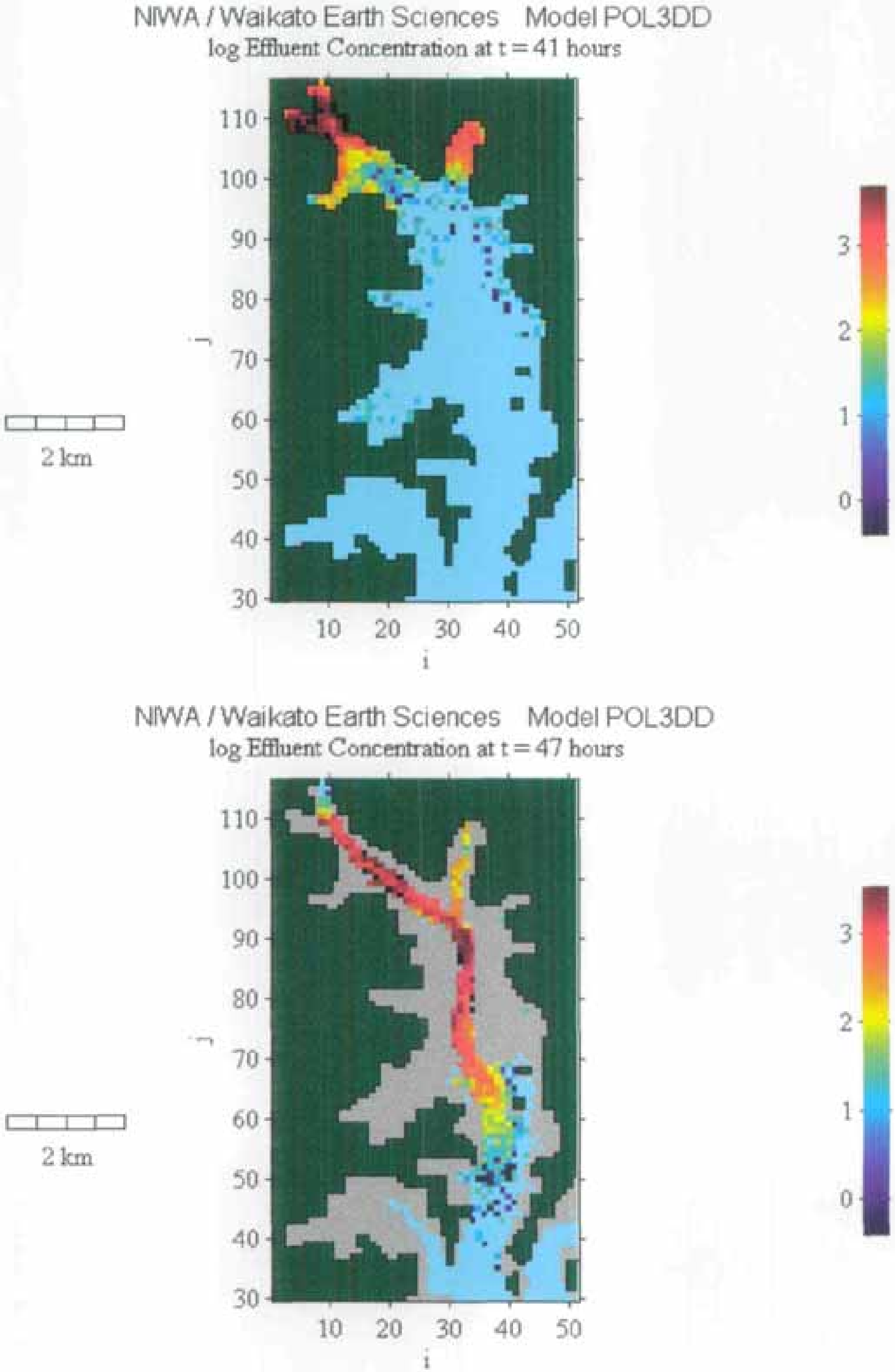


Figure 20m. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary for the 4th high and low waters after the start of a four hour overflow event with 5 cumecs freshwater inflows. (Examples: $2=10^2$ FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)

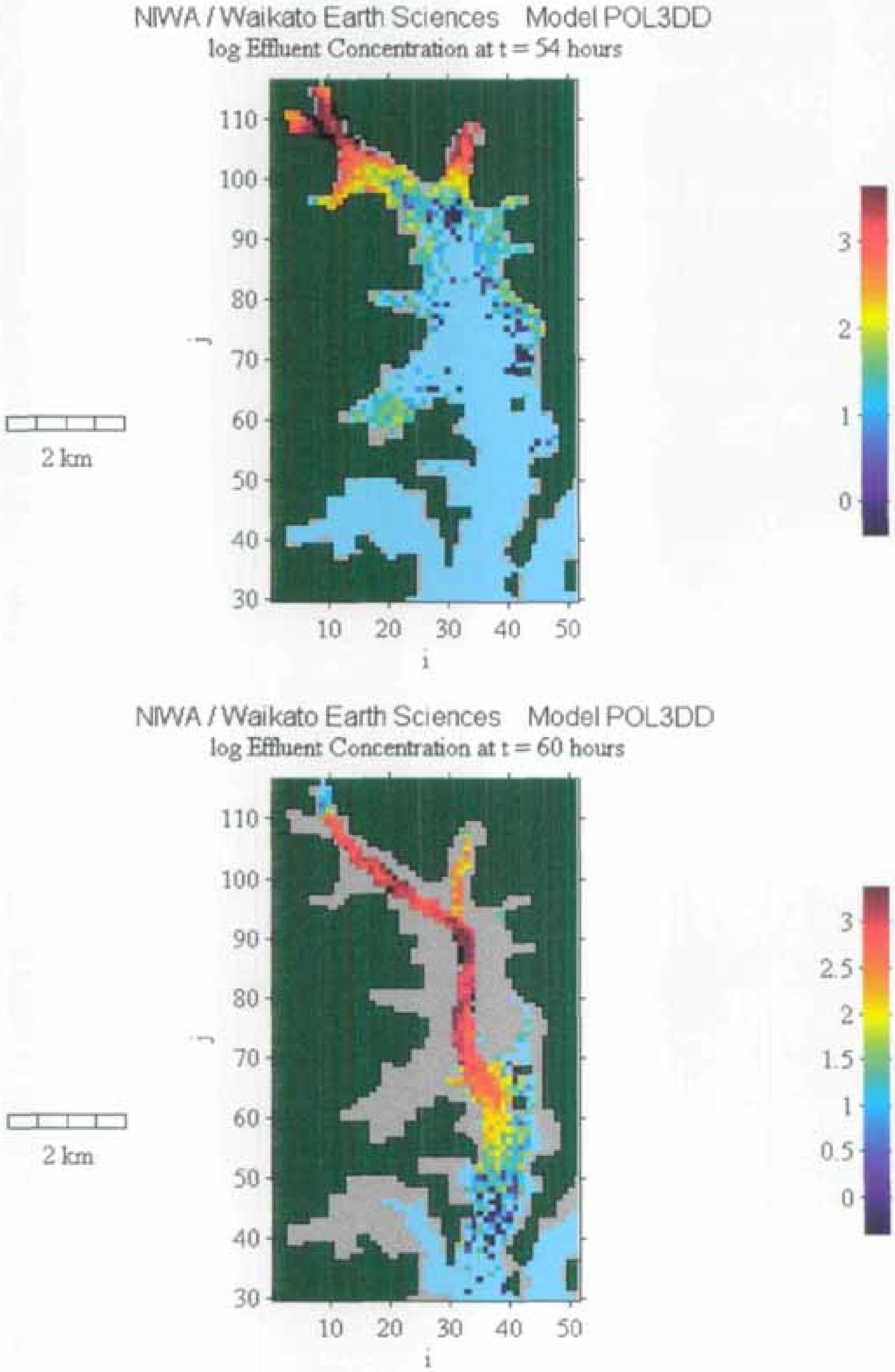


Figure 20n. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary for the 5th high and low waters after the start of a four hour overflow event with 5 cumecs freshwater inflows. (Examples: $2=10^2$ FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)

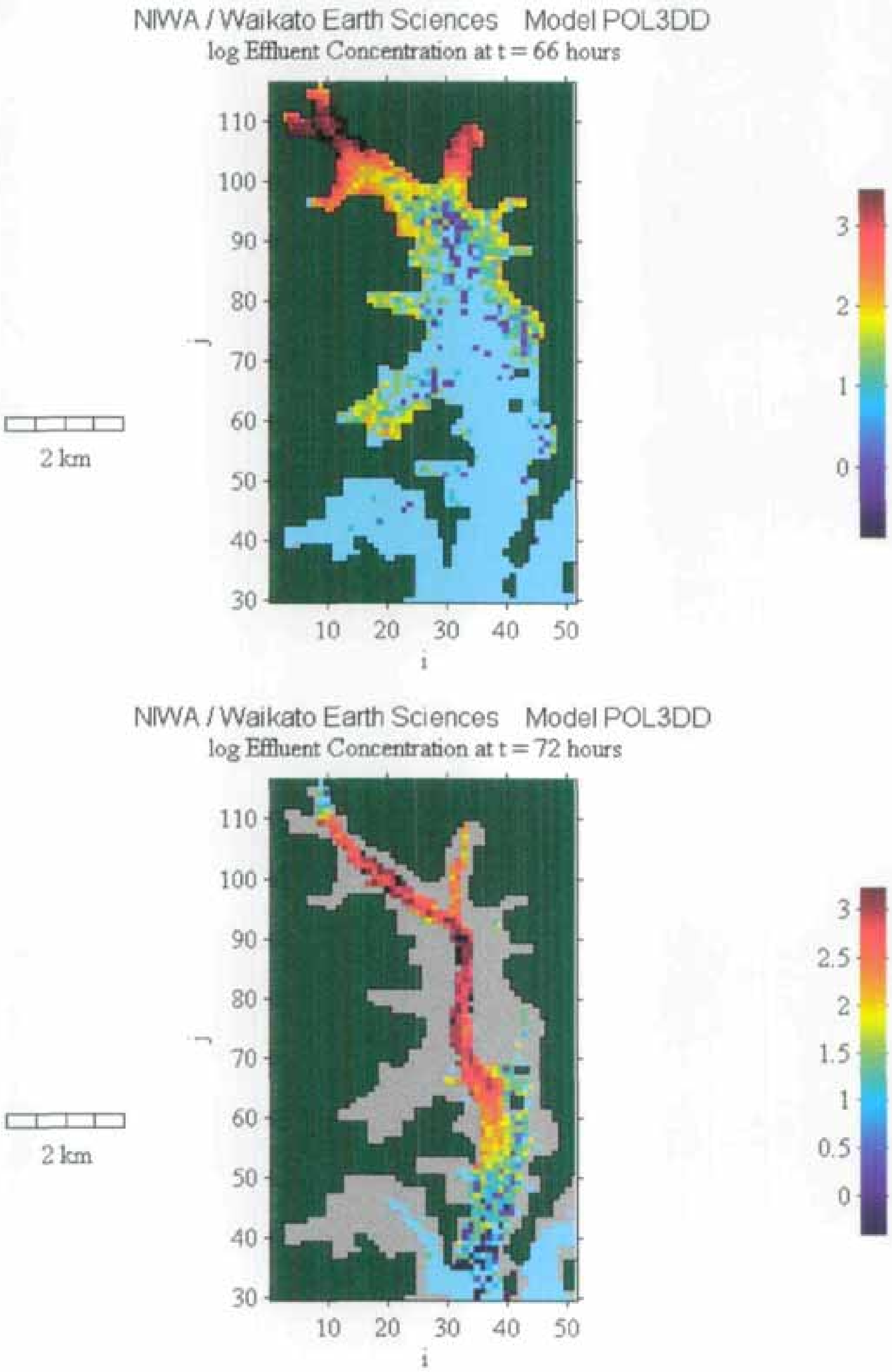


Figure 20o. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary for the 6th high and low waters after the start of a four hour overflow event with 5 cumecs freshwater inflows. (Examples: $2=10^2$ FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)

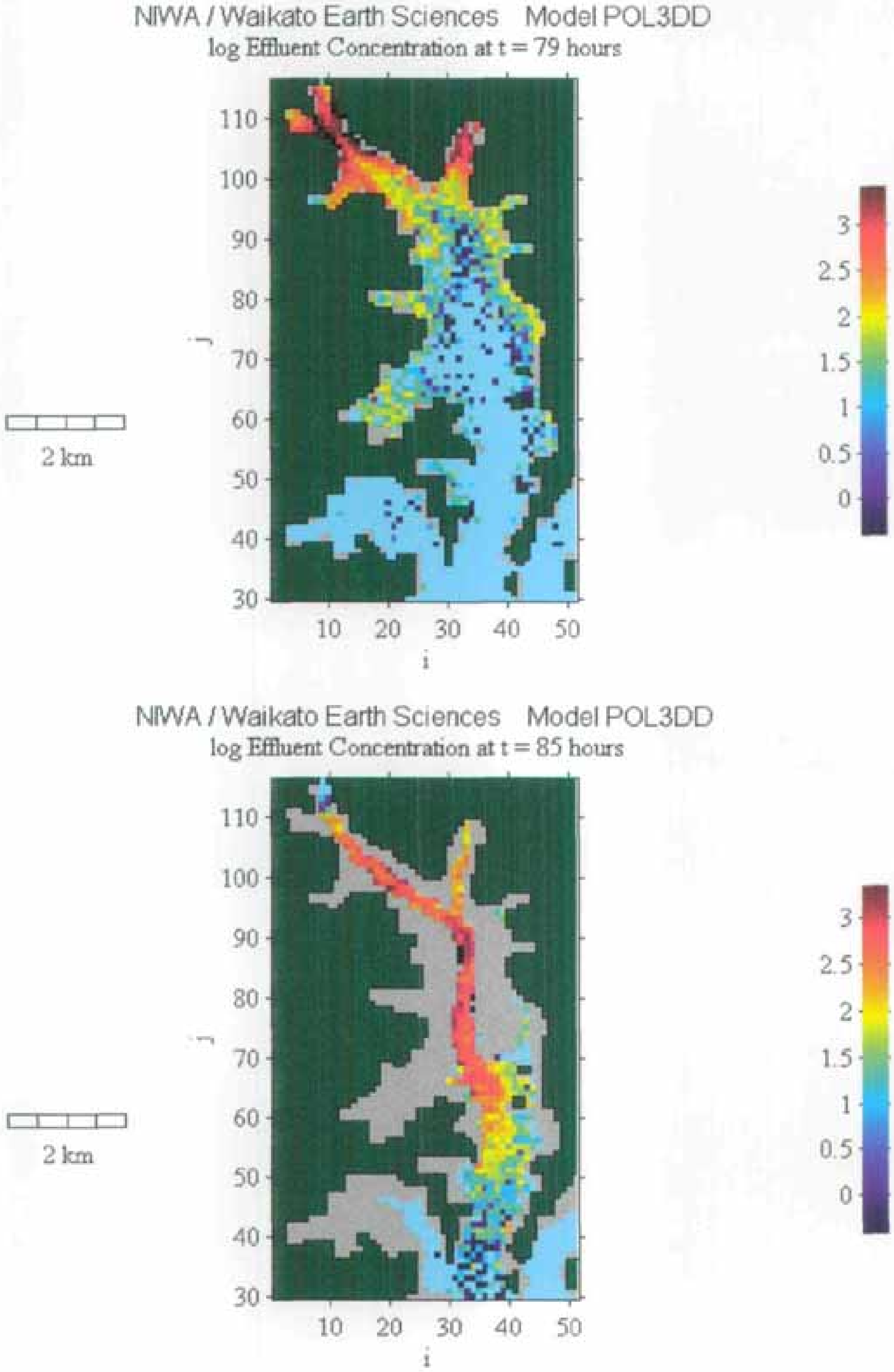


Figure 20p. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary for the 7th high and low waters after the start of a four hour overflow event with 5 cumecs freshwater inflows. (Examples: $2=10^2$ FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)

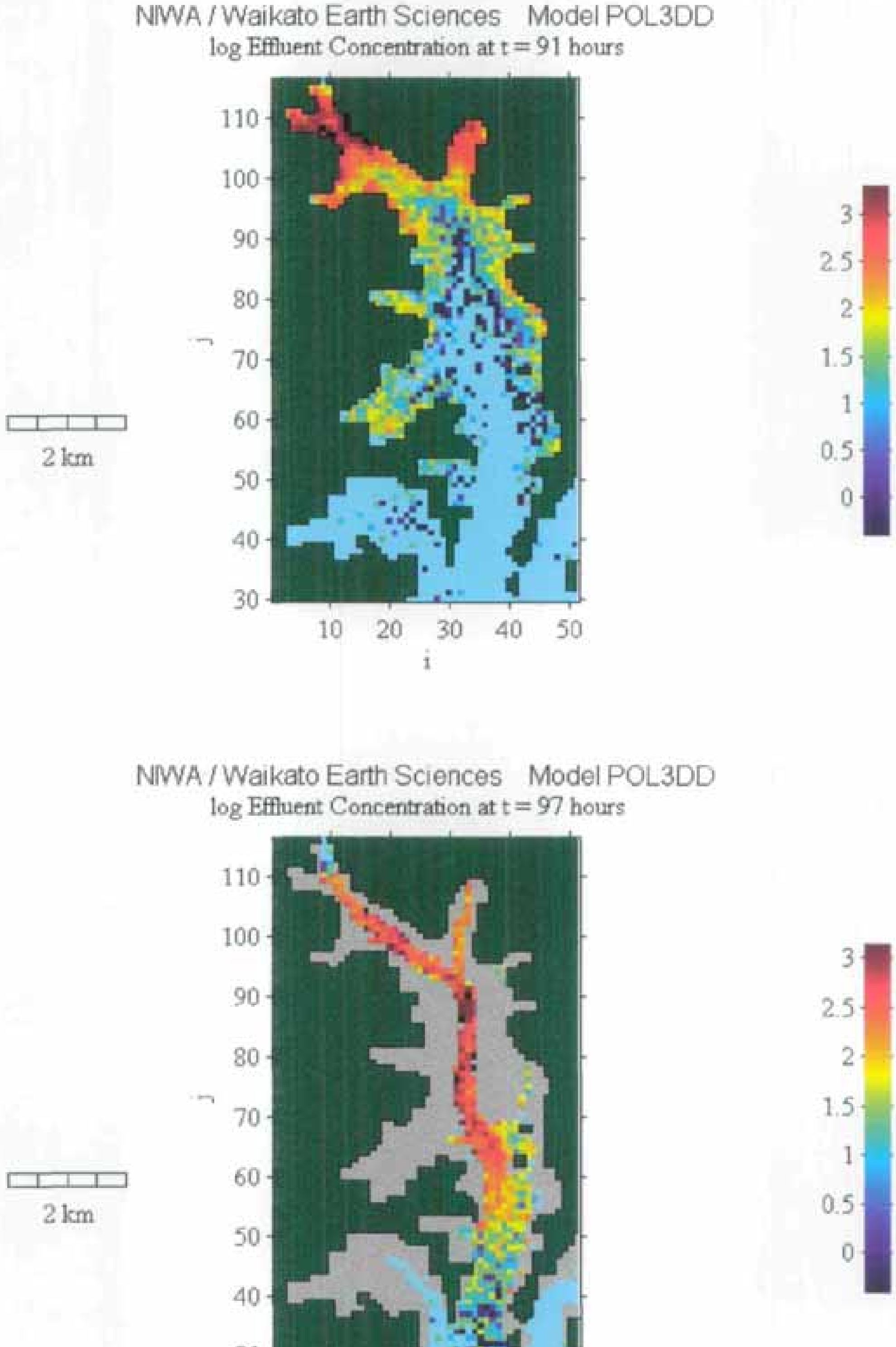


Figure 20q. Logarithm of the faecal coliform concentration (FC/100 ml) within the Mahurangi estuary for the 8th high and low waters after the start of a four hour overflow event with 5 cumecs freshwater inflows. (Examples: $2=10^2$ FC/100 ml and 0=1 FC/100 ml. Intertidal areas are shaded a grey colour)

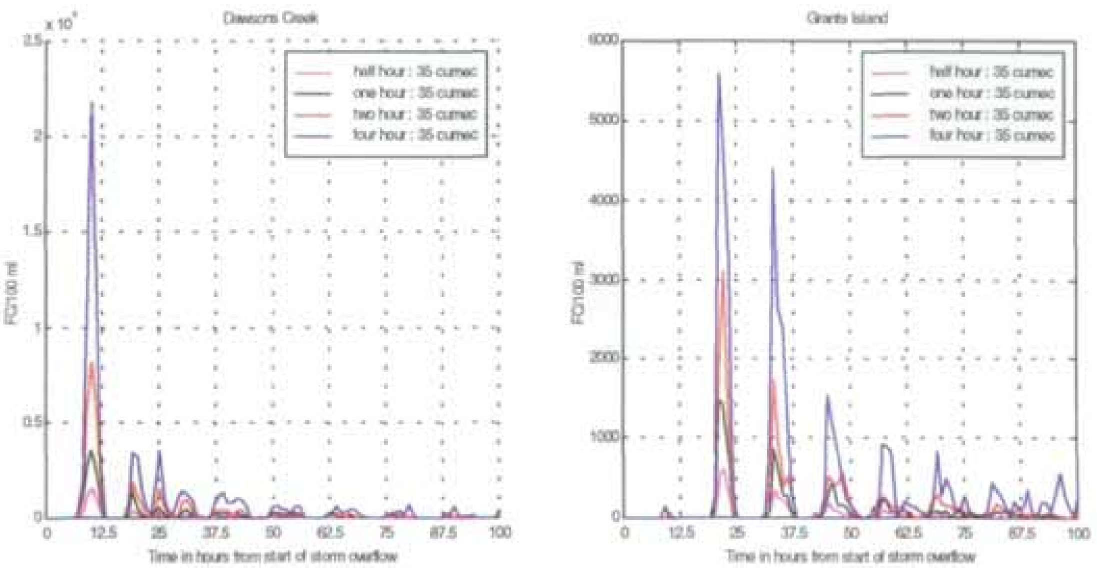


Figure 21a. Predicted faecal coliform concentrations within the main channel for different duration overflow events at a) Dawsons Creek and b) Grants Island

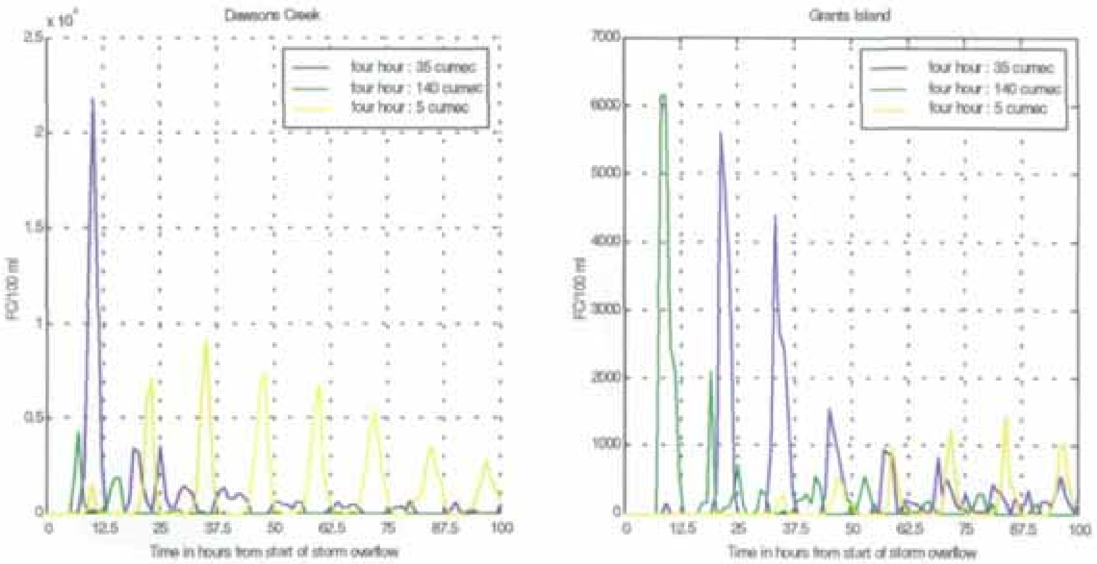


Figure 21b. Predicted faecal coliform concentrations within the main channel for different Mahurangi River inflows at a) Dawsons Creek and b) Grants Island