DERIVING A SEDIMENT PRESSURE LAYER FOR TAURANGA HARBOUR

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DERIVING A SEDIMENT PRESSURE LAYER FOR TAURANGA HARBOUR

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MIHI

Mihi i te tīmatanga
Ko te kore
Ko te pō
Nā te pō ka puta
ko te Kukune
Ko te Pupuke
Ko te Hihiri
Ko te Mahara
Ko te Manako
Ka puta i te whei ao ki te ao mārama
Tihēi Mauri ora
Ki nga maunga
Ki nga moana
Ki nga whare maha e karopoiti nei i Te Awanui
E rere ana nga mihi ki a ratau kua moe nga whatu
Takoto ma i te moenga roa
Kia tatau e pikau ana i nga ahuatanga o te ao turoa
Tatau e kowhaiwhai ana nei nga wawata o ratau ma
Tena koutou, tena koutou, tena koutou katoa.

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EXECUTIVE SUMMARY

As part of the Manaaki Taha Moana research programme, we are estimating the cumulative impact of the multiple stressors in Tauranga Harbour. This report describes the development of geographic information system (GIS) layers that contain estimates of the ecological pressure of river-sourced sediment within the harbour.

Sediment discharged from land and dispersed within Tauranga Harbour was estimated under two scenarios: reference conditions of total native forest cover representing pre-development conditions, and contemporary (current) conditions (1990s land cover) representing post-development conditions.

Two sediment dispersion functions with different resultant distributions were used to transport sediment within and out of the harbour.

Estimates of sediment values under the two scenarios were compared to illustrate the distribution of the pressure from increased sediment levels. This pressure distribution is an appropriate layer for addition to a Halpern cumulative impact model.

Eight GIS raster data layers accompany this report:

- SedimentLoadInvSq_Reference
- SedimentLoadInvSq_Contemp
- SedimentLoadInvSqRoot_Reference
- SedimentLoadInvSqRoot_Contemp
- SedimentPressureInvSq_Difference
- SedimentPressureInvSq_Ratio
- SedimentPressureInvSqRoot_Difference
- SedimentPressureInvSqRoot_Ratio

The first four data layers are the sediment load estimates for the reference and contemporary scenarios, as distributed by two dispersion functions. The second four layers are the Halpern-inspired pressure estimates derived from these sediment loads. Of these pressure layers, two were calculated as the simple difference between reference and contemporary conditions. The other two were calculated as the ratio between reference and contemporary conditions.

The sediment load layers can be used as estimates of reference and contemporary sediment loads throughout the harbour. The pressure layers represent the change between reference and contemporary, expressed as a difference or a ratio, and will be used as a component of the model being developed to produce a map of the cumulative impact of multiple stressors on Tauranga Harbour.

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1. BACKGROUND

1.1. Background to the Manaaki Taha Moana (MTM) project

This report is one in a series of reports and other outputs from the research programme “Enhancing Coastal Ecosystems for Iwi: Manaaki Taha Moana” (MAUX0907), funded by the Ministry of Business Innovation and Employment (including what was previously known as the Foundation for Research Science and Technology). Readers should refer to the MTM website (www.mtm.ac.nz) for ongoing updates.

Manaaki Taha Moana (MTM) is a 6-year programme, running from October 2009 to September 2015, which aims to assist iwi to maintain and enhance coastal ecosystems of cultural significance. Research is conducted primarily in two areas; Tauranga moana and the Horowhenua coast.

1.1.1. MTM research team

Professor Murray Patterson of Massey University is the Science Leader for MTM, and a number of organisations are contracted to deliver the research:

- Te Manaaki Awanui Trust (previously Te Manaaki Taiao Trust and Waka Taiao Ltd); with the Tauranga moana case study
- Te Reo a Taiao Ngāti Raukawa Environmental Resource Unit (Taiao Raukawa) and Dr Huhana Smith; with the Horowhenua coast case study
- Waka Digital Ltd
- Cawthron Institute
- Massey University.

The research team seeks to engage with local communities and end users through a variety of means. Readers are encouraged to visit the MTM programme website (www.mtm.ac.nz) to read more about this research programme.

1.2. MTM objectives

The central research question of MTM is: “How can we best enhance and restore the value and resilience of coastal ecosystems and their services to make a positive contribution to iwi identity, survival and welfare in the case study regions?” Accordingly, our research aims to restore and enhance coastal ecosystems and their services of importance to iwi and hapū, through a better knowledge of these ecosystems and the degradation processes that affect them.

The MTM teams utilise both western science and mātauranga Māori knowledge to assist iwi, hapū and whanau groups to evaluate and define preferred options for enhancing / restoring coastal ecosystems. This evaluation of options is assisted by the development of innovative information technology and decision support tools.

The research team works closely with iwi and hapū in the case study regions to develop tools and approaches to facilitate the uptake of this knowledge and its practical implementation. Mechanisms will also be put in place to facilitate uptake amongst other iwi throughout New Zealand. The key features of this research are that it is: cross-cultural, interdisciplinary, applied/problem solving, technologically innovative, and integrates the ecological, environmental, cultural and social factors associated with coastal restoration.

In Tauranga moana, our work to date has included:

- a comprehensive review of the health of the harbour (Sinner *et al.* 2011)
- a study of the system dynamics of the harbour involving mediated modelling by a group of diverse stakeholders (van den Belt *et al.* 2012)
- the development of a three-dimensional physical model of the harbour by Waka Digital
- a broad-scale ecological survey of the harbour (Ellis *et al.* 2013)
- a survey of intertidal shellfish (report in progress)

In addition to the cumulative impacts study, which is the subject of this report, other work in progress for the Tauranga moana case study includes a report on Mātauranga Māori of Te Awanui Tauranga Harbour and the development and application of a cultural health index for the harbour.

1.3. Halpern's cumulative impact model

Halpern *et al.* (2008) mapped the cumulative impacts of 25 human activities on 19 marine habitats along the California coast. The study identified numerous sites that were impacted by multiple stressors and showed which human activities posed the top threats.

The Halpern approach has three main components:

1. GIS layers of habitat types
2. GIS layers of human stressors
3. A matrix of impact scores, one for the impact of each stressor on each habitat type

Data in each stressor layer is transformed so that all stressors are on the same 0-1 scale and can be compared. Each habitat layer is converted to the smallest practical spatial scale (e.g. 1 km^2 grid cells) and recorded as presence-absence (i.e. 0 or 1) for each cell. For each cell, each habitat layer is multiplied by the scaled stressor layer, and then by the impact score for that combination. The sum of these scores in a particular 1 km^2 cell represents the cumulative impacts of human activities on the identified ecosystems.

From the MTM broadscale survey and other sources, we have GIS layers for most of the habitat types in Tauranga Harbour, although the sand and mud layers could be improved. We also have some data on human stressors in Tauranga Harbour, but most of this data needs further analysis to convert to GIS layers that are in appropriate units and are spatially distributed. Sediment is one such stressor, and this report describes the development of a GIS layer depicting the distribution of sediment in Tauranga Harbour.

Other layers of ecological pressure on Tauranga Harbour are being developed and together will be used to estimate, and produce a map of, the cumulative impacts of multiple stressors on the harbour ecosystems. The map can then be used both to identify areas and habitats within the harbour that are under particular pressure and to explore how the impacts might change under different scenarios such as changes in land use or new approaches to stormwater management.

This work represents an application of the Halpern model at a local scale, with the further intention of testing the outputs from the model against actual ecological data from the MTM ecological survey of Tauranga Harbour (Ellis *et al.* 2013). This will be the first time that such a validation has been attempted since the publication of Halpern’s paper in 2008.

2. METHODOLOGY

Elevated sediment loading is recognised as a major stressor affecting the health and function of New Zealand coasts and estuaries (Hewitt *et al*. 2005, 2009; Rodil *et al.* 2011; Lohrer *et al.* 2012). This report describes the development of data layers that contain estimates of the distribution of river-sourced sediment within the harbour. This is part of a larger study to estimate the cumulative impacts of multiple stressors in Tauranga Harbour, following a framework developed by Halpern *et al.* (2008).

This work was undertaken as follows:

- Estimated sediment yields at each river mouth in Tauranga Harbour, under both reference (all land in forest) and contemporary (1990s land cover) were obtained from an external model.
- Multiple functions were developed and tested to estimate the dispersion of these sediment loads within and out of the harbour. Two functions were selected as most realistic and were applied to both reference and contemporary estimates of sediment loads.
- Estimates of change in ecological pressure were derived by comparing the estimated reference and contemporary distributions of sediment within the harbour, for each of the two dispersion functions using two different modes of comparison.

Each step was performed in ArcGIS, a geographical information system that represents data spatially. The resulting four layers all show sediment pressure on Tauranga Harbour in a spatially explicit manner.

2.1. Sediment yield modelling

The output from this first step was a table of the sediment yields of each river mouth in tons per year. These values estimate the total amount of sediment that was transported down the river network from the land in the catchment areas that drain into Tauranga Harbour. Pre- and post- development sedimentation levels were both available in the table.

The sediment yield of the catchment draining into Tauranga Harbour was modelled in CLUES (Catchment Land Use for Environmental Sustainability: Semadeni-Davies *et al.*2011) under two scenarios. In the first scenario (‘contemporary’), the land use was set to the best estimate of land use as of 1990, as determined by the Land Cover Database (LCDB2; Ministry for the Environment, 2004). In the second scenario (‘reference’), all land use was reset to ‘native forest’. The CLUES model accounts for the change in sediment released from land under different land uses (land cover), due to agricultural machinery *etc.* disturbing land, and reduced retention of sediment by mature forest. The CLUES model passes sediment released from land into the downhill waterway, from which it enters the network of streams and is propagated downward toward the ocean. Values are calculated for each river in units of thousands of tons per year (kt/y), and range in the reference state from 0.0001 to 15.5 kt/y discharged from different river mouths, and in the contemporary state from 0.0002 to 27.4 kt/y.

The ratio of contemporary-state estimates of sediment loading in streams to reference-state estimates of sediment loading in streams is shown in Figure 1. Higher numbers (red) indicate a greater increase in sediment loading since pre-development.

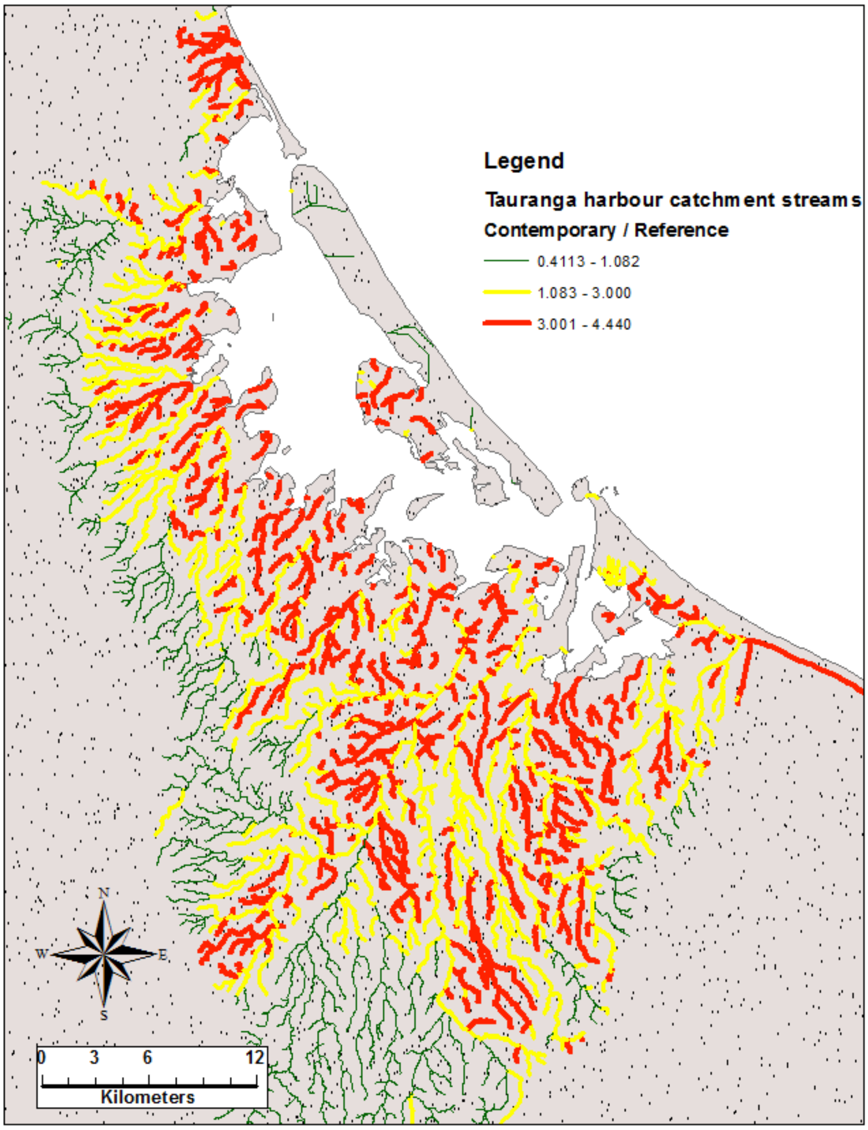


Figure 1. Ratio of contemporary sediment load to reference sediment load estimates for rivers in the catchments surrounding Tauranga Harbour. Higher numbers (red) indicate a greater increase in sediment loading since pre-development.

The stream and river network enters Tauranga Harbour at a number of river mouths, which discharge the sediment transported from their associated upstream catchments. The quantities of sediment discharged from each river mouth into the harbour vary between the two modelled scenarios (contemporary and reference), with the contemporary scenario yielding higher sediment levels (Figure 2).

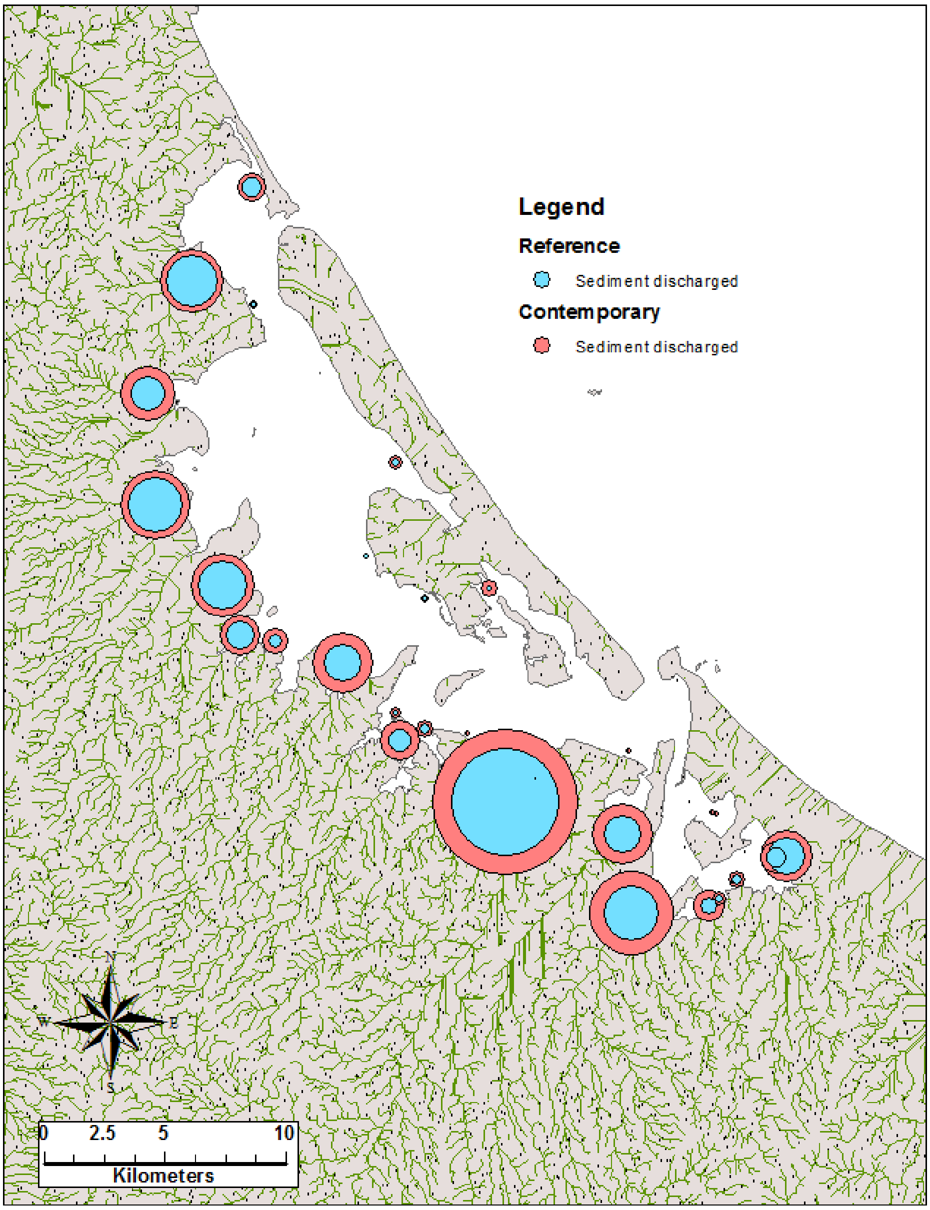


Figure 2. Sediment discharge into Tauranga Harbour at major river mouths under reference (blue) and contemporary (red) land-use scenarios. Symbol area proportional to mass per year. Rivers and streams in the catchment are shown in green.

2.2. Sediment transport modelling

The outputs from this second step were maps of the distribution of sediment throughout the harbour, in kilograms of sediment per square metre per year. The units of these values imply the rate of deposition of sediment, but it is not implied that the deposited sediment is accreted permanently. Rather, the values should be interpreted as the potential for impact by sediment, some of which occurs through deposition and some through water column effects, and it is more appropriate to use the values as indicators of relative impact.

We spent a considerable effort with hydrodynamic current modelling software to disperse sediment via a particle-tracking methodology (Knight *et al.* 2009). Unfortunately, the model for Tauranga Harbour was not mature, and we reached a point where the remaining effort required to obtain satisfactory results was unknown and potentially still significant, so this approach was abandoned. Such an approach, however, is still attractive, particularly in the near-shore environment and at the scale of this study, as the currents within the harbour are likely to make a significant contribution to the dispersion of sediment and of other stressors.

In the absence of a satisfactory hydrodynamic model, sediment was transported within the harbour by simple diffusion schemes, consistent with Halpern's approach. Halpern[1] describes the dispersal of sediment for his cumulative impact model:

> "… spread of the driver values into coastal waters at each pour point was modelled with a cost-path surface (S6) on the basis of a decay function that assigns a fixed amount of the driver (in our case, 0.5% of the value in the previous cell) in the initial cell and then evenly distributes the remaining amount of driver in all adjacent and 'unvisited' cells, repeated until a minimum threshold (0.05% of global maximum) is reached."

These diffusion schemes did not incorporate any data on bathymetry or currents, but worked by decreasing the discharged sediment load as a function of distance from the river mouth, taking the coastline into account. That is, the distance was measured along a path that could only traverse ocean, and could not pass over land, reflecting the path that sediment transport would take.

Various functions of distance were evaluated, such as the classic "inverse square law", by which light attenuates, and inverse proportionality. These result in different levels of smoothing (as shown in Figure 3), ranging from very focussed impact hotspots at the discharge locations through to very evenly spread sediment impact throughout the modelled domain.

[1] Supplementary online material to Halpern (2008).

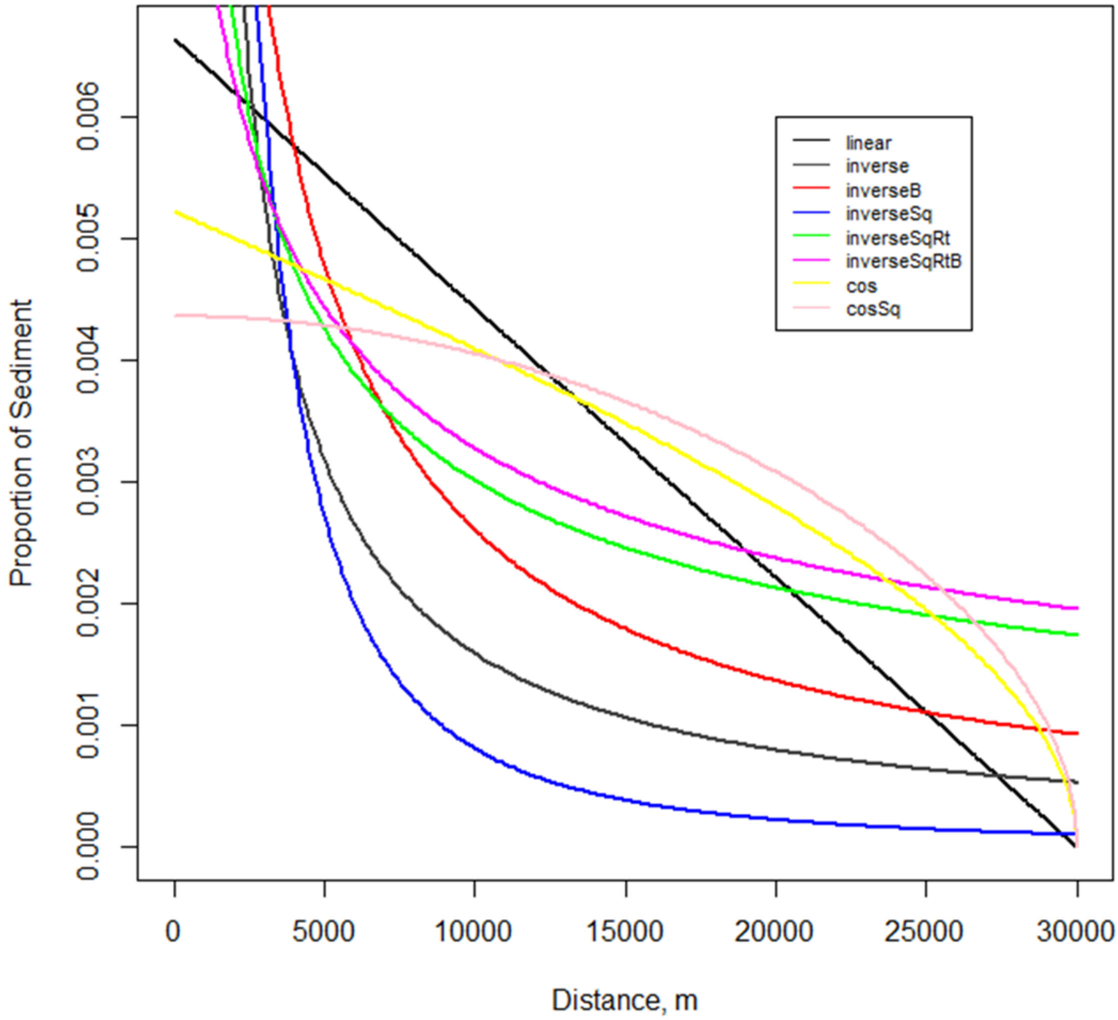


Figure 3. Sediment dispersal functions vary in the distance to which they transport sediment.

The extreme functions were considered unrealistic, and intermediate levels of smoothing were considered more appropriate to represent sediment impact patterns.

Two sediment dispersal functions were retained:

$$amount\ of\ sediment\ at\ distance\ = \frac{discharged\ total}{\sqrt{distance}+1000} \qquad \text{Equation 1}$$

$$amount\ of\ sediment\ at\ distance\ = \frac{discharged\ total}{(distance+1000)^2} \qquad \text{Equation 2}$$

Equation 1 is an inverse square root function (magenta line on graph in Figure 3) with the addition of the parameter 1000 in the denominator, which has the effect of removing the first 1000 metres of the distribution and thus reducing the amount of sediment in the immediate vicinity of the discharge. For example, the amount of sediment at a distance of 100 metres is estimated as the total discharge divided by the square root of 1100 metres, which is a smaller number than if the denominator was the square root of 100 metres.

Equation 2 (blue line on graph in Figure 3) is an inverse square function, also with the addition of a parameter in the denominator to remove the first 1000 metres of the distribution, reducing the intensity of ‘hotspots’ near river mouths. As the square of a distance is a larger number than the square root, the value of this function declines much more rapidly with distance than does Equation 1, resulting in more concentrated effects close to the point of discharge.

The sediment distributions generated by these diffusion functions are illustrated in Figure 4. At present we have no basis for selecting between these alternatives, so both are offered as potentially relevant to different situations.

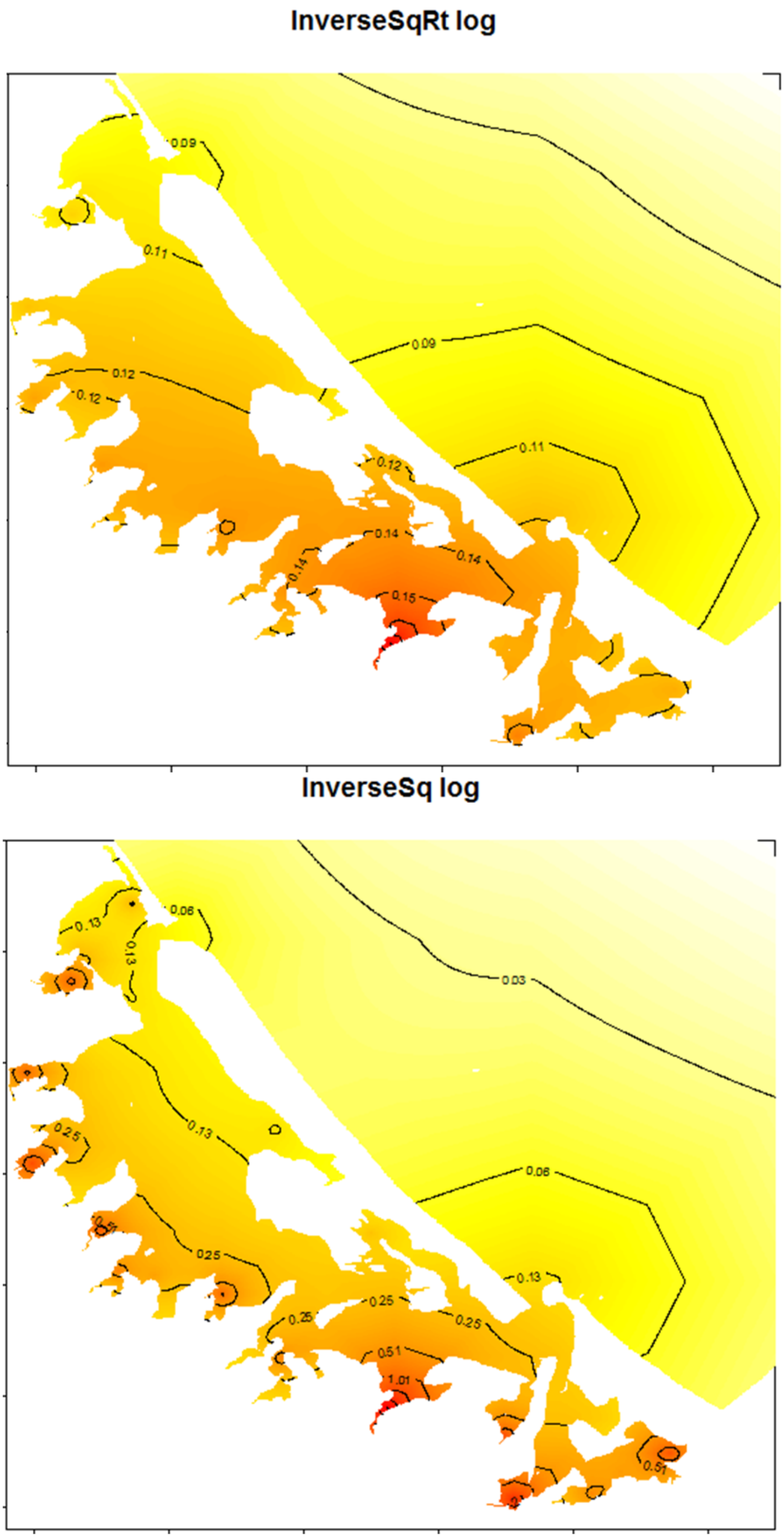


Figure 4. Sediment dispersal generated by inverse square root dispersion (top) and inverse square dispersion (bottom), log transformed for display.

Any point in the harbour may be exposed to sediment sourced from more than one river. The multiple rivers' influences need to be combined for all points in the harbour. The algorithm used to estimate the cumulative sediment load across the harbour domain from individual river mouths was as follows:

For each dispersion function:
For each river mouth:
Calculate by-ocean distances to each point in the domain (in ArcMap, Figure 5)
For each scenario:
Take the sediment discharge estimate for this river mouth (discharged total)
For each point in the domain:
Calculate the amount of sediment (using the dispersion function)
Sum the total sediment in the domain.

$$\sum amount\ of\ sediment$$

Scale the sediment at each point so that the total in the harbour equals the estimated total discharged from all rivers,

$$amount\ of\ sediment = amount\ of\ sediment * \frac{sediment\ discharge\ estimate}{\sum amount\ of\ sediment}$$

Sum the grids for each river mouth to get total sediment for each scenario.

R code implementing this algorithm is presented in Appendix 1.

Figure 5 illustrates the first step in the algorithm: the by-sea distances from a single river mouth (at the focus of the yellow area, indicated by a black crosshairs).

Scaling the sediment-per-point grid by the discharge estimate ensures that the total amount of sediment in the domain is equal to the total amount discharged at the river mouth. This implies that no sediment leaves the modelled domain, which is unrealistic. However, because the domain includes a large area of open ocean outside the harbour, it does not imply that all the sediment remains within the harbour.

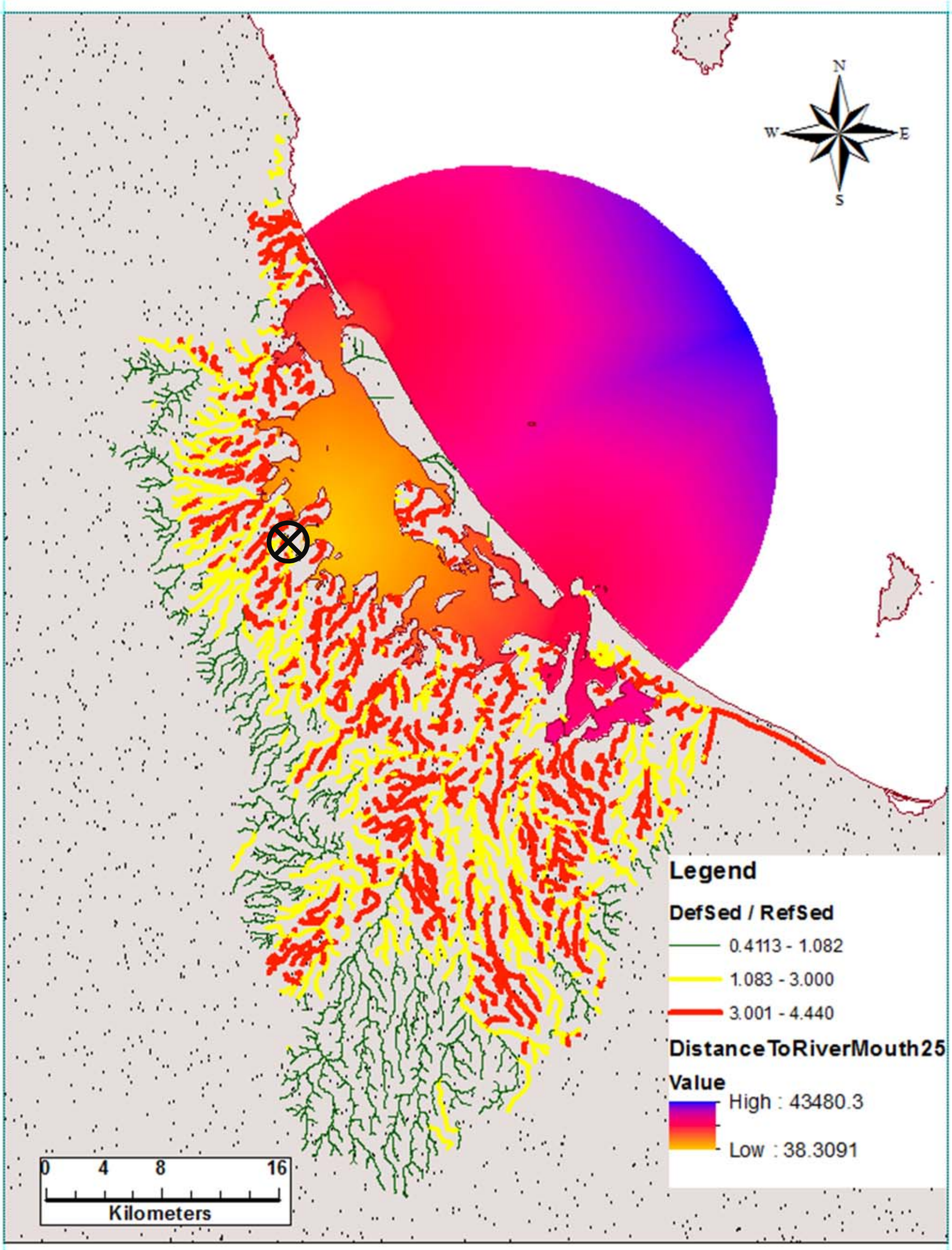


Figure 5. By-sea distance (coloured shading) from a single river mouth (black crosshairs). Colours of stream segments represent sediment increase between reference and contemporary states.

Figure 6 shows the sediment load estimates under reference state and contemporary state, as dispersed by the inverse square root function (Equation 1). Figures on the contour lines are in kg $m^{-2}y^{-1}$. These sediment load estimates are available as GIS raster layers: SedimentLoadInvSqRoot_Reference and SedimentLoadInvSqRoot_Contemp.

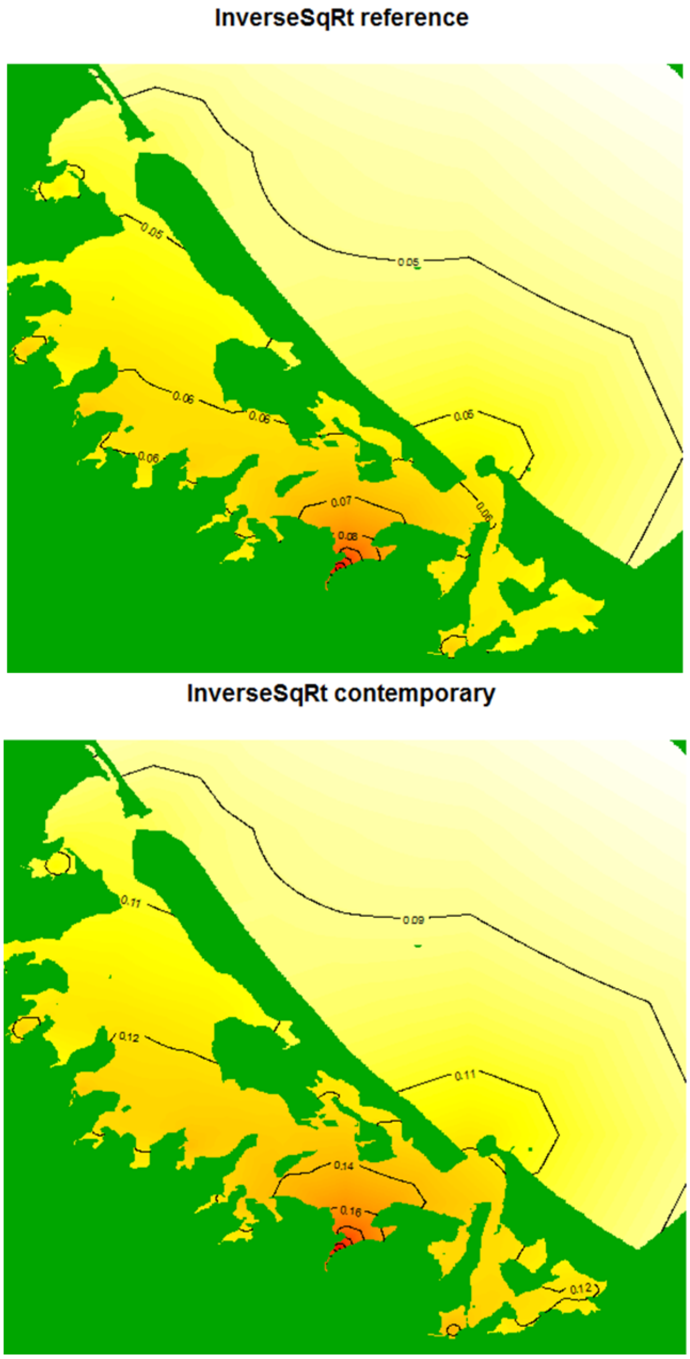


Figure 6. Reference (top) and contemporary (bottom) sediment load estimates for Tauranga Harbour, as distributed by inverse square root dispersion. Figures on the contour lines are in $kgm^{-2}y^{-1}$. These data are provided as GIS raster layers SedimentLoadInvSqRoot_Reference and SedimentLoadInvSqRoot_Contemporary.

Figure 7 shows the sediment levels under reference state and contemporary state, as dispersed by the inverse square function (Equation 2). Figures on the contour lines are in $kgm^{-2}y^{-1}$. These sediment load estimates are available as GIS raster layers: SedimentLoadInvSq_Reference and SedimentLoadInvSq_Contemp. While this inverse square dispersion appears to predict lower levels of sediment than the inverse square root dispersion, this appearance is due to the much higher peaks, which affect the colour scale. Note that the values labelled on the contour lines are in fact higher in the inverse square dispersion.

Figure 7. Reference (top) and contemporary (bottom) sediment load estimates for Tauranga Harbour, as distributed by inverse square dispersion. Figures on the contour lines are in $kgm^{-2}y^{-1}$. These data are provided as GIS raster layers SedimentLoadInvSq_Reference and SedimentLoadInvSq_Contemporary.

2.3. Conversion to pressure

The ecological pressure resulting from an increase in sediment levels could arise in a number of ways. For example, the pressure could be a function of the absolute difference in sedimentation levels, or of the relative difference in sedimentation levels. That is, an increase in sedimentation from 5 kgm^{-2} to 15 kgm^{-2} could be seen as a 10 kgm^{-2} increase, or a 3-fold increase. This has implications for the relative increase in pressure across different sites in the harbour, as shown by the contrast between the two plots shown in Figure 8 and in Figure 9. For each dispersion function, both absolute and relative differences have been retained for further consideration in the cumulative impact model.

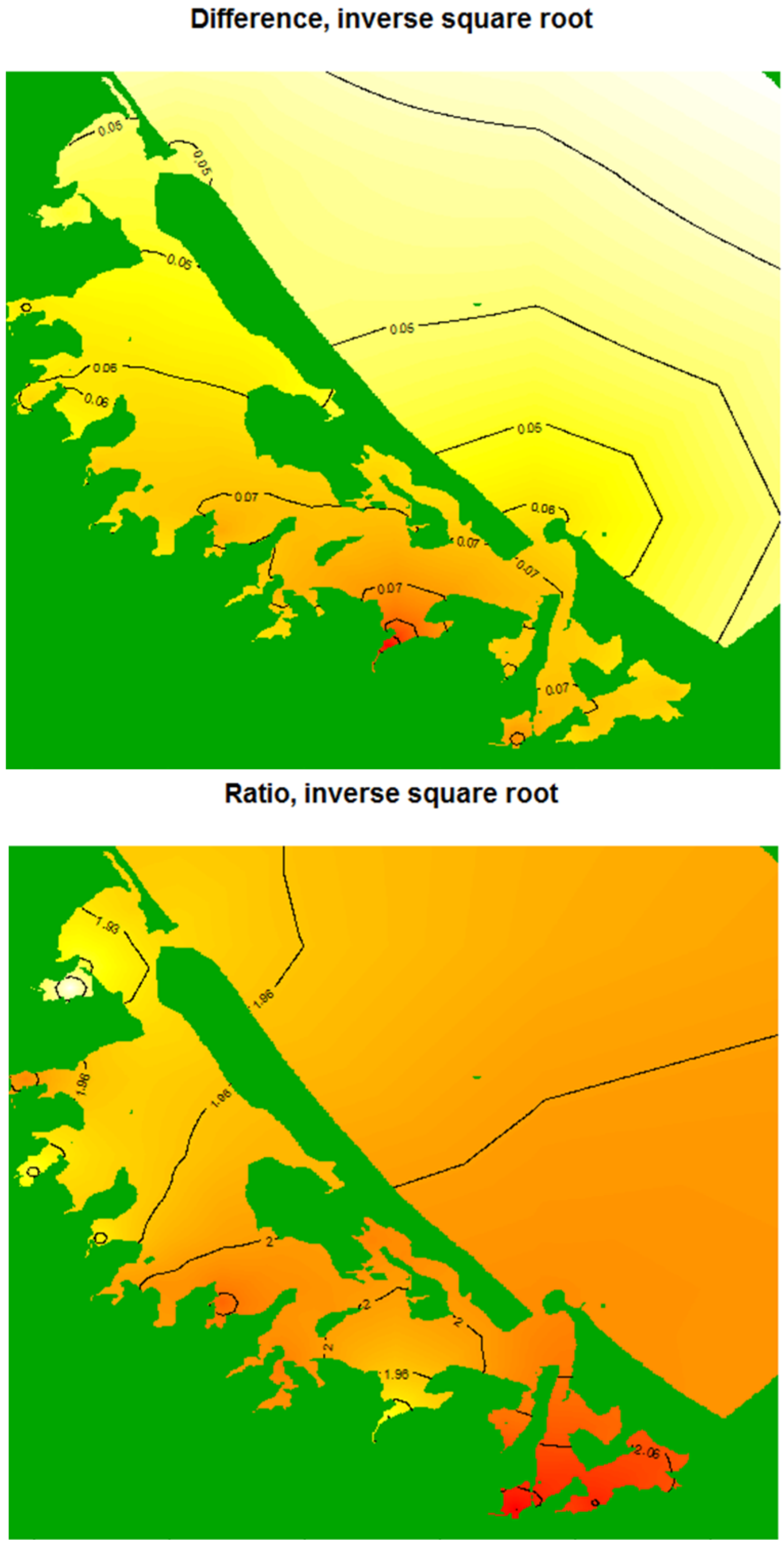
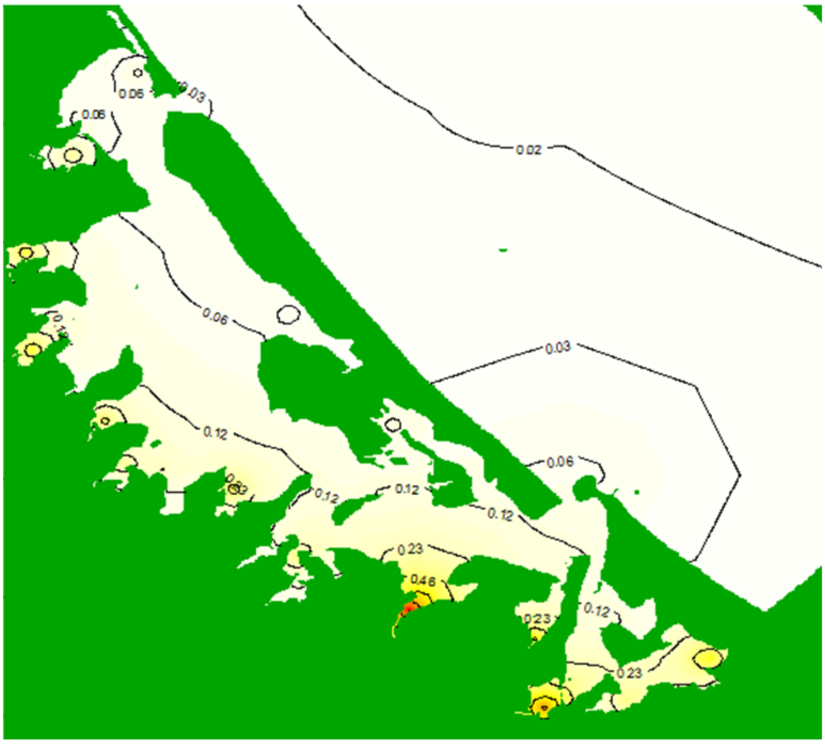


Figure 8. Absolute (top) and relative increase in sedimentation in Tauranga Harbour between reference and contemporary states, as dispersed by inverse square root function. Units are $kgm^{-2}y^{-1}$ difference (top) and ratio change (bottom).

Difference, inverse square



Ratio, inverse square

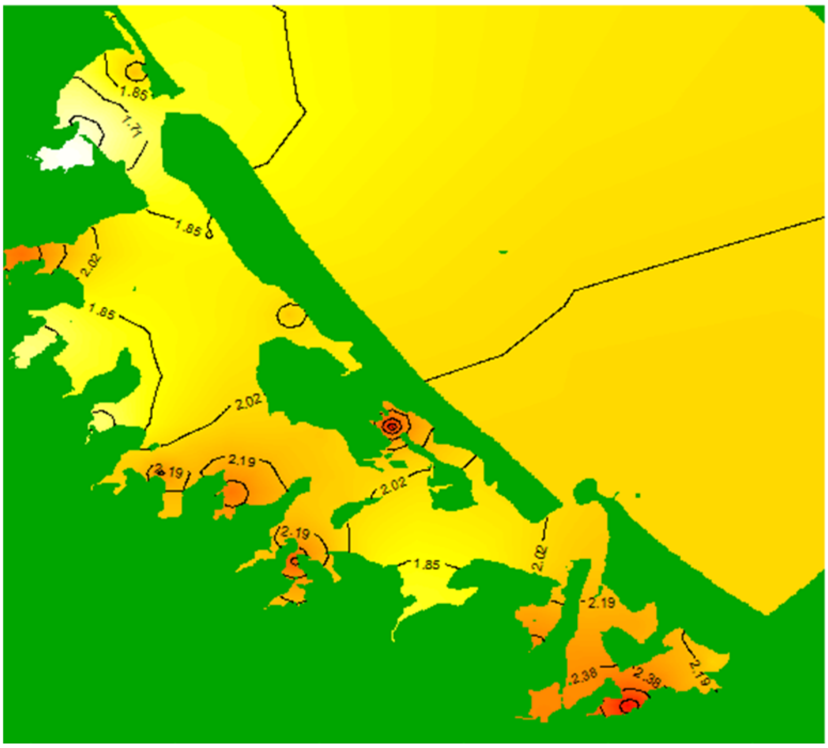


Figure 9. Absolute (top) and relative (bottom) increase in sedimentation in Tauranga Harbour between reference and contemporary states, as dispersed by inverse square function. Units are $kgm^{-2}y^{-1}$ difference (top) and ratio change (bottom).

For incorporation into a Halpern cumulative impacts model, each component impact such as this one is log-transformed and scaled between 0.0 and 1.0. The absolute sediment increase, and relative sediment increase, log-transformed and scaled 0 to 1 are shown in Figure 10. These sediment pressure estimates are available as GIS raster layers:

- SedimentPressureInvSqRoot_Difference
- SedimentPressureInvSqRoot_Ratio
- SedimentPressureInvSq_Difference
- SedimentPressureInvSq_Ratio.

With sediment increase considered in isolation, this log transformation does not affect the distribution of pressure, only the scale of values. It only becomes relevant when pressure due to sedimentation is combined or compared with other pressures, such as fishing or discharge of toxic chemicals, which will be done in a subsequent phase of this study.

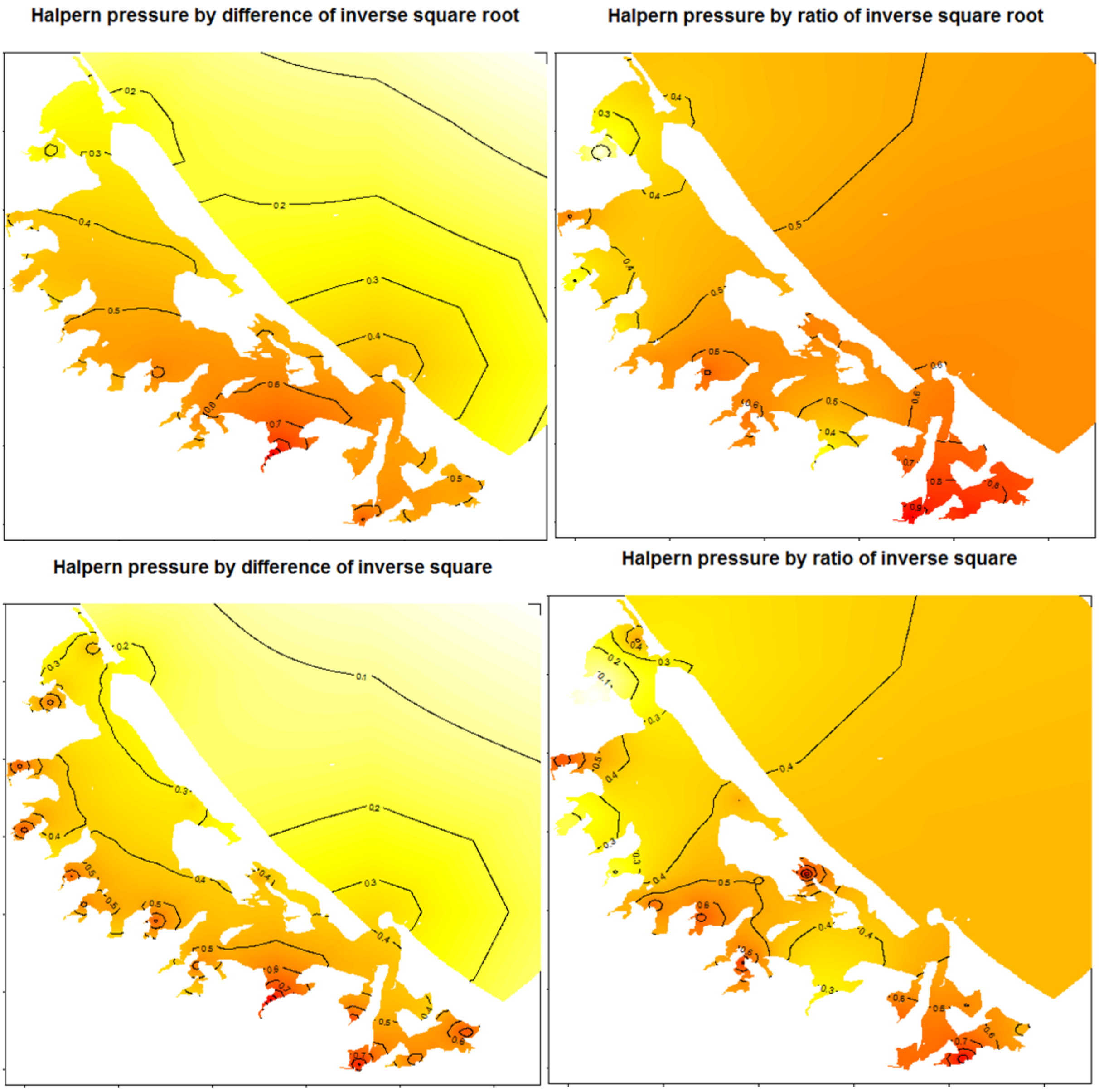


Figure 10. Absolute difference (left) and relative increase (right), for the inverse square root (top) and inverse square (bottom) dispersion functions. Effects are log-transformed and scaled 0-1. These sediment pressure estimates are available as GIS raster layers: SedimentPressureInvSqRoot_Difference, SedimentPressureInvSqRoot_Ratio, SedimentPressureInvSq_Difference, and SedimentPressureInvSq_Ratio.

3. CONCLUSIONS

Four sediment pressure layers were developed for Tauranga Harbour for use in a cumulative impact model. Differences between the four layers result from the dispersion function used (inverse square root versus inverse square) and the way ecological pressure was calculated (absolute difference versus relative difference). At present we have no basis for selecting between the alternate sediment pressure layers, so all four are offered as potentially relevant to different situations.

Future work will combine one of these sediment pressure layers with other layers of ecological pressure in Tauranga Harbour to estimate, and produce a map of, the cumulative impacts of multiple stressors on harbour ecosystems. The map can then be used both to identify areas and habitats within the harbour that are under particular pressure and to explore how the impacts might change under different scenarios such as changes in land use or new approaches to stormwater management.

This work represents an application of the Halpern model at a local scale, with the further intention of testing the outputs from the model against actual ecological data from the MTM ecological survey of Tauranga Harbour (Ellis *et al.* 2013). This will be the first time that such a validation has been attempted since the publication of Halpern's paper in 2008.

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5. APPENDIX

Appendix 1. Code developed to combine sediment load estimates from multiple rivers in Tauranga Harbour, and derive Halpern pressure components.

```
rotate = function(mat) t(mat[nrow(mat):1,,drop=FALSE])
scaling=read.csv('SediExits.txt')                      #This is outputs from a CLUES modeling run
sediRasters=dir(pattern='sedicost*',include.dirs=T)    #These are distances to each sediment exit (river
mouth)
sediRasters=sediRasters[-c(13,14)]

#Here we set up matrices to hold the distances scaled by the magnitude of the sediment load
inverseSqRtBTotMatrixREF=matrix(data=0,nrow=1458,ncol=1436)
inverseSqRtBTotMatrixDEF=matrix(data=0,nrow=1458,ncol=1436)
inverseSqTotMatrixREF=matrix(data=0,nrow=1458,ncol=1436)
inverseSqTotMatrixDEF=matrix(data=0,nrow=1458,ncol=1436)

for (sediRaster in sediRasters){
  setwd(paste('c:/projects/MTM/',sediRaster,sep=''))
  exitnum=as.numeric(substr(sediRaster,9,nchar(sediRaster)))
  r <- raster("w001001.adf")
  distance=as.matrix(r)
  rm(r)
  REFsedimentload=scaling$Sum_RefSed[which(scaling$OBJECTID==(exitnum+1))]
  DEFsedimentload=scaling$Sum_DefSed[which(scaling$OBJECTID==(exitnum+1))]

  distance[distance<0]=NA

#  image(rotate(distance))
```

```
  inverseSqRtBEffectREF = REFsedimentload/(distance+1000)^0.5
  inverseSqRtBEffectDEF = DEFsedimentload/(distance+1000)^0.5
  inverseSqEffectREF = REFsedimentload/(distance+1000)^2
  inverseSqEffectDEF = DEFsedimentload/(distance+1000)^2

  inverseSqRtBTotEffREF=sum(inverseSqRtBEffectREF,na.rm=T)
  inverseSqRtBTotEffDEF=sum(inverseSqRtBEffectDEF,na.rm=T)
  inverseSqTotEffREF=sum(inverseSqEffectREF,na.rm=T)
  inverseSqTotEffDEF=sum(inverseSqEffectDEF,na.rm=T)

  inverseSqRtBEffectREF=inverseSqRtBEffectREF*REFsedimentload/inverseSqRtBTotEffREF
  inverseSqRtBEffectDEF=inverseSqRtBEffectDEF*DEFsedimentload/inverseSqRtBTotEffDEF
  inverseSqEffectREF=inverseSqEffectREF*REFsedimentload/inverseSqTotEffREF
  inverseSqEffectDEF=inverseSqEffectDEF*DEFsedimentload/inverseSqTotEffDEF

  inverseSqRtBTotMatrixREF = inverseSqRtBTotMatrixREF + inverseSqRtBEffectREF
  inverseSqRtBTotMatrixDEF = inverseSqRtBTotMatrixDEF + inverseSqRtBEffectDEF
  inverseSqTotMatrixREF = inverseSqTotMatrixREF + inverseSqEffectREF
  inverseSqTotMatrixDEF = inverseSqTotMatrixDEF + inverseSqEffectDEF
}


rm(list=ls(pattern='Eff'))
rm(distance)
rm(REFsedimentload,DEFsedimentload,sediRaster)

#################################
```

```
#Plotting
#grids are 38.3m on a side = 1466.9 square metres.
#currently the load grids are in kilotons per grid cell
#so dividing by 1466.9 gives kilotons per square metre,
#then multiplying by 1000 gives tons per square metre.
#then multiplying by 1000 gives kg per square metre.
totmatrixDEFa=(inverseSqTotMatrixDEF/1466.9*1000*1000); DEFtita="InverseSq current"
totmatrixREFa=(inverseSqTotMatrixREF/1466.9*1000*1000); REFtita="InverseSq reference"

totmatrixDEFb=(inverseSqRtBTotMatrixDEF/1466.9*1000*1000); DEFtitb="InverseSqRt current"
totmatrixREFb=(inverseSqRtBTotMatrixREF/1466.9*1000*1000); REFtitb="InverseSqRt reference"

windows()
image(rotate((totmatrixDEFa)),col=rev(heat.colors(n=100)),
      zlim=c(min((totmatrixDEFa),na.rm=T),max((totmatrixDEFa),na.rm=T)),
      breaks=(seq(min((totmatrixDEFa),na.rm=T),max((totmatrixDEFa),na.rm=T),length.out=101)),
      xlim=c(.18,0.75),ylim=c(0.18,0.8))
contour(rotate((totmatrixDEFa)),add=T,drawlabels=T,levels=(seq(min((totmatrixDEFa),na.rm=T),max((totmatri
xDEFa),na.rm=T),length.out=10)),
        labels=round((seq(min((totmatrixDEFa),na.rm=T),max((totmatrixDEFa),na.rm=T),length.out=10)),2))
title(DEFtita)

image(rotate((totmatrixDEFb)),col=rev(heat.colors(n=100)),
      zlim=c(min((totmatrixDEFb),na.rm=T),max((totmatrixDEFb),na.rm=T)),
      breaks=(seq(min((totmatrixDEFb),na.rm=T),max((totmatrixDEFb),na.rm=T),length.out=101)),
      xlim=c(.18,0.75),ylim=c(0.18,0.8))
contour(rotate((totmatrixDEFb)),add=T,drawlabels=T,levels=(seq(min((totmatrixDEFb),na.rm=T),max((totmatri
xDEFb),na.rm=T),length.out=10)),
```

```
        labels=round((seq(min((totmatrixDEFb),na.rm=T),max((totmatrixDEFb),na.rm=T),length.out=10)),2))
title(DEFtitb)


windows()
image(rotate((totmatrixREFa)),col=rev(heat.colors(n=100)),
      zlim=c(min((totmatrixREFa),na.rm=T),max((totmatrixREFa),na.rm=T)),
      breaks=(seq(min((totmatrixREFa),na.rm=T),max((totmatrixREFa),na.rm=T),length.out=101)),
      xlim=c(.18,0.75),ylim=c(0.18,0.8))
contour(rotate((totmatrixREFa)),add=T,drawlabels=T,levels=(seq(min((totmatrixREFa),na.rm=T),max((totmatri
xREFa),na.rm=T),length.out=10)),
        labels=round((seq(min((totmatrixREFa),na.rm=T),max((totmatrixREFa),na.rm=T),length.out=10)),2))
title(REFtita)

image(rotate((totmatrixREFb)),col=rev(heat.colors(n=100)),
      zlim=c(min((totmatrixREFb),na.rm=T),max((totmatrixREFb),na.rm=T)),
      breaks=(seq(min((totmatrixREFb),na.rm=T),max((totmatrixREFb),na.rm=T),length.out=101)),
      xlim=c(.18,0.75),ylim=c(0.18,0.8))
contour(rotate((totmatrixREFb)),add=T,drawlabels=T,levels=(seq(min((totmatrixREFb),na.rm=T),max((totmatri
xREFb),na.rm=T),length.out=10)),
        labels=round((seq(min((totmatrixREFb),na.rm=T),max((totmatrixREFb),na.rm=T),length.out=10)),2))
title(REFtitb)

windows()
image(rotate(totmatrixDEFa-totmatrixREFa),col=rev(heat.colors(n=100)),zlim=c(min(totmatrixDEFa-
totmatrixREFa,na.rm=T),max(totmatrixDEFa-totmatrixREFa,na.rm=T)),
      breaks=(seq(min(c(totmatrixDEFa-totmatrixREFa),na.rm=T),max(c(totmatrixDEFa-
totmatrixREFa),na.rm=T),length.out=101)),xlim=c(.18,0.75),ylim=c(0.18,0.8))
```

```
contour(rotate((totmatrixDEFa-totmatrixREFa)),levels=exp(seq(min(log(totmatrixDEFa-
totmatrixREFa),na.rm=T),max(log(totmatrixDEFa-
totmatrixREFa),na.rm=T),length.out=10)),add=T,labels=round(exp(seq(min(log(totmatrixDEFa-
totmatrixREFa),na.rm=T),max(log(totmatrixDEFa-totmatrixREFa),na.rm=T),length.out=10)),2))
title('Difference, inverse square')

image(rotate(totmatrixDEFb-totmatrixREFb),col=rev(heat.colors(n=100)),zlim=c(min(totmatrixDEFb-
totmatrixREFb,na.rm=T),max(totmatrixDEFb-totmatrixREFb,na.rm=T)),
      breaks=(seq(min(c(totmatrixDEFb-totmatrixREFb),na.rm=T),max(c(totmatrixDEFb-
totmatrixREFb),na.rm=T),length.out=101)),xlim=c(.18,0.75),ylim=c(0.18,0.8))
contour(rotate((totmatrixDEFb-totmatrixREFb)),levels=exp(seq(min(log(totmatrixDEFb-
totmatrixREFb),na.rm=T),max(log(totmatrixDEFb-
totmatrixREFb),na.rm=T),length.out=10)),add=T,labels=round(exp(seq(min(log(totmatrixDEFb-
totmatrixREFb),na.rm=T),max(log(totmatrixDEFb-totmatrixREFb),na.rm=T),length.out=10)),2))
title('Difference, inverse square root')

windows()
image(rotate(totmatrixDEFa/totmatrixREFa),col=rev(heat.colors(n=100)),
      zlim=c(min(totmatrixDEFa/totmatrixREFa,na.rm=T),max(totmatrixDEFa/totmatrixREFa,na.rm=T)),

breaks=(seq(min(totmatrixDEFa/totmatrixREFa,na.rm=T),max(totmatrixDEFa/totmatrixREFa,na.rm=T),length.out=
101)),
      xlim=c(.18,0.75),ylim=c(0.18,0.8))
contour(rotate((totmatrixDEFa/totmatrixREFa)),add=T,

levels=exp(seq(min(log(totmatrixDEFa/totmatrixREFa),na.rm=T),max(log(totmatrixDEFa/totmatrixREFa),na.rm=T
),length.out=10)),
```

```
labels=round(exp(seq(min(log(totmatrixDEFa/totmatrixREFa),na.rm=T),max(log(totmatrixDEFa/totmatrixREFa),n
a.rm=T),length.out=10)),2))
title('Ratio, inverse square')

image(rotate(totmatrixDEFb/totmatrixREFb),col=rev(heat.colors(n=100)),
      zlim=c(min(totmatrixDEFb/totmatrixREFb,na.rm=T),max(totmatrixDEFb/totmatrixREFb,na.rm=T)),

breaks=(seq(min(totmatrixDEFb/totmatrixREFb,na.rm=T),max(totmatrixDEFb/totmatrixREFb,na.rm=T),length.out=
101)),
      xlim=c(.18,0.75),ylim=c(0.18,0.8))
contour(rotate((totmatrixDEFb/totmatrixREFb)),add=T,

levels=exp(seq(min(log(totmatrixDEFb/totmatrixREFb),na.rm=T),max(log(totmatrixDEFb/totmatrixREFb),na.rm=T
),length.out=10)),

labels=round(exp(seq(min(log(totmatrixDEFb/totmatrixREFb),na.rm=T),max(log(totmatrixDEFb/totmatrixREFb),n
a.rm=T),length.out=10)),2))
title('Ratio, inverse square root')

logdiffa=log(rotate(totmatrixDEFa-totmatrixREFa))
lograta=log(rotate(totmatrixDEFa/totmatrixREFa))
logdiffb=log(rotate(totmatrixDEFb-totmatrixREFb))
logratb=log(rotate(totmatrixDEFb/totmatrixREFb))

scadiffa=logdiffa-min(logdiffa,na.rm=T)
scadiffa=scadiffa/max(scadiffa,na.rm=T)
scadiffb=logdiffb-min(logdiffb,na.rm=T)
```

```
scadiffb=scadiffb/max(scadiffb,na.rm=T)

scarata=lograta-min(lograta,na.rm=T)
scarata=scarata/max(scarata,na.rm=T)
scaratb=logratb-min(logratb,na.rm=T)
scaratb=scaratb/max(scaratb,na.rm=T)

image(scarata,col=rev(heat.colors(n=100)),
      zlim=c(min(scarata,na.rm=T),max(scarata,na.rm=T)),

breaks=seq(min(scarata,na.rm=T),max(scarata,na.rm=T),length.out=101),xlim=c(.18,0.75),ylim=c(0.18,0.8))
contour(scarata,nlevels=10,add=T,drawlabels=T)
title('Halpern pressure by ratio of inverse square')

image(scadiffa,col=rev(heat.colors(n=100)),
      zlim=c(min(scadiffa,na.rm=T),max(scadiffa,na.rm=T)),

breaks=seq(min(scadiffa,na.rm=T),max(scadiffa,na.rm=T),length.out=101),xlim=c(.18,0.75),ylim=c(0.18,0.8))
contour(scadiffa,nlevels=10,add=T,drawlabels=T)
title('Halpern pressure by difference of inverse square')

image(scaratb,col=rev(heat.colors(n=100)),
      zlim=c(min(scaratb,na.rm=T),max(scaratb,na.rm=T)),

breaks=seq(min(scaratb,na.rm=T),max(scaratb,na.rm=T),length.out=101),xlim=c(.18,0.75),ylim=c(0.18,0.8))
contour(scaratb,nlevels=10,add=T,drawlabels=T)
title('Halpern pressure by ratio of inverse square root')
```

```
image(scadiffb,col=rev(heat.colors(n=100)),
      zlim=c(min(scadiffb,na.rm=T),max(scadiffb,na.rm=T)),

breaks=seq(min(scadiffb,na.rm=T),max(scadiffb,na.rm=T),length.out=101),xlim=c(.18,0.75),ylim=c(0.18,0.8))
contour(scadiffb,nlevels=10,add=T,drawlabels=T)
title('Halpern pressure by difference of inverse square root')
```

Halpern, B. S., Walbridge, S., Selkoe, K. A., Kappel, C. V., Micheli, F., D'Agrosa, C., . . . Fox, H. E. (2008). A global map of human impact on marine ecosystems. *Science*, *319*(5865), 948-952.