Auckland Regional Council
TE RAUHĪTANGA TAIAO

# Central Waitemata Harbour Contaminant Study

## USC-3 Model Description, Implementation and Calibration

December TR 2008/042

Auckland Regional Council
Technical Report No.042 December 2008
ISSN 1179-0504 (Print)
ISSN 1179-0512 (Online)
ISBN 978-1-877483-83-7

Technical Report, first edition.

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| Date: 12 December 2009 | Date: 18 December 2009 |

## Recommended Citation:

GREEN, M., 2008. Central Waitemata Harbour Contaminant Study. USC-3 Model Description, Implementation and Calibration. Prepared by NIWA Ltd for Auckland Regional Council. Auckland Regional Council Technical Report 2008/042.

# Central Waitemata Harbour Contaminant Study. USC-3 Model Description, Implementation and Calibration

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**Prepared for**
Auckland Regional Council

NIWA Client Report: HAM2007-167
December 2007

NIWA Projects: ARC06221, ARC07241 and ARC08250

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# Preface

The Waitemata Harbour is comprised of tidal creeks, embayments and the central basin. The harbour receives sediment and stormwater chemical contaminant run-off from urban and rural land from a number of subcatchments, which can adversely affect the ecology. An earlier study examined long-term accumulation of sediment and stormwater chemical contaminants in the Upper Waitemata Harbour. However, previously little was known about the existing and long-term accumulation of sediment and stormwater chemical contaminants in the central harbour. The Central Waitemata Harbour Contaminant Study was commissioned to improve understanding of these issues. This study is part of the 10-year Stormwater Action Plan to increase knowledge and improve stormwater management outcomes in the region. The work was undertaken by the National Institute of Water and Atmospheric Research (NIWA).

The scope of the study entailed:

1) field investigation,

2) development of a suite of computer models for

   a. urban and rural catchment sediment and chemical contaminant loads,

   b. harbour hydrodynamics and

   c. harbour sediment and contaminant dispersion and accumulation,

3) application of the suite of computer models to project the likely fate of sediment, copper and zinc discharged into the central harbour over the 100-year period 2001 to 2100, and

4) conversion of the suite of computer models into a desktop tool that can be readily used to further assess the effects of different stormwater management interventions on sediment and stormwater chemical contaminant accumulation in the central harbour over the 100-year period.

The study is limited to assessment of long-term accumulation of sediment, copper and zinc in large-scale harbour depositional zones. The potential for adverse ecological effects from copper and zinc in the harbour sediments was assessed against sediment quality guidelines for chemical contaminants.

The study and tools developed address large-scale and long timeframes and consequently cannot be used to assess changes and impacts from small subcatchments or landuse developments, for example. Furthermore, the study does not assess ecological effects of discrete storm events or long-term chronic or sub-lethal ecological effects arising from the cocktail of urban contaminants and sediment.

The range of factors and contaminants influencing the ecology means that adverse ecological effects may occur at levels below contaminant guideline values for individual chemical contaminants (i.e., additive effects due to exposure to multiple contaminants may be occurring).

Existing data and data collected for the study were used to calibrate the individual computer models. The combined suite of models was calibrated against historic sedimentation and copper and zinc accumulation rates, derived from sediment cores collected from the harbour.

Four scenarios were modelled: a baseline scenario and three general stormwater management intervention scenarios.

The baseline scenario assumed current projections (at the time of the study) of

- future population growth,
- future landuse changes,
- expected changes in building roof materials,
- projected vehicle use, and
- existing stormwater treatment.

The three general stormwater management intervention scenarios evaluated were:

1) source control of zinc by painting existing unpainted and poorly painted galvanised steel industrial building roofs;

2) additional stormwater treatment, including:

    - raingardens on roads carrying more than 20,000 vehicles per day and on paved industrial sites,
    - silt fences and hay bales for residential infill building sites and
    - pond / wetland trains treating twenty per cent of catchment area; and

3) combinations of the two previous scenarios.

## International Peer Review Panel

The study was subject to internal officer and international peer review. The review was undertaken in stages during the study, which allowed incorporation of feedback and completion of a robust study. The review found:

- a state-of-the-art study on par with similar international studies,
- uncertainties that remain about the sediment and contaminant dynamics within tidal creeks / estuaries, and
- inherent uncertainties when projecting out 100 years.

## Key Findings of the Study

Several key findings can be ascertained from the results and consideration of the study within the context of the wider Stormwater Action Plan aim to improve stormwater outcomes:

- Henderson Creek (which drains the largest subcatchment and with the largest urban area, as well as substantial areas of rural land) contributes the largest loads of sediment, copper and zinc to the Central Waitemata Harbour. The second largest loads come from the Upper Waitemata Harbour.

- Substantial proportions of the subcatchment sediment, copper and zinc loads are accumulating in the Henderson, Whau, Meola and Motions tidal creeks and in the Shoal Bay, Hobson Bay and Waterview embayments.

- Central Waitemata Harbour bed sediment concentrations of copper and zinc are not expected to reach toxic levels based on current assumptions of future trends in urban landuse and activities.

- Zinc source control targeting industrial building roofs produced limited reduction of zinc accumulation rates in the harbour because industrial areas cover only a small proportion of the catchment area and most unpainted galvanised steel roofs are expected to be replaced with other materials within the next 25 to 50 years.

- Given that the modelling approach used large-scale depositional zones and long timeframes, differences can be expected from the modelling projections and stormwater management interventions contained within these reports versus consideration of smaller depositional areas and local interventions. (For example, whereas the study addresses the Whau River as a whole, differences exist within parts of the Whau River that may merit a different magnitude or type of intervention than may be inferred from considering the Whau River and its long-term contaminant trends as a whole.) As a consequence, these local situations may merit further investigation and assessment to determine the best manner in which to intervene and make improvements in the short and long terms.

## Research and Investigation Questions

From consideration of the study and results, the following issues have been identified that require further research and investigation:

- Sediment and chemical contaminant dynamics within tidal creeks.

- The magnitude and particular locations of stormwater management interventions required to arrest sediment, copper and zinc accumulation in tidal creeks and embayments, including possible remediation / restoration opportunities.

- The fate of other contaminants derived from urban sources.

- The chronic / sub-lethal effects of marine animal exposure to the cocktail of urban contaminants and other stressors such sediment deposition, changing sediment particle size distribution and elevated suspended sediment loads.

- Ecosystem health and connectivity issues between tidal creeks and the central basin of the harbour, and the wider Hauraki Gulf.

## Technical reports

The study has produced a series of technical reports:

Technical Report TR2008/032
Central Waitemata Harbour Contaminant Study. Landuse Scenarios.

Technical Report TR2008/033
Central Waitemata Harbour Contaminant Study. Background Metal Concentrations in Soils: Methods and Results.

Technical Report TR2008/034
Central Waitemata Harbour Contaminant Study. Harbour Sediments.

Technical Report TR2008/035
Central Waitemata Harbour Contaminant Study. Trace Metal Concentrations in Harbour Sediments.

Technical Report TR2008/036
Central Waitemata Harbour Contaminant Study. Hydrodynamics and Sediment Transport Fieldwork.

Technical Report TR2008/037
Central Waitemata Harbour Contaminant Study. Harbour Hydrodynamics, Wave and Sediment Transport Model Implementation and Calibration.

Technical Report TR2008/038
Central Waitemata Harbour Contaminant Study. Development of the Contaminant Load Model.

Technical Report TR2008/039
Central Waitemata Harbour Contaminant Study. Predictions of Stormwater Contaminant Loads.

Technical Report TR2008/040
Central Waitemata Harbour Contaminant Study. GLEAMS Model Structure, Setup and Data Requirements.

Technical Report TR2008/041
Central Waitemata Harbour Contaminant Study. GLEAMS Model Results for Rural and Earthworks Sediment Loads.

Technical Report TR2008/042
Central Waitemata Harbour Contaminant Study. USC-3 Model Description, Implementation and Calibration.

Technical Report TR2008/043
Central Waitemata Harbour Contaminant Study. Predictions of Sediment, Zinc and Copper Accumulation under Future Development Scenario 1.

Technical Report TR2008/044
Central Waitemata Harbour Contaminant Study. Predictions of Sediment, Zinc and Copper Accumulation under Future Development Scenarios 2, 3 and 4.

Technical Report TR2009/109
Central Waitemata Harbour Contaminant Study. Rainfall Analysis.

# Contents

# 1 Executive Summary

The main aim of the Central Waitemata Harbour (CWH) Contaminant Study is to model contaminant (zinc, copper) and sediment accumulation within the CWH for the purposes of, amongst other things, identifying significant contaminant sources, and testing efficacy of stormwater treatment and zinc source control of industrial roofs.

This report describes the USC-3 ("Urban Stormwater Contaminant") model, which has been developed specifically for the Study. The model, which functions as a decision-support scheme, predicts sedimentation and accumulation of contaminants (including zinc and copper) in the bed sediments of estuaries on the "planning timescale", which is decades and greater.

The original USC model was applicable to simple estuaries that consist of a single "settling zone" (where settling of suspended sediments and associated contaminants is enhanced). The USC-2 model was developed to apply to more complex estuaries consisting of a number of interlinking settling zones and "secondary redistribution areas" (where waves and/or currents mobilise and redisperse sediments and associated contaminants). The secondary redistribution areas were limited to low energy areas. The USC-3 model has been developed for the Central Waitemata Harbour Contaminant Study. It also applies to more complex harbours, although the secondary redistribution areas are no longer limited to low energy.

Because the USC-3 model makes explicit use of estimates of future heavy metal and sediment loads from the catchment, it is truly a predictive model compared to, say, simply extrapolating past heavy metal concentrations in harbour bed sediments. Because future sediment and heavy metal loads will change according to management practice and policy, model predictions can be used to compare performance of competing development scenarios and to evaluate efficacy of zinc source control of industrial roofs.

In addition, the model tracks the movement of sediments and contaminants, which enables links between sources (on the land) and sinks (in the estuary) to be identified. This facilitates targeting of management intervention and planning.

As for model **capability**:

- Predictions are made at the scale of the subestuary, which corresponds to km-scale compartments of the harbour with common depth, exposure and bed-sediment particle size. The catchment is divided into sub-catchments on a similar scale. Each sub-catchment discharges through one outlet to the harbour.
- The model simulates the deposition of sediment that occurs under certain conditions (eg, in sheltered parts of the harbour, or on days when there is no wind), and the erosion of sediment that occurs under other conditions (eg, in parts of the harbour where there are strong tidal currents or on days when it is windy). It also simulates the dispersal of sediments that are eroded from the land when it rains and discharged into the harbour with freshwater run-off.

- Heavy metals are attached to sediments. Hence, heavy metals are discharged into the estuary when it rains together with the land-derived sediments that are eroded from the catchment. Heavy metals are also eroded, dispersed and deposited inside the estuary together with the estuarine sediments. Heavy metals are accumulated in the sediment layers that form in the harbour by deposition, and they are placed in suspension in the water column when sediment layers are eroded.
- Concentrations of heavy metals in the surface mixed layer are evaluated in the model by taking account of mixing of the bed sediment, which has the effect of reducing extreme concentration gradients in the bed sediment that would otherwise occur in the absence of mixing.
- The principal model output is the change through time of the concentration of heavy metals in the surface mixed layer of the estuary bed sediments, which can be compared with sediment-quality guidelines to determine ecological effects.

Also described in this report is the particular way in which the model has been **implemented** for the study. This consists of specifying the sediment particle sizes to be addressed in the model, defining subestuaries and sub-catchments, specifying the weather time series used to drive the model, defining the way land-derived sediments and associated heavy metals are to be fed into the harbour at the sub-catchment outlets, evaluating the various terms that control sediment and associated heavy metal transport and deposition inside the harbour, and defining the way heavy metal concentration in the estuarine bed-sediment surface mixed layer is to be evaluated.

The main drivers of the **model behaviour** are demonstrated by way of a simple analogy. The harbour can be viewed as a bucket (for the purposes of the analogy, ignore the fact that the harbour comprises a number of subestuaries) that contains sediment and metal, and sediment and metal from another bucket – the catchment – gets tipped into the harbour bucket as the simulation proceeds. At the start of the simulation, metal is present in the harbour bucket at some average concentration. If metal is present in the catchment bucket at the same concentration, then the concentration in the harbour bucket will not change as the simulation proceeds. On the other hand, if metal is present in the sub-catchment at a greater (or lesser) concentration, then the concentration in the harbour bucket will increase (or decrease) as the simulation proceeds. If there is enough time and if the metal concentration in the catchment bucket does not change, then the concentration in the harbour bucket will attain the same concentration as in the catchment bucket, which is termed "equilibrium". All other things being equal, the rate at which equilibrium is approached varies directly with how far from equilibrium the harbour is, that is, the difference between the metal concentration in the harbour and the metal concentration in sediment from the catchment.

The role of the mixing depth is also explained and explored. The greater the mixing depth relative to the thickness of any deposited sediment layer, the more pre-existing sediment will be incorporated in the new surface mixed layer, and the smaller will be the change in metal concentration in the new surface mixed layer as a result. This equates to a slower change in metal concentration in the surface mixed layer over time under repeated deposition events. Given a particular set of sediment and heavy metal inputs from the catchment, the model predictions of heavy metal concentration in the surface mixed layer of the estuary bed sediments are most sensitive to variations in the mixing depth. In effect, the mixing depth determines the "inertia" of the system.

The **calibration** of the model is described, which was achieved by running the model for the historical period 1940 to 2001, with sediment and metal (zinc, copper) inputs from the catchment appropriate to that period. The aim of the calibration process was to adjust various terms in the USC-3 model for which no measurements exist, so that its hindcasts of the historical period came to match observations from that same period.

The first part of the calibration process consisted of adjusting (1) the areas over which sediments may deposit and (2) the rate at which sediments and metals are lost to both pre-defined and "dynamic" sinks, until realistic sedimentation rates and patterns of sediment dispersal were obtained. The calibrated model produced a convincing picture of, firstly, the fate of sediments from the sub-catchments surrounding the Central Waitemata Harbour and, secondly, the sources of sediments depositing in the subestuaries. Hindcast sedimentation rates were compared to radioisotopic sedimentation rates, which were determined by radioisotopic dating of sediment cores. The hindcast sedimentation rates were generally smaller than the radioisotopic sedimentation rates, however the patterns of sedimentation were similar in all important respects.

The second part of the calibration process consisted of adjusting a "metal retention factor" until a good match was obtained between hindcast and observed zinc and copper concentrations in the bed sediments of three test subestuaries at the end of the historical period. The metal retention factor, which is the fraction of the metal load emanating from each sub-catchment that is attached to the corresponding sediment particulate load, was used to reduce the concentration at which metals are delivered to the harbour in the model. A value for the factor was chosen to yield a time-rate-of-change of metal concentrations over the historical period that ended in target concentrations being achieved. The term (1 – metal retention factor) may be interpreted as representing the loss of metal to a dissolved phase and/or the attachment of metal to very fine sediment that never settles in the harbour, neither of which is explicitly accounted for in the USC-3 model. The metal retention factor may also be accounting for errors in predictions of sediment and metal run-off from the catchment. Subsequent work has provided experimental confirmation of the value of the metal retention factor determined in the calibration.

The USC-3 model is now ready to make predictions for future catchment development scenarios.

# 2 Introduction

Modelling and empirical data indicate that stormwater contaminants are rapidly accumulating in the highly urbanised side branches of the Central Waitemata Harbour (CWH). However, there is no clear understanding of the fate of contaminants exported from these side branches into the main body of the harbour, or that of contaminants discharged directly into the harbour.

The main aim of the study is to model contaminant (zinc, copper) and sediment accumulation within the CWH for the purposes of, amongst other things, identifying significant contaminant sources, and testing efficacy of stormwater treatment and zinc source control of industrial roofs.

## 2.1 Study aims

The study aims to:

- predict contaminant loads based on past, present and future land use and population growth for each sub-catchment discharging into the CWH, allowing for stormwater treatment and zinc source control of industrial roofs;
- predict dispersal and accumulation (or loss) of sediment and stormwater contaminants in the CWH;
- calibrate and validate the dispersal/accumulation model;
- apply the various models to predict catchment contaminant loads and accumulation of copper, zinc and sediment in the CWH under specific scenarios that depict various combinations of projected land use/population growth, stormwater treatment efficiency, and zinc source control of industrial roofs;
- determine from the model predictions the relative contributions of sediment and contaminant from individual sub-catchments and local authorities;
- provide an assessment of the environmental consequences of model outputs;
- provide technical reports on each component of the work; and
- provide a desktop application suitable for use by ARC personnel.

## 2.2 Model suite

The study centres on the application of three models that are linked to each other in a single suite:

- The **GLEAMS** sediment-generation model, which predicts **sediment** erosion from the land and transport down the stream channel network. Predictions of sediment supply are necessary because, ultimately, sediment eroded from the land dilutes the concentration of contaminants in the bed sediments of the harbour, making them less harmful to biota[1].

- The **CLM** contaminant/sediment-generation model, which predicts **sediment** and **contaminant** concentrations (including zinc, copper) in stormwater at a point source, in urban streams, or at end-of-pipe where stormwater discharges into the receiving environment.
- The **USC-3** (Urban Stormwater Contaminant) contaminant/sediment accumulation model, which predicts **sedimentation** and **accumulation of contaminants** (including zinc, copper) in the bed sediments of the estuary. Underlying the USC-3 model is yet another model: an estuarine sediment-transport model, which simulates the dispersal of contaminants/sediments by physical processes such as tidal currents and waves.

## 2.3 This report

This report describes the USC-3 ("Urban Stormwater Contaminant") model, which has been developed specifically for the Central Waitemata Harbour Contaminant Study.

The model, which functions as a decision-support scheme, predicts sedimentation and accumulation of contaminants (including zinc and copper) in the bed sediments of estuaries on the "planning timescale", which is decades and greater.

The implementation of the USC-3 model for the Central Waitemata Harbour is also described. This consists of specifying the sediment particle sizes to be addressed in the model, defining subestuaries and sub-catchments, specifying the weather time series used to drive the model, defining the way land-derived sediments and associated heavy metals are to be fed into the harbour at the sub-catchment outlets, evaluating the various terms that control sediment and associated heavy metal transport and deposition inside the harbour, and defining the way heavy metal concentration in the estuarine bed-sediment surface mixed layer is to be evaluated.

Other information required to drive the model, including harbour bed-sediment initial conditions (eg, particle size, metal concentration in the surface mixed layer, sub-catchment sediment and metal loads), varies depending on the particular scenario being addressed. This information is not treated as part of the model implementation; instead, it is reported where the scenario model runs are reported.

The main drivers of the model behaviour are demonstrated, which includes a discussion of the mixing depth and the sensitivity of model predictions to this parameter. Given a particular set of sediment and metal inputs from the catchment, the model predictions of metal concentration in the surface mixed layer of the estuary bed sediments are most sensitive to variations in the mixing depth. In effect, the mixing depth determines the "inertia" of the system.

[1] We use the term "contaminant" herein to mean chemical contaminants such as zinc and copper, and we refer to "sediments" separately.

Finally, three sets of terms are adjusted to calibrate the model. These are the area over which deposition in each subestuary may occur, the rate at which sediments and metals are lost to both pre-defined and "dynamic" sinks, and a "metal retention factor". Calibration is achieved by running the model for the historical period 1940 to 2001, with sediment and metal inputs from the catchment appropriate to that period. The aim of the calibration process is to adjust various terms in the USC-3 model so that hindcasts of sediment dispersal, sedimentation, and zinc and copper accumulation over the historical period come to match observations from that same period.

# 3 Model Description and Overview

## 3.1 Introduction

The USC-3 ("Urban Stormwater Contaminant") contaminant-accumulation model predicts sedimentation and accumulation of contaminants (including zinc and copper) in the bed sediments of estuaries on the "planning timescale", which is decades and greater. The model is physically-based, and functions as a decision-support scheme.

The model is intended to support decision-making by predicting various changes in the harbour bed sediments associated with catchment development scenarios that will cause changes in sediment and contaminant loads in the run-off from the catchment. The model provides:

- Predictions of sedimentation in different parts of the estuary, which may be compared and used in an assessment of sediment effects.
- Predictions of the change in bed composition over time, which reflects degradation of habitat (eg, change of sandy substrate to silt), and which may bring associated ecological degradation (eg, mangrove spread, loss of shellfish beds).
- Predictions of the accumulation of heavy metals in the surface mixed layer of the estuary bed sediments, which may be compared to sediment-quality guidelines to infer associated ecological effects.
- An explicit analysis of the links between sediment sources in the catchment and sediment sinks in the estuary. This type of analysis effectively links "subestuary effects" to "sub-catchment causes", thus showing where best management practices on the land can be most effectively focused. Without an understanding of the link between source and sink, assessment of sediment sources on the land lacks any effects context.

The original USC model was applicable to simple estuaries that consist of a single "settling zone" (where settling of suspended sediments and associated contaminants is enhanced). A small embayment fed by a single tidal creek is an example of where this model would apply. The USC model was initially applied in Lucas and Hellyers Creeks in the Auckland region.

The USC-2 model was developed to apply to more complex estuaries consisting of a number of interlinking settling zones and "secondary redistribution areas" (where waves and/or currents mobilise and redisperse sediments and associated contaminants). The secondary redistribution areas were limited to low energy. The USC-2 model was initially applied in the Upper Waitemata Harbour for the Auckland Regional Council.

The USC-3 model has been developed for the Central Waitemata Harbour Contaminant Study. It also applies to more complex harbours, although the secondary redistribution areas are no longer limited to low energy.

The USC-3 model requires as inputs:

- estimates of future heavy metal loads from the land;
- estimates of future sediment loads and particle sizes from the land; and
- estimates of the natural metal concentrations on catchment soils.

Parameters required by the model include:

- bed-sediment mixing depth in the harbour; and
- bed-sediment active layer thickness in the harbour.

Patterns of sediment transport and deposition in the harbour, including the way land-derived sediments are discharged and dispersed in the harbour during and following rainstorms, need to be known.

Model initial conditions include:

- present day particle size distribution of harbour bed sediments; and
- present day metal concentrations on harbour bed sediments.

Assumptions need to be made regarding the association of heavy metals with sediment particulate matter.

The model is calibrated against annual-average sedimentation rates in the harbour and metal concentrations in harbour bed sediments.

Because the model makes explicit use of estimates of future heavy metal and sediment loads from the catchment, it is truly a predictive model compared to, say, simply extrapolating past heavy metal concentrations in harbour bed sediments. Because future sediment and heavy metal loads will change according to management practice and policy, model predictions can be used to compare performance of competing development scenarios and to evaluate efficacy of intervention options.

In addition, the model tracks the movement of sediments and contaminants, which enables links between sources (on the land) and sinks (in the estuary) to be identified. This facilitates targeting of management intervention.

## 3.2 Model overview

The USC-3 model makes predictions of sedimentation, change in bed-sediment composition and accumulation of heavy metals in the surface mixed layer of estuary bed sediments over a 100-year timeframe, given sediment and heavy metal inputs from the surrounding catchment on that same timeframe.

Predictions are made at the scale of the subestuary, which corresponds to km-scale compartments of the harbour with common depth, exposure and bed-sediment particle size.

The catchment is divided into sub-catchments on a similar scale. Each sub-catchment discharges through one outlet to the harbour.

A long-term weather sequence is used to drive the model over time. The weather sequence that drives the model may be constructed randomly or biased to represent worst-case or best-case outcomes. The weather sequence may also reflect the anticipated effects of climate change.

The model simulates the deposition of sediment that occurs under certain conditions (eg, in sheltered parts of the harbour, or on days when there is no wind), and the erosion of sediment that occurs under other conditions (eg, in parts of the harbour where there are strong tidal currents or on days when it is windy). It also simulates the dispersal of sediments and contaminants eroded from the land when it rains and discharged (or "injected") into the harbour with freshwater run-off.

Physically-based "rules" are used by the model to simulate the injection into the harbour of land-derived sediments and contaminants from the catchment when it is raining. The particular rule that is applied depends on the weather and the tide at the time. Sediment/contaminant is only injected into the harbour when it is raining.

Another set of physically-based rules is used to simulate the erosion, transport and deposition of estuarine sediments and associated contaminants inside the estuary by tidal currents and waves. "Estuarine" sediments and contaminants refers to all of the sediment and contaminant that is already in the harbour on the day at hand, and includes all of the land-derived sediment and contaminant that was discharged into the harbour previous to the day at hand.

The model has a mixed timestep, depending on the particular processes being simulated:

- For the injection into the harbour of sediment that is eroded from the land when it rains the model timestep is two complete tidal cycles (referred to herein as "one-day").
- For the resuspension of estuarine bed sediments by waves and tidal currents the model timestep is also one-day.
- Each day an injection and/or resuspension event may occur, or no event may occur. The rainfall, wind and tide range on the day govern whether or not an event occurs. The rainfall, wind and tide range on each day is determined by the long-term weather sequence that drives the model.
- The rainfall, wind and tide range on the day govern the way land-derived sediment is injected into the harbour. At the end of the day on which injection occurs, land-derived sediment may be settled onto the bed in any part of the harbour, may be in suspension in any part of the harbour, or may be lost to sinks. The part of the land-derived sediment load that is in suspension at the end of the injection day is further dispersed throughout the harbour on days following the injection day until it is all

accounted for by settlement to the bed (in any part of the harbour) and loss to sinks. This may take different lengths of time to achieve, depending on where the dispersal/deposition process begins at the end of the injection day. Hence, the timestep for this process is variable.

- The wind and tide range on the day govern the way estuarine bed sediment is resuspended. At the end of the day on which resuspension occurs, resuspended sediment may be settled onto the bed in any part of the harbour, may be in suspension in any part of the harbour, or may be lost to sinks. The part of the resuspended sediment load that is in suspension at the end of the resuspension day is further dispersed throughout the harbour on days following the resuspension day until it is all accounted for by settlement to the bed (in any part of the harbour) and loss to sinks. This may take different lengths of time to achieve, depending on where the dispersal/deposition process begins at the end of the resuspension day. Hence, the timestep for this process is variable.

The model builds up the set of predictions by "adding together"; over the duration of the simulation, injection and resuspension events and the subsequent dispersal and deposition of injected and resuspended sediment. The simulation duration is typically 50 or 100 years. In essence, the model simply moves sediment/contaminant between the various sub-catchments and various subestuaries each time it rains (according to the rules), and between the various subestuaries to account for the action of waves of tidal currents (again, according to the rules).

Mass is conserved in the model.

A key feature of the model is that the bed sediment in each subestuary is represented as a column comprising a series of layers, which evolves as the simulation proceeds. The sediment column holds both sediments and contaminants.

The bed sediment evolves in the model by addition of layers when sediment is deposited, and by removal of those same layers when sediment is eroded. At any given time and in any given subestuary, there may be zero layers in the sediment column, in which case the bed sediment consists of "pre-existing" bed sediment only. This corresponds to the initial conditions mentioned above. Layer thicknesses may vary, depending on how they develop during the simulation.

Both land-derived and estuarine sediments may be composed of multiple constituent particle sizes (eg, clay, silt, fine sand, sand). The proportions of the constituent particle sizes in each layer of the sediment column may vary, depending on how they develop in the simulation. This results in finer or coarser layers as the case may be.

Under some circumstances, the constituent particle sizes in the model interact with each other and under other circumstances they act independently of each other.

For example, the erosion rate is determined by a weighted-mean particle size of the bed sediment that reflects the combined presence of the constituent particle sizes. This has a profound consequence: if the weighted-mean particle size of the bed sediment increases, it becomes more difficult to erode, and so becomes "armoured" as a whole. This reduces the erosion of **all** of the constituent particle sizes, including the finer fractions, which otherwise might be very mobile. The bed-sediment weighted-mean particle size is calculated over the thickness of the bed-sediment "active layer".

In contrast, the individual particle sizes, once released from the bed by erosion and placed in suspension in the water column, are dispersed independently of any other particle size that may also be in suspension. Dispersion of suspended sediments is in fact very sensitive to particle size, which has a profound consequence: the constituent particle sizes may "unmix" once in suspension and go their separate ways. This can cause some parts of the harbour to, for instance, accumulate finer sediments over time and other parts to accumulate coarser sediments. This is reflected in a progressive fining or coarsening, as the case may be, of the bed sediment. The model accounts for this process.

In some parts of the harbour or under some weather sequences, sediment layers may become permanently sequestered by the addition of subsequent layers of sediment, which raises the level of the bed and results in a positive sedimentation rate. In other parts of the harbour or under other weather sequences, sediment layers may be exhumed, resulting in a net loss of sediment, which gives a negative sedimentation rate. Other parts of the harbour may be purely transportational, meaning that erosion and sedimentation balance, over the long-term. However, even in that case, it is possible (with a fortuitous balance) for there to be a progressive coarsening or fining of the bed sediments.

Because model predictions are sensitive to sequences of events (as just described), a series of 100-year simulations is run, with each simulation in the series driven by a different, randomly-chosen weather sequence. The predictions from the series of simulations are averaged to yield one average prediction of contaminant accumulation over the 100-year duration. Each weather sequence in the series is constructed so that long-term weather statistics are recovered.

Heavy metals are "attached" to sediments. Hence, heavy metals are discharged into the estuary when it rains together with the land-derived sediments that are eroded from the catchment. Heavy metals are also eroded, transported and deposited inside the estuary together with the estuarine sediments. Heavy metals are accumulated in the sediment layers that form in the harbour by deposition, and they are placed in suspension in the water column when sediment layers are eroded.

Heavy metals may be differently associated with the different constituent sediment particle sizes. Typically, heavy metals are preferentially attached to fine sediment particles. This means that where fine particles accumulate in the harbour, so too will the attached heavy metals accumulate. On the other hand, there may be certain parts of the harbour where heavy metals are not able to accumulate. Bands of fine sediment in the sediment column may also be accompanied by higher concentrations of heavy metals, and vice versa.

The principal model output is the change through time of the concentration of heavy metal in the surface mixed layer of the estuary bed sediments, which can be compared with sediment-quality guidelines to determine ecological effects.

Concentration of heavy metal in the surface mixed layer is evaluated in the model by taking account of mixing of the bed sediment, which has the effect of reducing extreme concentration gradients in the bed sediment that would otherwise occur in the absence of mixing.

Mixing of the bed sediment is caused by bioturbation and/or disturbance by waves and currents. Any number of layers in the sediment column that have been deposited since the beginning of the simulation may be included in the mixed layer. Mixing may also extend down into the pre-existing bed sediment (ie, the bed sediment as specified by the model initial conditions).

### 3.2.1 Comparison with the USC-2 model

The USC-2 model allowed for erosion of bed sediment by waves and currents between rainfall events, but only in a limited way. In effect, only sediment / contaminant that was deposited in the immediately-previous rainfall event was allowed to be eroded and redispersed/redeposited throughout the harbour in any given between-rainfall period. This had the effect of "ratcheting up" deposition, as sediment deposited during previous events became sequestered, which is appropriate in sheltered basins, such as the Upper Waitemata Harbour. This will not be acceptable in the case of more open water bodies, such as the Central Waitemata Harbour.

The USC-3 model works differently. It allows erosion of any portion of the bed sediment that has been deposited since the beginning of the simulation, including all of it. The USC-3 model does in fact allow for the net change in bed level over the duration of the simulation to be negative (erosional regime). However, as implemented for the CWH study, this is prevented by not allowing erosion to occur below a certain basement level that is set at the start of the simulation. A subestuary may be purely transportational over the duration of the simulation, meaning that the net change in sediment level can be zero.

# 4 Model Details

## 4.1 Characteristics of special subestuaries

### 4.1.1 Tidal creeks

Sediments may not be resuspended inside those subestuaries designated as tidal creeks. Sediments resuspended elsewhere in the harbour by waves and currents that get deposited inside tidal creeks will therefore be sequestered, which will enhance the accumulation of sediments and contaminants in the tidal creeks. This is expected, since tidal creeks are sheltered from the waves (in particular) and currents that could otherwise erode them, and thereby reduce accumulation, on a daily basis. Tidal creeks also attenuate (ie, retain a portion of) the land-derived sediment load that passes through them, carried by freshwater run-off on the way to the main body of the harbour. The attenuated part of the land-derived sediment load deposits in the tidal creek.

### 4.1.2 Sinks

Sediments and contaminants deposited in those subestuaries designated as sinks also may not be subsequently removed by resuspension. (Unlike tidal creeks, there is no special arrangement for attenuating land-derived sediment loads that pass through sinks.)

### 4.1.3 Deep channels

Sediments are not allowed to erode from or deposit in subestuaries designated as deep channels.

## 4.2 Resuspension of estuarine bed sediments by waves and currents

### 4.2.1 Introduction

Every day, estuarine sediments and their associated contaminants may be resuspended (in the USC-3 model) by tidal currents and waves, and redispersed and redeposited elsewhere in the estuary. "Estuary sediments" here includes all the land-derived sediments injected into the harbour prior to the day at hand.

The USC-3 model predicts this on the basis of the tide range and the wind speed and direction. The tide range controls the strength of tidal currents and possibly the residual circulation patterns. The wind speed and direction control the generation of waves, which are principally responsible for resuspension of bed sediments. In addition, the wind may generate currents that are superimposed on tidal currents and that therefore affect patterns of sediment dispersal.

Daily movement of sediments and attached contaminants in the harbour is controlled by *ED50, R5*, *R5SUSP* and *RFS*, which are determined by the DHI estuary model suite[2].

- *ED50* is an erosion depth on the resuspension day.
- *R5* and *R5SUSP* describe sediment dispersal and deposition on the resuspension day.
- *RFS* describes sediment dispersal and deposition on the days following the resuspension day.

Table 1 summarises the meaning of the terms *ED50*, *R5*, *R5SUSP* and *RFS*. Refer to this table during the following detailed description.

Figure 1 shows how *ED50*, *R5*, *R5SUSP* and *RFS* are applied. Refer to this figure during the following detailed description

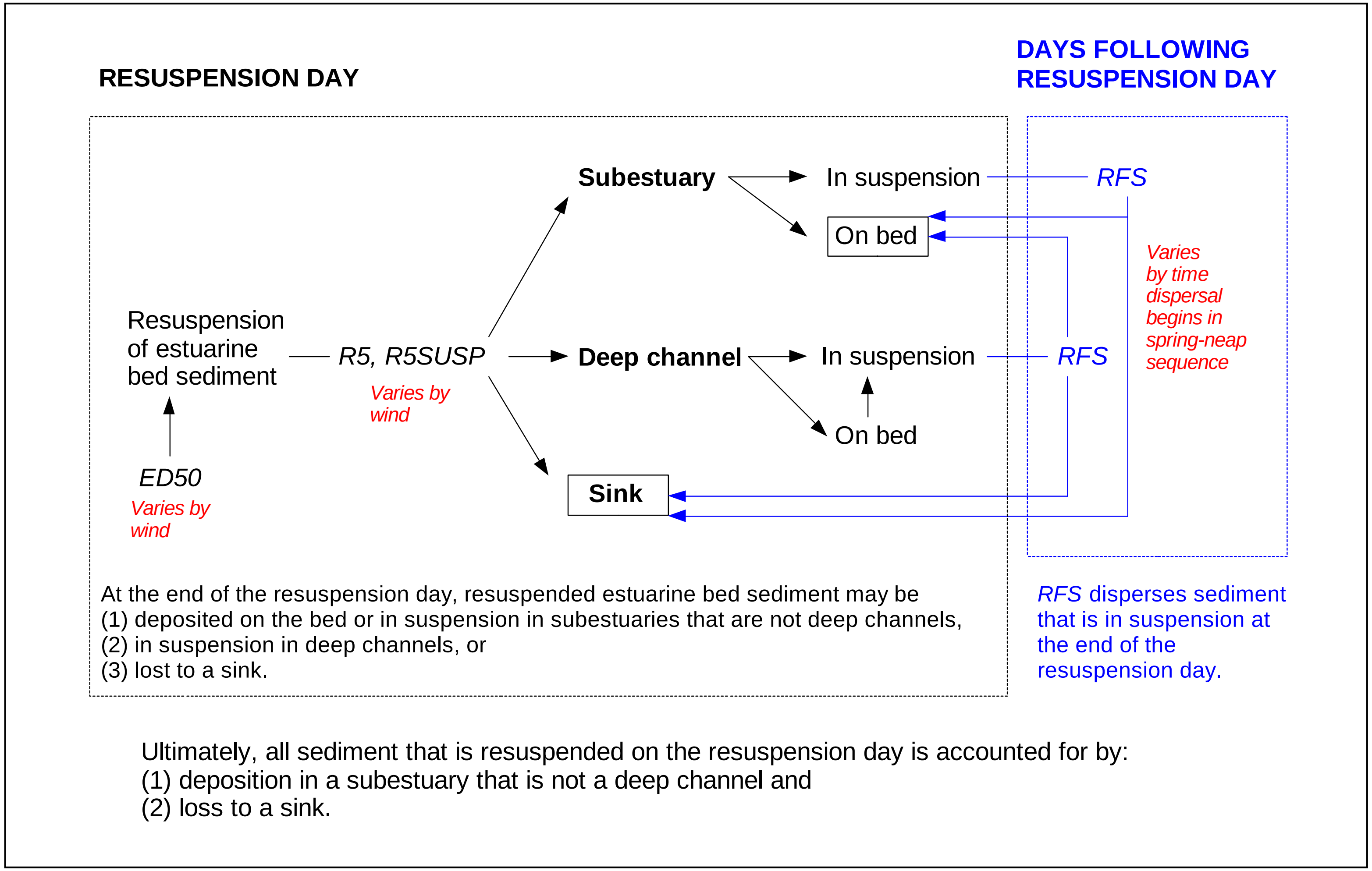
**Table 1**
Summary of the meaning of the terms *ED50*, *R5*, *R5SUSP* and *RFS*.

| Term | Applies to | Describes | Varies with | Specified for | Applied at | Special conditions |
|---|---|---|---|---|---|---|
| ED50 | Estuary bed sediment | Erosion | Weighted-mean particle size of bed sediment ($D_{50}$) | Every subestuary | End of resuspension day | Zero in tidal creeks, sinks, deep channels |
| R5 | Estuary bed sediment | Dispersal | Size of constituent particle ($D_{con}$) | Every origin subestuary ↦ destination subestuary combination | End of resuspension day | Cannot deposit sediment in deep channel |
| R5SUSP | Estuary bed sediment | Dispersal | Size of constituent particle ($D_{con}$) | Every origin subestuary ↦ destination subestuary combination | End of resuspension day | All sediment in deep channels is left in suspension |

[2] The "DHI estuary model suite" comprises the DHI Water and Environment (DHI) MIKE3 FM hydrodynamic model, the DHI MIKE3 MT sediment transport model, and the SWAN wave model. Further details are given in the chapter in this report on implementation of the USC-3 model.

| Term | Applies to | Describes | Varies with | Specified for | Applied at | Special conditions |
|---|---|---|---|---|---|---|
| RFS | Estuary bed sediment that is left in suspension by R5SUSP | Dispersal | Size of constituent particle ($D_{con}$) | Every origin subestuary ↦ destination subestuary combination | Until all sediment left in suspension at end of resuspension day deposits or is lost to sink | Cannot deposit sediment in deep channel |

**Figure 1**
Summary of the way the terms ED50, R5, R5SUSP and RFS are applied.



### 4.2.2 Details

#### 4.2.2.1 ED50

In each subestuary in the USC-3 model domain, excluding those subestuaries designated as tidal creeks, sinks and deep channels, tidal currents and waves each day may resuspend sediments to a depth of *ED50*.

- *ED50* is determined for each subestuary using the DHI model suite for each of a number of bed-sediment weighted-mean particle sizes (termed $D_{50}$ in the following) under each of a number of environmental conditions (eg, tides, winds). A separate simulation is run for each origin subestuary. Each DHI simulation duration is one-day (two complete tidal cycles), and each simulation begins with estuarine sediments in the subestuary at hand stationary (ie, on the bed).
- *ED50* is an erosion depth: it is evaluated at the end of each one-day timestep, it is averaged over the subestuary, and it has units of metres. *ED50* may be zero.
- *ED50* = 0 in subestuaries designated as tidal creeks, sinks or deep channels.

#### 4.2.2.2 R5 and R5SUSP

Once eroded from the bed and placed in suspension, each constituent particle size disperses and settles in the USC-3 model according to its own settling speed and as though it is the only particle size in suspension. In this way, the various particle sizes in the bed can become "uncoupled" from each other once in suspension.

The fraction of constituent particle size *iparticle* that is eroded from subestuary *kestorigin* and deposited in subestuary *kestdestination* by the end of the resuspension day is given by $R5_{particle,kestorigin,kestdestination}$. The total mass of constituent particle size *iparticle* that comes to be deposited in subestuary *kestdestination* by the end of the resuspension day is given by:

$$\sum_{kestorigin=1}^{nest}(SEDIMENTMASS_{iparticle,kestorigin} \times R5_{iparticle,kestorigin,kestdestination})$$

where $SEDIMENTMASS_{iparticle,kestorigin}$ is the mass of constituent particle size *iparticle* that is released by resuspension in origin subestuary *kestorigin* by erosion to a depth of $ED50_{iparticle,kestorigin}$. This is explained in detail in a later section, when the layering of the bed sediment is explained.

The fraction of constituent particle size *iparticle* that is eroded from subestuary *kestorigin* and that remains in suspension in subestuary *kestdestination* at the end of the resuspension day is given by $R5SUSP_{iparticle,kestorigin,kestdestination}$. The total mass of constituent particle size *iparticle* that is in suspension in subestuary *kestdestination* at the end of the resuspension day is given by:

$$\sum_{kestorigin=1}^{nest}(SEDIMENTMASS_{iparticle,kestorigin} \times R5SUSP_{iparticle,kestorigin,kestdestination})$$

- If *kestdestination* corresponds to a deep channel, then *R5* is forced to 0, since sediments are not allowed to settle to the bed in deep channels.
- *R5* and *R5SUSP* between them account for all of the sediment that is resuspended in each origin subestuary:

$$\sum_{kestdestination=1}^{nest}(R5_{iparticle,kestorigin,kestdestination} + R5SUSP_{iparticle,kestorigin,kestdestination}) = 1$$

- For every combination of origin subestuary and destination subestuary, *R5* and *R5SUSP* are determined using the DHI model suite for each of a number of constituent particle sizes under each of a number of environmental conditions (eg, tides, winds). A separate simulation is run for each origin subestuary. Each DHI simulation duration is one-day (two complete tidal cycles), and each simulation begins with estuarine sediments in the subestuary at hand stationary (ie, on the bed).
- *R5* is evaluated at the end of each one-day timestep. It is averaged over the subestuary, and is dimensionless. *R5* may vary according to particle size, which permits different particle sizes to disperse independently around the harbour, once released by erosion from the bed sediment.
- *R5SUSP* is evaluated at the end of each one-day timestep. It is averaged over the subestuary, and is dimensionless. *R5SUSP* may vary according to particle size, which permits different particle sizes to disperse independently around the harbour.

#### 4.2.2.3 RFS

The term *RFS* governs the fate of sediment that remains in suspension at the end of the resuspension day.

- For every combination of origin subestuary and destination subestuary, *RFS* is determined using the DHI model suite for each of a number of constituent particle sizes under each of a number of environmental conditions (eg, tides, winds). A separate simulation is run for each origin subestuary. Each DHI simulation begins with a unit load of estuarine sediment in suspension in the origin subestuary at hand. Each simulation is run until all of the suspended sediment is accounted for by settlement to the bed (anywhere in the harbour) or loss to a sink.
- *RFS* is averaged over the subestuary, and is dimensionless. *RFS* may vary according to particle size, which permits different particle sizes to disperse independently around the harbour.

$RFS_{iparticle,kestorigin,kestdestination}$ is the fraction of constituent particle size *iparticle* that is in suspension in origin subestuary *kestorigin* at the end of the resuspension day and that ultimately gets deposited in destination subestuary *kestdestination*.

Following the application of *RFS* in the USC-3 model, all of the estuarine sediment that was eroded from the bed of each origin subestuary (which cannot include subestuaries designated as tidal creeks, sinks or deep channels) on resuspension day is deposited in a destination subestuary (which can be the same as the origin subestuary, but which cannot be a deep channel).

Following the application of *RFS*, the total mass of estuarine sediment of constituent particle size *iparticle* deposited in subestuary *kestdestination* is given by:

$$\sum_{kestorigin=1}^{nest}(SEDIMENTMASS_{iparticle,kestorigin} \times R5_{iparticle,kestorigin,kestdestination}) +$$

$$\sum_{kestorigin=1}^{nest}(SEDIMENTMASS_{iparticle,kestorigin} \times R5SUSP_{iparticle,kestorigin,kestdestination} \times$$

$$RFS_{iparticle,kestorigin,kestdestination})$$

#### 4.2.2.4 Heavy metals

The same terms *R5*, *R5SUSP* and *RFS* govern the movements of heavy metals associated with estuarine sediments by tidal currents and waves.

Using the same terms *R5*, *R5SUSP* and *RFS* to describe the dispersal of both sediments and heavy metals following erosion of the bed sediment has the effect of "locking" the heavy metals to the sediments. Thus, as different sediment particle sizes disperse independently around the harbour in the USC-3 model, so the heavy metals associated with the different particle sizes also disperse.

## 4.3 Injection into the harbour of sediments and contaminants when it rains

### 4.3.1 Introduction

During and in the immediate aftermath of rainstorms, sediment is eroded from the land, and heavy metals such as zinc and copper are scoured and flushed from various reservoirs and sources. There are two types of source: natural and anthropogenic. Natural metals derive from the soils of both rural and urban areas. Anthropogenic metals derive from human activity in urban areas.

The heavy metals (both natural and anthropogenic) released by rainfall travel down through the stream channel and stormwater networks, initially in solution, but increasingly in suspension, attached to particulate suspended sediments in the stormwater. Sediments and contaminants that find their way into the main body of the harbour will be dispersed and deposited by waves and currents.

The USC-3 model does three things each time the long-term weather sequence presents a day on which rainfall occurs: (1) Land-derived sediment and contaminant loads for that day are evaluated at the base of the catchment (BOC); (2) Land-derived sediment and contaminant loads for that day are evaluated at the edge of the main body of the harbour (EMB). For some stormwater outfalls, BOC is the same as EMB. For others, sediments and heavy metals have to be transferred through tidal creeks to get to EMB. During this step, heavy metals get attached to sediment particulate matter. (3) The sediment loads with heavy metals attached are discharged from EMB into the main body of the harbour, and dispersed and deposited.

### 4.3.2 Land-derived sediment and contaminant loads at BOC

$LANDSEDIMENT\underline{BOC}MASS_{jcatch,iparticle}$ is the sediment load at the base of sub-catchment *jcatch* split amongst constituent particle sizes. These loads will vary by rainfall. Here, "*BOC*" means at the base of the sub-catchment.

- For the implementation of the USC-3 model in the Central Waitemata Harbour, the GLEAMS model is used to predict sediment run-off from rural areas. Hence, for this implementation, "GLEAMS sediments" is synonymous with "sediments from sources in rural areas". Note that GLEAMS provides daily sediment loads for each sub-catchment split by constituent particle size. The exact way these are prepared for input into the USC-3 model is described in the next chapter.
- Also for this implementation, the CLM contaminant-generation model is used to predict sediment from urban areas. Hence "CLM sediments" is synonymous with "sediments from sources in urban areas". Note that the CLM provides annual sediment loads, also split by constituent particle size. The exact way these are prepared for input into the USC-3 model is described in the next chapter.

The corresponding heavy metal load from each sub-catchment on the day at hand is $LANDHEAVYMETAL\underline{BOC}MASS_{jcatch}$. Again, "*BOC*" means at the base of the sub-catchment.

- The CLM contaminant-generation model provides annual anthropogenic (urban) heavy metal loads for each sub-catchment, split by constituent sediment particle size that carries the load.
- Natural heavy metal loads, which get added to anthropogenic loads to form total loads, are calculated by multiplying the total (rural plus urban) sediment load by the concentration at which natural heavy metals are carried on soils. This is described in detail in the next chapter.

### 4.3.3 Transfer of land-derived sediment and contaminant loads to EMB

Stormwater outfalls in the CWH catchment may discharge along the fringes of the main body of the harbour (there are no outfalls in the interior of the Central Waitemata Harbour) or they may discharge into freshwater creeks. Freshwater creeks may, in turn, drain into the main body of the harbour through relatively extensive tidal creeks, or they may, in effect, discharge directly along the fringes of the main body. Another possibility is that outfalls may discharge at the head of tidal creeks.

The way heavy metals become attached to land-derived particulate sediments depends on the route they take to the harbour.

For instance, geochemical processes in tidal creeks associated with the mixing between fresh and saline water may accelerate the attachment of zinc to sediment particulate matter. On the other hand, zinc may remain primarily in the dissolved phase – with very little attachment to sediment – in stormwater that discharges directly along the fringes of the main body of the harbour.

Sediments that pass through tidal creeks that drain into the main body of the harbour may be subjected to flocculation, which causes settlement in the tidal creek before reaching the estuary main body. This will also result in sequestration in the bed sediment within the tidal creek of any attached heavy metals. This results in a so-called "attenuation" – or reduction – of the sediment and contaminant loads between BOC and EMB. The degree of attenuation depends on the hydrodynamics of the tidal creek, which is largely dependent on the interaction between the freshwater discharge from the land and the saline water. In the extreme case, the freshwater discharge may be so large, under very heavy rainfall, that the tidal creek acts a simple extension of the freshwater drainage network, jetting the sediment/contaminant load directly into the main body of the estuary.

The aim, then, in this step is to convert (1) $LANDSEDIMENT\underline{BOC}MASS_{jcatch,iparticle}$ into $LANDSEDIMENT\underline{EMB}MASS_{jcatch,\ iparticle}$ and (2) $LANDHEAVYMETAL\underline{BOC}MASS_{jcatch}$ into $LANDHEAVYMETAL\underline{EMB}MASS_{jcatch,\ iparticle}$ The second conversion will also deal with the attachment of heavy metals to sediment particulate matter. The particular scheme used to accomplish these conversions depends on where the outfall discharges, as follows.

#### 4.3.3.1 Outfalls that discharge into freshwater creeks that in turn discharge directly into the main body of the harbour

**Conversion 1**. In this case, there is no load attenuation and so $LANDSEDIMENT\underline{BOC}MASS_{jcatch,iparticle} = LANDSEDIMENT\underline{EMB}MASS_{jcatch,\ iparticle}$.

**Conversion 2**. $LANDHEAVYMETAL\underline{BOC}MASS_{jcatch}$ is converted to $LANDHEAVYMETAL\underline{EMB}MASS_{jcatch,\ iparticle}$ by using a set of attachment factors:

$LANDHEAVYMETAL\underline{EMB}MASS_{jcatch,\ iparticle} = LANDHEAVYMETAL\underline{BOC}MASS_{jcatch} \times ATTACH_{jcatch,iparticle}$.

The attachment factors partition the heavy metal load amongst the various constituent particle sizes, which has the effect of locking the heavy metals to particulate sediment. The amount of heavy metal remaining in the dissolved phase at EMB is given by:

$$(1-\sum_{iparticle=1}^{nparticle} ATTACH_{jcatch,iparticle})LANDHEAVYMETALBOCMASS_{jcatch,iparticle}$$

Any heavy metal that remains in the dissolved fraction at EMB is lost from the system. That is, the USC-3 model does not treat any dissolved metals in the harbour.

#### 4.3.3.2 Outfalls that discharge directly into the main body of the harbour

Conversion 1. As above, there is no load attenuation and so $LANDSEDIMENT\underline{BOC}MASS_{jcatch,iparticle} = LANDSEDIMENT\underline{EMB}MASS_{jcatch,\ iparticle}$.

Conversion 2. As above, $LANDHEAVYMETAL\underline{BOC}MASS_{jcatch}$ is converted to $LANDHEAVYMETAL\underline{EMB}MASS_{jcatch,\ iparticle}$ by using a set of attachment factors. Again, some portion of the heavy metal load may remain in the dissolved phase at EMB, which will be lost from the system.

#### 4.3.3.3 Outfalls that discharge into the main body through a tidal creek

Conversion 1. The attenuation of the land-derived sediment loads in the tidal creek is now accounted for by applying the factor $RTC_{subestuary,jcatch,iparticle}$, where *subestuary* refers to a subestuary that has been designated as a tidal creek and *jcatch* refers to the sub-catchment that discharges into that tidal creek subestuary.

Table 2 summarises the meaning of the term *RTC*. Refer to this table during the following detailed description.

**Table 2**

Summary of the meaning of the term *RTC*.

| Term | Applies to | Describes | Varies with | Specified for | Applied at |
|---|---|---|---|---|---|
| *RTC* | Land-derived sediment | Attenuation of sediment load in tidal creek | Size of constituent particle ($D_{con}$) | Every sub-catchment that discharges into a subestuary that is defined as a tidal creek | End of injection day |

*RTC* is the fraction of sediment load $LANDSEDIMENT\underline{BOC}MASS_{jcatch,iparticle}$ presented at the base of the catchment that passes through the tidal creek and emerges at the edge of the main body of the estuary. *RTC* is dimensionless. Hence:

$LANDSEDIMENT\underline{EMB}MASS_{jcatch,\ iparticle} = LANDSEDIMENT\underline{BOC}MASS_{jcatch,iparticle} \times RTC_{subestuary,jcatch,iparticle}$.

Note that *RTC* may vary by constituent particle size, reflecting the influence of particle size on particle dynamics, and by rainfall, reflecting the influence of freshwater discharge on tidal creek dynamics.

Conversion 2. $LANDHEAVYMETAL\underline{BOC}MASS_{jcatch}$ is converted to $LANDHEAVYMETAL\underline{BOC}MASS_{jcatch,\ iparticle}$ using a set of attachment factors as above. Also as above, some fraction of the heavy metal load may not become attached to particulate matter, which results in loss from the system. Note that the attachment factors here yield the heavy metal attached to particle sizes at BOC, not EMB (which was the case previously). $LANDHEAVYMETAL\underline{BOC}MASS_{jcatch,\ iparticle}$ so created is then transferred through the tidal creek by using the same value of *RTC* that was used to transfer sediment through the tidal creek:

$LANDHEAVYMETAL\underline{EMB}MASS_{jcatch,\ iparticle} = LANDHEAVYMETAL\underline{BOC}MASS_{jcatch,iparticle} \times RTC_{subestuary,jcatch,iparticle}$.

Note that the portion of the sediment and heavy metal loads that do not escape from the tidal creeks (ie, $LANDSEDIMENT\underline{BOC}MASS_{jcatch,iparticle} \times (1-RTC_{subestuary,jcatch,iparticle})$ and $LANDHEAVYMETAL\underline{BOC}MASS_{jcatch,iparticle} \times (1-RTC_{subestuary,jcatch,iparticle})$, respectively) are accumulated on the bed of the tidal creek. Predictions of contaminant accumulation inside the subestuaries designated as tidal creeks are presented as an output of the study. These should be treated as nominal predictions only, since there is no other detailed treatment of within tidal creek processes in the model. Provision of nominal predictions in tidal creeks accords with the scope of the CWH Contaminant Study.

### 4.3.4 Dispersal inside the harbour of sediment and contaminant loads presented to EMB

Dispersal of land-derived sediments and contaminants in the harbour on the day they are injected into the harbour (with the freshwater run-off) is accomplished using *R*, *RSUSP* and *RFS*, which are determined by the DHI estuary model suite.

- *R* and *RSUSP* describe sediment dispersal and deposition on the injection day.
- *RFS* describes sediment dispersal and deposition on the days following the injection day.

Table 3 summarises the meaning of the terms *R, RSUSP* and *RFS*.

Figure 2 shows how *R, RSUSP* and *RFS* are applied. This also shows the role of *RTC*. Refer to this figure during the following detailed description

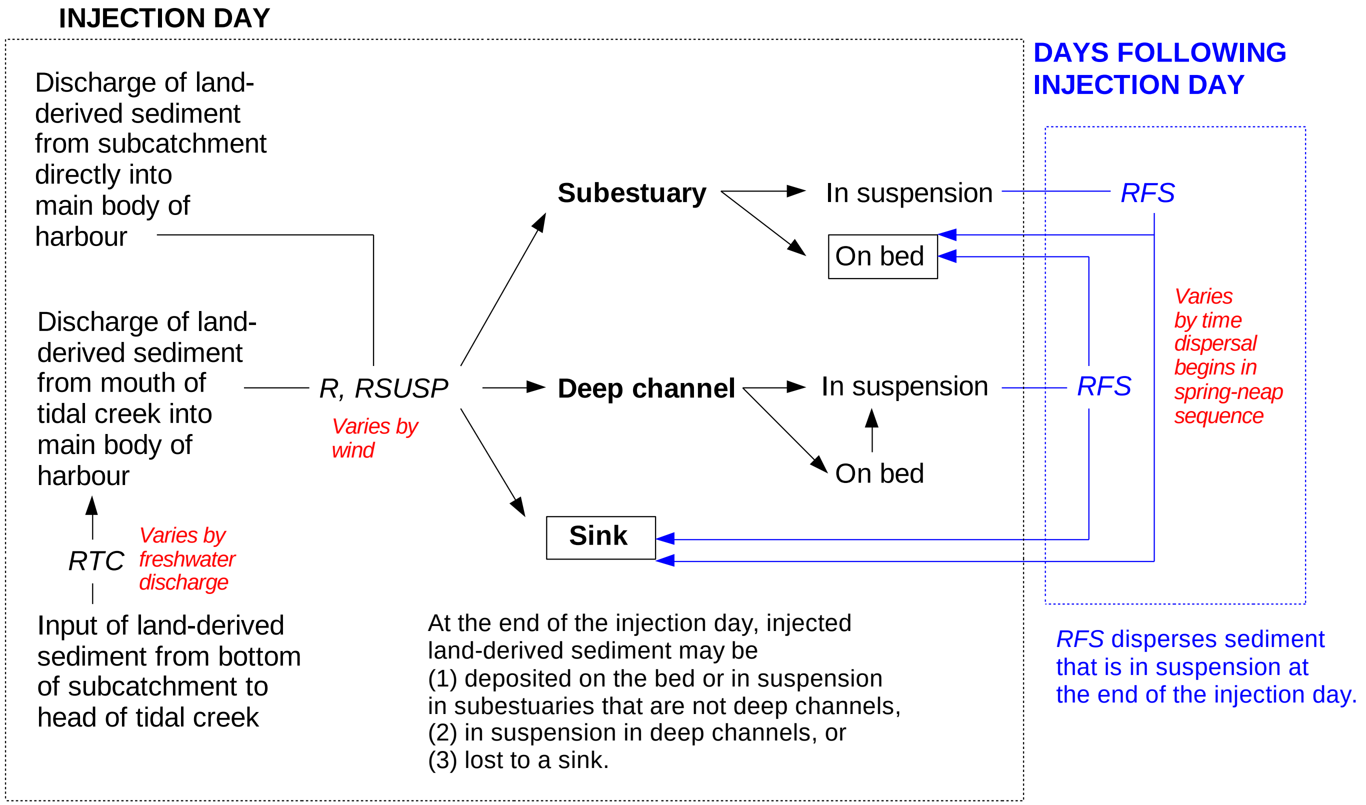
**Table 3**

Summary of the meaning of the terms *R, RSUSP* and *RFS*.

| Term | Applies to | Describes | Varies with | Specified for | Applied at | Special conditions |
|---|---|---|---|---|---|---|
| *R* | Land-derived sediment | Dispersal | Size of constituent particle ($D_{con}$) | Every origin subestuary ↦ destination subestuary combination | End of injection day | Cannot deposit sediment in deep channel |
| *RSUSP* | Land-derived sediment | Dispersal | Size of constituent particle ($D_{con}$) | Every origin subestuary ↦ destination subestuary combination | End of injection day | All sediment in deep channels is left in suspension |
| *RFS* | Land-derived sediment that is left in suspension by *RSUSP* | Dispersal | Size of constituent particle ($D_{con}$) | Every origin subestuary ↦ destination subestuary combination | Until all sediment left in suspension at end of injection day deposits or is lost to sink | Cannot deposit sediment in deep channel |

**Figure 2**

Summary of the way the terms *RTC, R, RSUSP and RFS* are applied.




Ultimately, all sediment that is injected on the injection day is accounted for by:
(1) deposition in a subestuary that is not a deep channel and
(2) loss to a sink.

$R_{catch,kest,iparticle}$ is the fraction of the land-derived sediment load of constituent particle size *iparticle* from sub-catchment *jcatch* that is presented at EMB and that gets deposited in subestuary *kest* at the end of the injection day.

$RSUSP_{catch,kest,iparticle}$ is the fraction of the land-derived sediment load of constituent particle size *iparticle* from sub-catchment *jcatch* that is presented at EMB and that remains in suspension in subestuary *kest* at the end of the injection day.

The total mass of constituent particle size *iparticle* injected into the harbour from all sub-catchments that comes to be deposited in subestuary *kest* by the end of the injection day is given by:

$$\sum_{jcatch=1}^{ncatch}(LANDSEDIMENTEMBMASS_{jcatch,iparticle} \times R_{jcatch,kest,iparticle})$$

The total mass of constituent particle size *iparticle* injected into the harbour from all sub-catchments that remains in suspension in subestuary *kest* at the end of the injection day is given by:

$$\sum_{jcatch=1}^{ncatch}(LANDSEDIMENTEMBMASS_{jcatch,iparticle} \times RSUSP_{jcatch,kest,iparticle})$$

- If *kest* corresponds to a deep channel, $R$= 0 and $RSUSP$ = 1, since sediments are not allowed to settle to the bed in deep channels.
- $R$ and $RSUSP$ between them account for all of the land-derived sediment that is injected into the harbour on injection day:

$$\sum_{kestdestination=1}^{nest}(R_{jcatch,kest,iparticle} + RSUSP_{jcatch,kest,iparticle}) = 1$$

For every sub-catchment, $R$ and $RSUSP$ are determined using the DHI model suite for each of a number of constituent particle sizes under each of a number of environmental conditions (eg, tides, winds, freshwater discharge). A separate simulation is run for each sub-catchment. Each DHI simulation duration is one-day (two complete tidal cycles).

$R$ and $RSUSP$ are evaluated at the end of each injection day. They are both averaged over the subestuary and they are both dimensionless. Both $R$ and $RSUSP$ may vary according to particle size, which permits different particle sizes to disperse independently around the harbour.

The term *RFS* governs the fate of land-derived sediment that remains in suspension at the end of the injection day. This is the same *RFS* that governs the fate of sediment that remains in suspension at the end of the resuspension day.

Following the application of *RFS* in the USC-3 model, all of the land-derived sediment that was injected from each sub-catchment on injection day is deposited in a subestuary (this cannot be a deep channel).

Following the application of *RFS*, the total mass of land-derived sediment of constituent particle size *iparticle* deposited in subestuary *kestdestination* is given by:

$$\sum_{jcatch=1}^{ncatch}(LANDSEDIMENTEMBMASS_{jcatch,iparticle} \times R_{jcatch,kest,iparticle} \times RFS_{iparticle,kestorigin,kestdestination})$$

Finally, the same terms *R*, *RSUSP* and *RFS* also govern the dispersal of heavy metals associated with land-derived sediments in the harbour.

Using the same terms *R* , *RSUSP* and *RFS* to describe the dispersal of both land-derived sediments and heavy metals has the effect of "locking" the heavy metals to the sediments. Thus, as different sediment particle sizes disperse independently around the harbour in the USC-3 model, so the heavy metals associated with the different particle sizes also disperse.

## 4.4 Building the bed-sediment column

In this section, the development of the bed sediment column, which also holds the heavy metals attached to the sediment particles, is described.

### 4.4.1 Days it is not raining

If it is not raining on the day at hand, then only any resuspension of estuarine bed sediments by waves and currents is accounted for.

Firstly, the $D_{50}$ particle size of the bed-sediment active layer is calculated in each subestuary. For homogenous bed sediment (ie, just one layer), $D_{50}$ is given by:

$$D_{50} = \sum_{iparticle=1}^{nparticle} F_{iparticle} \times D_{iparticle}$$

where $F_{iparticle}$ is the fraction of particle size *iparticle* in the bed sediment, $D_{iparticle}$ is the diameter of particle size *iparticle*, and there are *nparticle* constituent particle sizes in the bed sediment.

The same equation for $D_{50}$ holds when the bed sediment is layered but, in order to facilitate calculation, $F_{iparticle}$ is replaced by $FAL_{iparticle}$, which is the fraction of particle size *iparticle* in the active layer of the bed sediment:

$$FAL_{iparticle} = SEDIMENTMASSAL_{iparticle} / SEDIMENTMASSAL$$

Here, *SEDIMENTMASSAL* is the total mass of sediment (ie, all particle sizes) in the active layer:

$$SEDIMENTMASSAL = \sum_{iparticle=1}^{nparticle} SEDIMENTMASSAL_{iparticle}$$

and $SEDIMENTMASSAL_{iparticle}$ is the mass of particle size *iparticle* in the active layer

$$SEDIMENTMASSAL_{iparticle} = \sum_{ilayer=1}^{nlayersactive} SEDIMENTMASS_{ilayer,iparticle}$$

Here there are *nlayersactive* sediment layers in the active layer and $SEDIMENTMASS_{ilayer,iparticle}$ is the mass of particle size *iparticle* in layer *ilayer* of the bed sediment:

$$SEDIMENTMASS_{ilayer,iparticle} = F_{ilayer,iparticle} \times SEDIMENTMASS_{ilayer}$$

and $F_{ilayer,iparticle}$ is the fraction of particle size *iparticle* in layer *ilayer* of the bed sediment.

The erosion depth in each subestuary is found by going into the *ED50* lookup table at the value of $D_{50}$, for the subestuary at hand. *ED50* is selected from the lookup table at the closest value of $D_{50}$, in the table. Through the selection of *ED50* from the lookup table, erosion is made to occur when and where the bed shear stress due to the combined wave and current flow exceeds the critical shear stress for initiation of motion, $\tau_{critical}$. Through $D_{50}$, the different particle sizes that may constitute the bed sediment interact to govern erosion.

*ED50* is converted to a mass of sediment to be eroded from the bed. The mass of sediment eroded from the bed corresponding to *ED50* is given by *SEDIMENTMASS* = $\rho_{settled}$ x *A* x *ED50,* where $\rho_{settled}$ is the bulk density of the bed sediment and *A* is the area of the subestuary in question.

Layers are removed from the sediment column to supply the erosion. A certain number of layers of bed sediment will be released from the bed by the erosion. The mass of sediment contained in each sediment layer is given by $SEDIMENTMASS_{ilayer}$ = $\rho_{settled}$ x A x $THICK_{ilayer}$, where $THICK_{ilayer}$ is the thickness of sediment layer *ilayer*. Hence, *nlayerseroded* sediment layers will be eroded, where:

$$\sum_{ilayer=1}^{nlayerseroded} SEDIMENTMASS_{ilayer} = SEDIMENTMASS$$

The active layer may embrace many layers in the bed sediment, which will have resulted from previous sedimentation/erosion episodes. Erosion is therefore affected by the history of events, in the sense that sediment layers build up over time, and $D_{50}$ takes into account the layering of the bed sediment.

The mass of sediment corresponding to *ED50* is partitioned amongst the constituent particle sizes according to the percentage of each constituent particle size in the bed sediment. If erosion removes a number of sediment layers from the bed and each layer has a different particle size composition, then partitioning of the eroded sediment amongst the constituent particle sizes takes into account that layering, as follows:

$$SEDIMENTMASS_{iparticle} = \sum_{ilayer=1}^{nlayerseroded} F_{ilayer,iparticle} \times SEDIMENTMASS_{ilayer}$$

where $SEDIMENTMASS_{iparticle}$ is the mass of sediment assigned to constituent particle size *iparticle*. Note that:

$$\sum_{iparticle=1}^{nparticle} SEDIMENTMASS_{iparticle} = SEDIMENTMASS$$

A corresponding mass of heavy metal is removed from the bed sediment. There is a certain mass of heavy metal associated with each constituent particle size in each layer of the sediment column. Since erosion of the bed sediment to the depth of *ED50* releases sediment from *nlayerseroded* sediment layers in the sediment column, then the corresponding mass of heavy metal released from the heavy metal column is given by:

$$HEAVYMETALMASS_{iparticle} = \sum_{ilayer=1}^{nlayerseroded} HEAVYMETALMASS_{ilayer,iparticle}$$

where $HEAVYMETALMASS_{ilayer,iparticle}$ is the mass of heavy metal associated with constituent particle size *iparticle* in layer *ilayer* of the sediment column.

For each subestuary, sediment eroded from all the other subestuaries is deposited on the bed using the terms *R5*, *R5SUSP* and *RFS*, as described previously. The mass to be deposited is converted to a thickness and deposited in a single layer. The proportioning of the deposited-layer thickness amongst the particle sizes is identical to the proportioning of the deposited mass amongst the particle sizes.

Heavy metals are deposited correspondingly. The total mass of heavy metal to be deposited is deposited on the bed in a single layer with the sediments. In so doing, distribution of the heavy metals across the constituent particle sizes is maintained.

The resuspension of bed sediments and attached contaminants by waves and currents has now been accounted for, and the concentration of heavy metal in the surface mixed layer can be calculated, which is a primary model output. This calculation takes account of mixing of the bed sediment. The estimate of heavy metal concentration is made to apply at the end of the resuspension day (ie, the day the sediment was resuspended), even though *RFS* acts beyond that day to fully disperse and deposit resuspended sediment. The way heavy metal concentration is calculated is explained in the section on model implementation.

### 4.4.2 Days it is raining

If it is raining on the day at hand, then any resuspension of estuarine bed sediments and associated contaminants by waves and currents is accounted for first. Then any injection of land-derived sediments and contaminants into the harbour is accounted for.

The resuspension of estuarine bed sediments by waves and currents is accounted for as described above, to the point where all the resuspended estuarine sediment has been deposited on the estuary bed (ie, *RFS* has been applied).

The next steps deal with injection of land-derived sediments and contaminants into the harbour.

The mass of land-derived sediment of each constituent particle size *I particle* that is presented to the edge of the main body of the harbour and that now gets dispersed and deposited in the harbour is given by $LANDSEDIMENT\underline{EMB}MASS_{jcatch,\ iparticle}$. The corresponding heavy metal load is $LANDHEAVYMETAL\underline{EMB}MASS_{jcatch,\ iparticle}$. These loads may already have been attenuated if they passed through a tidal creek on their way from the bottom of the catchment to the edge of the main body of the harbour. Any such attenuation is achieved by applying the term *RTC* as previously described.

The total mass of land-derived sediment that is deposited in each subestuary is determined. This is accomplished by applying the terms *R, RSUSP* and *RFS*, as described previously, to $LANDSEDIMENT\underline{EMB}MASS_{jcatch,\ iparticle}$. The mass to be deposited is converted to a thickness and deposited in a single layer. The proportioning of the deposited-layer thickness amongst the particle sizes is identical to the proportioning of the deposited mass amongst the particle sizes.

Heavy metals are deposited correspondingly. The total mass of heavy metal to be deposited is deposited on the bed in a single layer with the land-derived sediments. In so doing, distribution of the heavy metals across the constituent particle sizes is maintained.

Both the injection of land-derived sediments on the day it was raining and the resuspension of estuarine bed sediments, also on the day it was raining, have now been accounted for and the concentration of heavy metal in the surface mixed layer can be calculated. This is the primary model output. The calculation takes account of mixing of the bed sediment. The estimate of heavy metal concentration is made to apply at the end of the day it was raining, even though *RFS* acts beyond that day to fully disperse and deposit both the injected land-derived sediments and the resuspended estuarine bed sediments. The way heavy metal concentration is calculated is explained in the section on model implementation.

# 5 Model Implementation

The implementation of the USC-3 model for the Central Waitemata Harbour consists of specifying the sediment particle sizes to be addressed in the model, defining subestuaries and sub-catchments, specifying the weather time series used to drive the model, defining the way land-derived sediments and associated heavy metals are to be fed into the harbour at the sub-catchment outlets, evaluating the various terms that control sediment and associated heavy metal transport and deposition inside the harbour, defining the way heavy metal concentration in the estuarine bed-sediment surface mixed layer is to be evaluated, and specifying the mixing depth.

Other information required to drive the model, including harbour bed-sediment initial conditions (eg, particle size, metal concentration in the surface mixed layer, sub-catchment sediment and metal loads), varies depending on the particular scenario being addressed. This information is not treated as part of the model implementation; instead, it is reported where the scenario model runs are reported.

## 5.1 Sediment particle sizes

### 5.1.1 Constituent particle sizes

#### 5.1.1.1 Estuarine bed sediment and suspended-sediment load

Four "constituent" sediment particle sizes ($D_{con}$) are treated by the model: 12, 40, 125 and 180 μm. These particle sizes are deemed to compose the estuarine bed sediment, and the suspended-sediment load that derives from the bed sediment. These represent fine silt, coarse silt, fine sand and medium sand, respectively.

The Stokes fall speed assuming sediment density of 2.65 g m$^{-3}$ (quartz) was assigned to each particle size: 0.0001 m s$^{-1}$, 0.001 m s$^{-1}$ and 0.01 m s$^{-1}$, respectively, for the 12, 40 and 125 μm fractions. The particle sizes 12, 40 and 125 μm were chosen to span orders of magnitude in settling speed, which is a principal control on sediment resuspension and transport.

Swales et al. (2008b), in the report on harbour bed sediments for the Central Waitemata Harbour Contaminant Study, found each of the 12, 40, 125 μm fractions present in harbour bed sediments. However, bed-sediment median particle size exceeded 125 μm in the more exposed parts of the harbour, which indicates the presence of a mode that is larger than 125 μm. Adding 180 μm as the fourth constituent particle size allows observed bed-sediment median particle sizes to be re-created in the USC-3 model.

The 180 μm fraction is not allowed to move in the USC-3 model, which makes it a passive diluent. There are no measurements of the typical particle size of suspended sediments in the Central Waitemata Harbour (the instrument intended to be used by Swales et al. for this purpose failed), but other studies in comparable harbours (eg, Green et al. 2007) indicate that sediment coarser than fine sand is not likely to be mobilised in any significant way by waves and currents in the Central Waitemata Harbour.

Because the Stokes fall speed is assigned on the assumption of quartz density, the 12, 40 and 125 µm particles are implied to be, as a result, in an unaggregated state. Were particles aggregated, $D_{con}$ as a consequence would refer to the size of the aggregate; the aggregate density would be lower; and the aggregate settling speed would be less.

The estuarine bed sediment, and the suspended-sediment load that derives therefrom, are assumed to be composed of unaggregated sediment particles because: (1) mud content of harbour bed sediment is typically <16 % (Swales et al. 2007); (2) the harbour is open and energetic, which will tend to cause the breakup of any aggregates that do form; and (3) suspended-sediment concentrations are typically too low (generally <100 mg $L^{-1}$; rarely exceeding 1000 mg $L^{-1}$) to promote aggregation (Oldman et al. 2006).

#### 5.1.1.2 Land-derived sediment

The same constituent particle sizes with the same fall speeds assigned on the basis of quartz density are also deemed to compose the land-derived sediment. Hence, land-derived sediment is treated in the model as though it is in an unaggregated state (the same as estuarine bed and suspended sediment).

For those sub-catchments that discharge at the head of tidal creeks, land-derived sediments may actually aggregate as they travel down the tidal creek, where the aggregation is promoted by large (relative to the open harbour) suspended-sediment concentrations and quiescent (again, relative to the open harbour) conditions. Once in the open harbour, it is assumed that any such aggregates will be broken down, for the same reasons it is assumed that estuarine bed sediments and associated suspended sediments in the open harbour exist in an unaggregated state.

There are three tidal creeks in the USC-3 model (Henderson Creek, Whau River and Hobsons Bay – to be described shortly). The DHI model simulations used to determine *RTC*, which is the fraction of the land-derived sediment exported from each of the tidal creeks, may therefore be in error if land-derived sediment passes down the tidal creeks in a largely aggregated state.

### 5.1.2 D50 particle sizes

Four "D50" particle sizes ($D_{50}$) are treated by the model. These are also 12, 40, 125 and 180 µm. The D50 particle size is equivalent to the median particle size of the bed sediment. It is used in the USC-3 model in the calculation of erosion depth, which depends on the properties of the bed sediment as a whole.

## 5.2 DHI estuary model suite

The "DHI estuary model suite" (or just the "DHI model") comprises the DHI Water and Environment (DHI) MIKE3 FM hydrodynamic model, the DHI MIKE3 MT sediment transport model, and the SWAN wave model. Together, these simulate tidal propagation within the harbour, tide- and wind-driven currents, freshwater mixing, waves, and sediment transport and deposition. SWAN uses the water levels and current fields predicted by the MIKE3 FM model in predicting wind-generated waves. The predicted wave heights, periods and directions are in turn used to quantify wave-induced bed shear stress, which then transports sediments in the MIKE3 MT model. The DHI model implementation and calibration for the Central Waitemata Harbour is described in Oldman et al. (2008). Field data collected for the purposes of DHI model calibration are described in Oldman et al. (2006).

The calibrated MIKE3 MT model was used to simulate the resuspension and transport of 12, 40 and 125 μm sediment particle sizes, and the various terms in the USC-3 model that describe sediment transport, resuspension and deposition were determined from the results of those simulations. (The 180 μm fraction does not move.)

Oldman et al. (2008) used measurements of suspended sediment concentration from several sites in the Central Waitemata Harbour to calibrate the MIKE3 MT sediment transport model. The resuspension and transport of 12, 40 and 125 μm constituent particle sizes were simulated by the model. The constituent concentrations were combined to yield a total concentration, which was compared to measurements. The calibration process consisted of adjusting deposition and erosion thresholds and the erosion rate to achieve a good match between measured and predicted concentrations. The calibrated model was able to satisfactorily reproduce the measurements of total suspended sediment concentration under tides alone, under weak winds that enhanced non-tidal circulation, and under strong winds that generated waves.

The MIKE3 MT model is properly constituted (with separate entrainment and settling fluxes) for the 12 and 40 μm fractions, but not necessarily the 125 μm fraction. Nevertheless, the 125 μm concentrations predicted by the model were shown by Oldman et al. (2008) to agree well with a reference-concentration formulation more normally applied to this fraction.

In any case, the 125 μm fraction was (correctly) predicted by the model to constitute only a small fraction of the total suspended-sediment load, which shows that that fraction is less mobile than the 12 and 40 μm particle size fractions. Furthermore, the bulk of the heavy metal load will always be carried on the 12 and 40 μm particle size fractions.

## 5.3 Subdivision of harbour and catchment

### 5.3.1 Subestuaries

The subdivision of the Central Waitemata Harbour into subestuaries for the purposes of application of the USC-3 model is shown in Figure 3. Further details of the subdivision are shown in Table 4

#### 5.3.1.1 Tidal creeks

Three subestuaries are designated as tidal creeks: Henderson Creek (HEN), Whau River (WHA) and Hobsons Bay (HBA). Sediments deposited in tidal creeks may not be subsequently removed by resuspension, and land-derived sediments that pass through tidal creeks are attenuated. Only nominal predictions of sedimentation and contaminant accumulation are made for the three tidal creeks in the model. This accords with the terms of the study.

#### 5.3.1.2 Sinks

Three of the subestuaries are designated as sinks: Hauraki Gulf (HGF), Waterview Embayment (WAT) and the Upper Waitemata Harbour (UWH). Sediments deposited in sinks also may not be subsequently removed by resuspension. Furthermore, sediments deposited in HGF and UWH are "removed from the model", meaning that no predictions are made of sediment or contaminant accumulation in those subestuaries.

- The designation of UWH as a sink is based on the assumption that the bulk of sediment transported into the Upper Waitemata Harbour from the Central Waitemata Harbour settles therein and does not re-enter the Central Waitemata Harbour. Although UWH is not allowed to supply sediment to the Central Waitemata Harbour through bed erosion (by virtue of its designation as a sink), sediment and contaminant loads from the Upper Waitemata Harbour are still treated, but as explicit sources. In effect, the Upper Waitemata Harbour is treated as a sub-catchment of the Central Waitemata Harbour.
- The designation of HGF as a sink is based on the assumption that the bulk of any sediment transported into the Gulf is dispersed widely and does not re-enter the Central Waitemata Harbour. By virtue of its designation as a sink, HGF is also prevented from eroding and supplying bed sediment to the Central Waitemata Harbour, which is viewed as reasonable given the physiographic setting of the inner Gulf.

#### 5.3.1.3 Deep channels

Five subestuaries are designated as deep channels. Simulations with the DHI model suite confirmed that the 12, 40 and 125 μm sediment particle sizes do not permanently settle to the bed in the subestuaries designated as deep channels. 180

μm sediment may remain on the bed in some deep channels during neap tides, but is resuspended during spring tides. Since sediment is not allowed to deposit in or erode from deep channels, predictions of sediment and contaminant accumulation are not made in these subestuaries.

**Figure 3**

Division of the Central Waitemata Harbour into subestuaries for the purposes of application of the USC-3 model. See Table 4 for naming and numbering scheme.

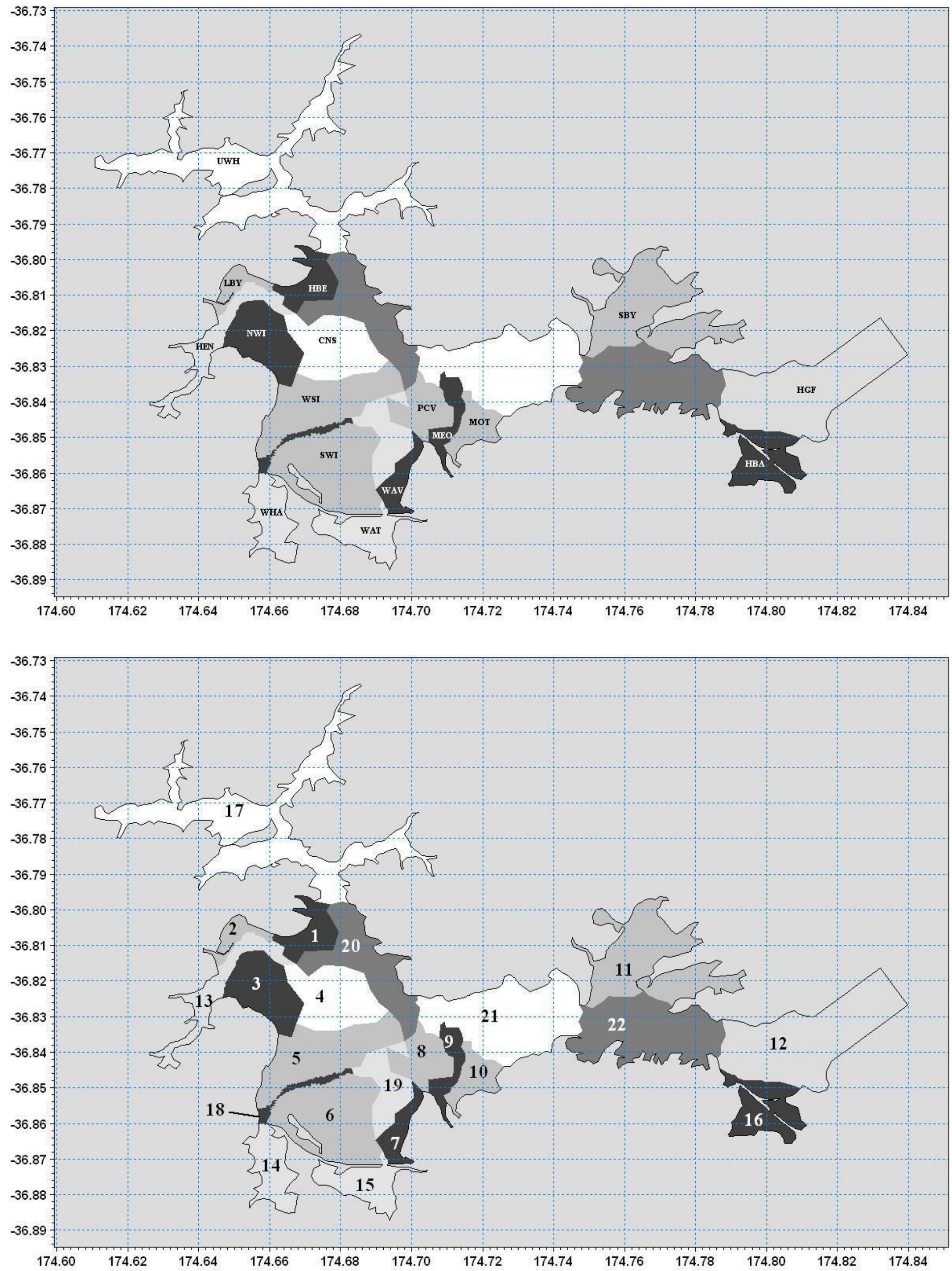


**Table 4**
Characteristics of subestuaries for the purposes of application of the USC-3 model. The area shown in the table is the total subestuary area.

| Code | Subestuary | Area ($m^2$) | Sink | Tidal Creek | Deep Channel | Predictions |
|---|---|---|---|---|---|---|
| 1 -HBE | Hobsonville | 1599322 | | | | Full |
| 2 - LBY | Limeburners Bay | 834747 | | | | Full |
| 3 - NWI | Northwestern Intertidal | 3052405 | | | | Full |
| 4 - CNS | Central Subtidal | 3677757 | | | | Full |
| 5 - WSI | Western Intertidal | 4693359 | | | | Full |
| 6 - SEI | Southwestern Intertidal | 5474496 | | | | Full |
| 7 - WAV | Waterview Flats | 1082372 | | | | Full |
| 8 - PCV | Point Chevalier | 1958962 | | | | Full |
| 9 - MEO | Meola | 1079382 | | | | Full |
| 10 - MOT | Motions | 1404598 | | | | Full |
| 11 - SBY | Shoal Bay | 6465419 | | | | Full |
| 12 - HGF | Hauraki Gulf | n/a | ✓ | | | None |
| 13 - HEN | Henderson Creek | 2277921 | | ✓ | | Nominal |
| 14 - WHA | Whau River | 2116217 | | ✓ | | Nominal |
| 15 - WAT | Waterview Embayment | 2129185 | ✓ | | | Full |
| 16 - HBA | Hobsons Bay | 2470576 | | ✓ | | Nominal |
| 17 - UWH | Upper Waitemata Harbour | n/a | ✓ | | | None |
| 18 - WC | Whau Channel | n/a | | | ✓ | n/a |
| 19 - WS | Whau Subtidal | n/a | | | ✓ | n/a |
| 20 - UC | Upper Channel | n/a | | | ✓ | n/a |
| 21 - MC | Middle Channel | n/a | | | ✓ | n/a |
| 22 - OC | Outer Channel | n/a | | | ✓ | n/a |

### 5.3.2 Sub-catchments

The subdivision of the catchment surrounding the Central Waitemata Harbour into sub-catchments for the purposes of application of the USC-3 model is shown in Table 5 and Figure 4.

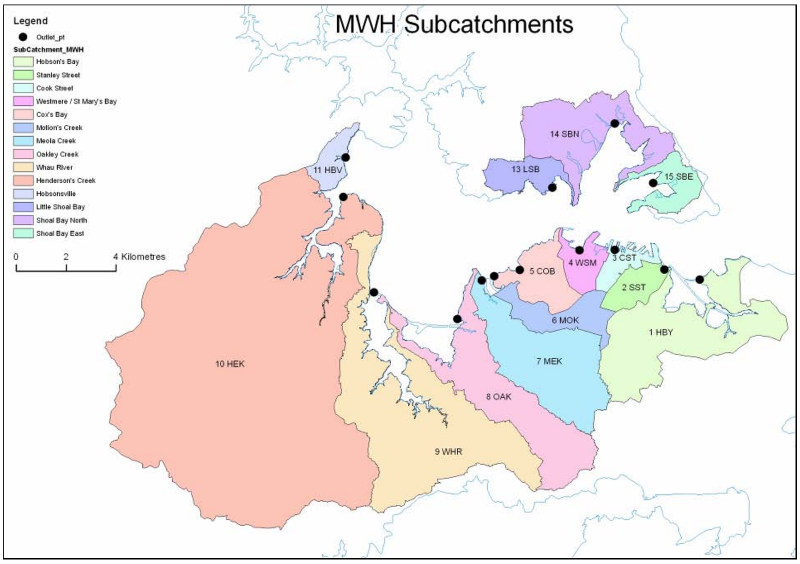
**Table 5**

Division of the catchment of the Central Waitemata Harbour into sub-catchments for the purposes of application of the USC-3 model.

| Code | Sub-catchment |
|---|---|
| 1 - HBY | Hobsons Bay |
| 2 - SST | Stanley Street |
| 3 - CST | Cook Street |
| 4 - WSM | Westmere/St Marys Bay |
| 5 - COB | Coxs Bay |
| 6 - MOK | Motions Creek |
| 7 - MEK | Meola Creek |
| 8 - OAK | Oakley Creek |
| 9 - WHR | Whau River |
| 10 - HEK | Henderson Creek |
| 11 - HBV | Hobsonville |
| 12 - UWH | Upper Waitemata Harbour |
| 13 - LSB | Little Shoal Bay |
| 14 - SBN | Shoal Bay North |
| 15 - SBE | Shoal Bay East |

**Figure 4**

Division of the catchment of the Central Waitemata Harbour into sub-catchments for the purposes of application of the USC-3 model.



## 5.4 Evaluation of land-derived sediment and contaminant loads at BOC

### 5.4.1 Sediment

#### 5.4.1.1 GLEAMS (rural) loads

The GLEAMS model provides daily land-derived sediment loads at the bottom of each sub-catchment split by constituent particle size. For this implementation, GLEAMS predicts sediments from all of the rural areas in each sub-catchment. Hence, "GLEAMS sediments" is synonymous with "sediments from sources in rural areas".

Even though the daily GLEAMS timestep matches the one-day timestep in the USC-3 model associated with injection of land-derived material into the harbour, there is still some manipulation required to assemble these loads for input into the USC-3 model. This is described and explained in this section.

Catchment land use in both the 100-year future period (for the purposes of this explanation, 2006–2106, which is the period of interest as far as management decisions and policy formulation are concerned) and the 50-year historical period (1940–2001, which is the period for calibrating and validating the USC-3 model) is typically fixed in 10-year blocks for input into the GLEAMS model. For example, in the future period, land use may be fixed in each of five 10-year blocks with (for example):

- block 1 representing the period 2006–2015;
- block 2 representing the period 2016–2025;
- block 3 representing the period 2026–2035;
- block 4 representing the period 2036–2045; and
- block 5 representing the period 2046–2055.

The final block, block 6, represents the 50-year period 2056–2106.

The land use specified in each of these future-period blocks of course reflects proposed development scenarios being considered in the study. (The land use specified in blocks that span the historical period are based on actual land use for those times.) In each block, the land use is fixed.

GLEAMS is run separately for each block, driven by a 50-year daily rainfall time series to create a corresponding 50-year daily rural sediment run-off time series from each sub-catchment. The 50-year rainfall series used to drive the GLEAMS simulations is typically from the **past** 50 years (ie, 1956–2006, or thereabouts), on the assumption that future weather will not be that much different to past weather. (That assumption, of course, may not be true, and future-period rainfall used to drive the GLEAMS model may be altered to reflect the anticipated changes in climate in future years.)

The GLEAMS model runs are then sub-sampled to create daily rural sediment loads from each sub-catchment, as follows.

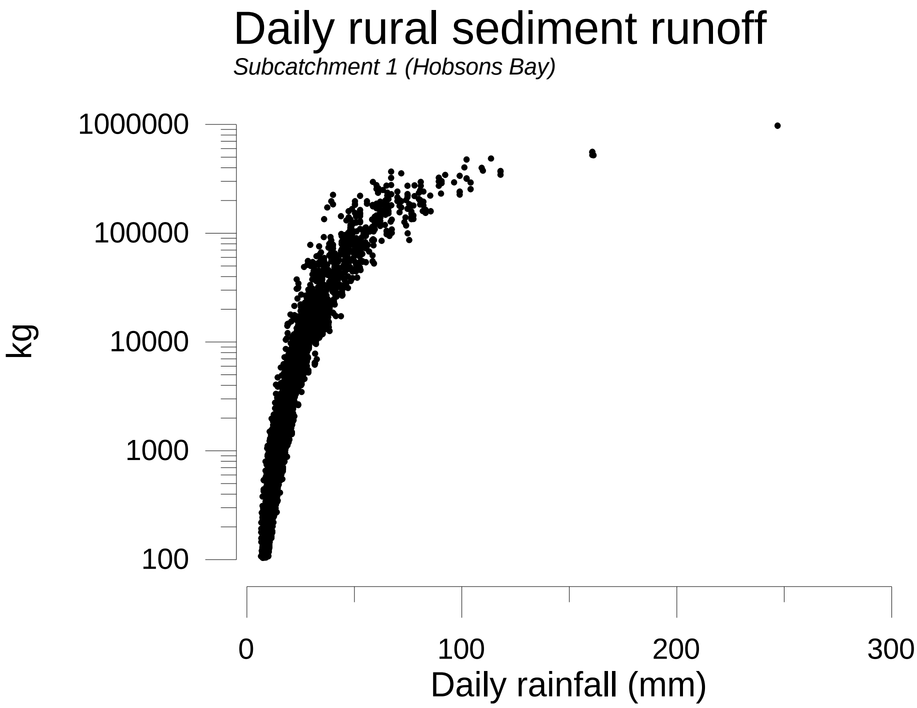
To create the daily rural sediment loads needed by the USC-3 model for the period 2006–2015, 5 x 2-year sub-blocks are randomly selected from the 50-year GLEAMS sediment run-off time series from block 1. The selected sub-blocks are placed back-to-back to provide the daily inputs for the 10-year period 2006–2015. This procedure is repeated, randomly selecting 5 x 2-year sub-blocks from each block of GLEAMS data, until the 100-year daily time series needed to drive the USC-3 model is created.

The advantage to this block-sampling scheme, which is significant, is that the effects on sediment generation of antecedent rainfall and rainfall intensity on the day of generation, both of which can create large variability in the response of the catchment to rainfall, can be captured. For example, sediment yield (sediment generation per rainfall) may be higher under intense rainfall after an extended period of dry weather compared to less intense rainfall when the ground is partly saturated. These effects are captured in GLEAMS, and they get transferred to the USC-3 model by using **sequences** of GLEAMS output to drive the USC-3 model (Figure 5). This was not the case in the previous version of the USC model (USC-2), which assigned a fixed sediment run-off to events covering a range of rainfalls.

Extreme sediment-generation events are captured in the 50-year series produced by GLEAMS (this is the reason GLEAMS is run for 50 years, even though the land use typically spans less than that period), but they are not necessarily captured in the USC-3 model by the scheme described this far. To ensure that extreme sediment-generation events do get captured in the USC-3 model, it is run in a "Monte Carlo package". Specifically, the USC-3 model is run $N$ times to create $N$ sets of predictions for the 100-year future period, where $N$ is of the order $10^2$. The $N$ sets of predictions are averaged to give one set of "average" predictions for the future period, and it is these average predictions that are delivered to the user. Each of the $N$ runs of the model is driven by a different time series of sediment run-off from rural sources, randomly constructed as just described. The set of $N$ simulations, constructed in this way, will properly account for extreme events, so long as $N$ is "large".

**Figure 5**

Daily rural sediment run-off versus daily rainfall, assembled from a 100-year time series of daily rural sediment run-off used to drive the USC-3 model. The 100-year time series was in turn constructed from a number of 50-year GLEAMS simulations as described in the text. This procedure results in noticeable variability in rural sediment yield (sediment run-off per rainfall), which then appears in the USC-3 model. Extreme events are captured by a number of 100-year time series (such extremes do appear in this example).




### 5.4.1.2 CLM (urban) loads

The CLM model predicts annual urban sediment loads, split by constituent particle size, that derive from all of the urban areas in each sub-catchment. Hence "CLM sediments" is synonymous with "sediments from sources in urban areas". The urban (CLM) sediment loads need to be added to the rural (GLEAMS) sediment loads, but because the annual timestep of the CLM does not match the daily timestep in the USC-3 model associated with injection of land-derived material into the harbour, the CLM loads need to be further manipulated before they can be added to the GLEAMS loads and used in the USC-3 model.

Each annual load of urban sediment is fully distributed over the days in that year such that no part of the annual load is "carried over" into a succeeding year. Specifically, the annual urban-sediment load emanating from each sub-catchment is broken down into daily loads over that same year in proportion to the daily GLEAMS sediment loads. For instance, if 1 % of the GLEAMS sediment load for a particular year appears on a particular day, then 1 % of the CLM annual sediment load is forced to appear on that same day.

### 5.4.2 Contaminant

#### 5.4.2.1 Anthropogenic

The CLM provides annual anthropogenic metal loads at the bottom of each sub-catchment, split by sediment constituent particle size that carries the load. Because the annual timestep of the CLM does not match the daily timestep in the USC-3 model associated with injection of land-derived material into the harbour, these loads need to be further manipulated before they can be used in the USC-3 model.

Each annual anthropogenic load of metal is fully distributed over the days in that year such that no part of the annual load is "carried over" into a succeeding year. Specifically, the annual anthropogenic heavy metal load emanating from sub-catchment *jcatch* is broken down into daily loads over that same year in proportion to the daily GLEAMS sediment load:

$$LANDHEAVYMETALBOCMASS_{jcatch,day} =$$

$$LANDHEAVYMETALBOCMASS_{jcatch} \times$$

$$[\sum_{iparticle=1}^{nparticle} LANDSEDIMENTBOCMASS_{jcatch,iparticle,day} /$$

$$\sum_{day=1}^{nday}\sum_{iparticle=1}^{nparticle} LANDSEDIMENTBOCMASS_{jcatch,iparticle,day}]$$

where:

- $LANDHEAVYMETAL\underline{BOC}MASS_{jcatch}$ is the annual anthropogenic heavy metal load emanating from sub-catchment *jcatch*;
- $LANDHEAVYMETAL\underline{BOC}MASS_{jcatch,day}$ is the daily anthropogenic heavy metal load emanating from sub-catchment *jcatch* over that same year;
- $LANDSEDIMENT\underline{BOC}MASS_{jcatch,iparticle,day}$ is the daily GLEAMS rural sediment load from sub-catchment *jcatch* and there are *nday* days in the year.

Using this scheme, the annual-average concentration (mass of metal per mass of sediment) at which anthropogenic heavy metals are carried to the harbour will vary from year-to-year, since the annual anthropogenic heavy metal load may vary independently of the annual sediment load.

#### 5.4.2.2 Natural

Natural heavy metal loads, which get added to anthropogenic loads to form total loads, are calculated by multiplying the total (rural plus urban) sediment load by the concentration at which natural heavy metals are carried on soils.

## 5.5 Transfer of land-derived sediment and contaminant loads to EMB

Conversion (1) accounts for any reduction (attenuation) of the land-derived sediment load as it transits between the bottom of catchment (BOC) and the edge of the main body of the harbour (EMB).

Conversion (2) accounts for any reduction of the land-derived metal load as it transits between BOC and EMB.  At the same time, the metal load is partitioned amongst the various constituent particle sizes that make up the land-derived sediment load.

### 5.5.1 Outfalls that discharge into freshwater creeks that in turn discharge directly into the main body of the harbour

Conversion 1. There is no load attenuation.

Conversion 2. There is no load attenuation, and the CLM will determine how the metal load is partitioned amongst the various constituent particle sizes that make up the land-derived sediment load.

### 5.5.2 Outfalls that discharge directly into the main body of the harbour

Conversion 1. There is no load attenuation.

Conversion 2. There is no load attenuation, and the CLM will determine how the metal load is partitioned amongst the various constituent particle sizes that make up the land-derived sediment load.

### 5.5.3 Outfalls that discharge into the main body through a tidal creek

Conversion 1. Load attenuation is achieved by applying *RTC*. This is described in the next section, where sediment transport in the harbour is described.

Conversion 2. Load attenuation is achieved by applying *RTC*. This is described in the next section, where sediment transport in the harbour is described.  The CLM will determine how the metal load is partitioned amongst the various constituent particle sizes that make up the land-derived sediment load.

## 5.6 Sediment transport in the harbour

Table 6 summarises the way the various terms that control sediment transport in the harbour are implemented in the USC-3 model of the Central Waitemata Harbour. (The particular rainfall bands, winds and tide sequences shown in the Table are explained in a later section.)

**Table 6**

The way the various terms that control sediment transport in the harbour are implemented in the USC-3 model of the Central Waitemata Harbour. (The particular rainfall bands, winds and tide sequences shown in the Table are explained in a later section.)

| Environmental conditions | Raining | | | Not raining | |
|---|---|---|---|---|---|
| | *RTC* | *R, RSUSP* | *ED50, R5, R5SUSP* | *ED50, R5, R5SUSP* | *RFS* |
| Tide range | Average | Average | Average | Average | Range (4):<br>Neap–mean–spring …<br>Mean–spring–neap …<br>Spring–mean–neap …<br>Mean–neap–mean … |
| Winds | Calm | Range (5):<br>Calm<br>9.07 m s$^{-1}$ NE<br>9.45 m s$^{-1}$ SE<br>10.87 m s$^{-1}$ SW<br>8.49 m s$^{-1}$ NW | | Range (5):<br>Calm<br>7.29 m s$^{-1}$ NE<br>6.04 m s$^{-1}$ SE<br>8.86 m s$^{-1}$ SW<br>7.07 m s$^{-1}$ NW | Calm |
| Freshwater inputs (rainfall) | Range (7):<br>0.9–4.6 mm<br>4.6–10.3 mm<br>10.3–18.8 mm<br>18.8–30.0 mm<br>30–60 mm<br>60–100 mm<br>>100 mm | Baseflow | Baseflow | Baseflow | Baseflow |
| DHI simulation duration | Equilibrium | 1 day | 1 day | 1 day | Equilibrium |

### 5.6.1 Resuspension of estuarine bed sediments by waves and currents

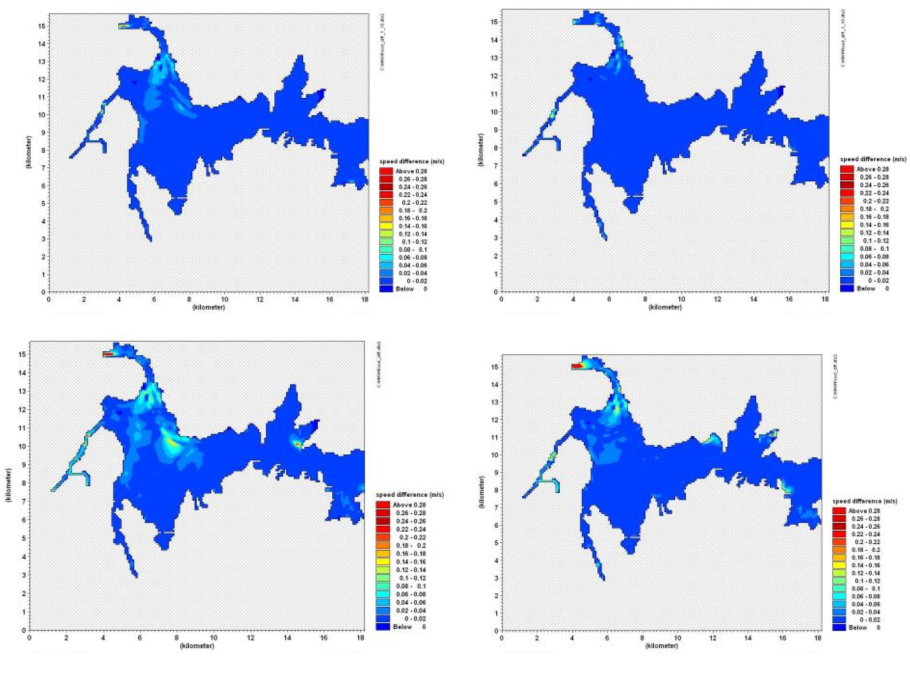
#### 5.6.1.1 ED50

*ED50* was determined for each of four $D_{50}$ particle sizes (12, 40, 125 and 180 μm) and two sets of environmental conditions.

One set of environmental conditions applies when it is raining, and the other set applies when it is not raining (Table 6). In each set of environmental conditions there are five winds. Wind was chosen to vary because it is the primary control on waves, which in turn controls resuspension of bed sediment. Wind is also the primary control on resuspension and dispersal of estuarine bed sediment on the day of resuspension.

The tide range and the freshwater inputs were fixed in each set of environmental conditions. Freshwater discharge has little effect on the wider circulation patterns in main body of harbour (Figure 6), so it was fixed. Tide range does have an effect on the wider circulation patterns in main body of harbour, but tide range was fixed nevertheless for practicality.

**Figure 6**
Tests with the DHI model to gauge the sensitivity of circulation patterns in the wider harbour to freshwater inflows. (Top) Differences in peak ebb (left) and flood (right) current speeds during a 10-year rainfall event compared to during mean freshwater inflow. (Bottom) Differences in peak ebb (left) and flood (right) current speeds during a 100-year rainfall event compared to during mean freshwater inflow.



The simulation duration in every case was one-day (two complete tidal cycles).

*ED50* for each environmental condition was calculated together with *R5* and *R5SUSP* for the same environmental condition from the one DHI model run. How this was done is described in the next section.

Appendix 1 shows erosion depth by the end of the resuspension day (*ED50*) in subestuaries 1 to 11 when it is not raining. *ED50* is zero in all other subestuaries.

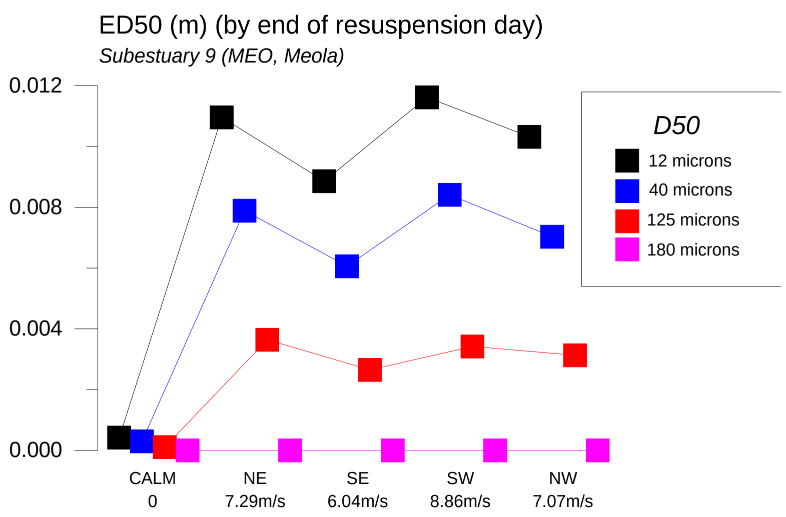
Appendix 2 shows erosion depth by the end of the resuspension day (*ED50*) in subestuaries 1 to 11 when it is raining. *ED50* is zero in all other subestuaries.

An example of *ED50* is shown in Figure 7. *ED50* is <0.01 m, which seems reasonable, but it is important to realise that *ED50* is really a **potential** erosion depth, not an actual one. This is because (described in next section) *ED50* is calculated using the DHI model on a subestuary-by-subestuary basis, with the whole harbour apart from the subestuary in question being "concreted". The **actual** erosion depth in any given subestuary arises from the combination of erosion in the subestuary in question **and** deposition of sediment from all other subestuaries in the harbour. It is because the latter is turned off in the DHI model runs used to determine *ED50* that *ED50* so calculated is not actual. (Of course deposition is accounted for in the USC-3 model.).

Note that *ED50* was determined for each of four $D_{50}$ particle sizes: 12, 40, 125 and 180 µm, which, in effect, creates a lookup table of values that is used by the USC-3 model. When bed-sediment erosion is applied in the USC-3 model, the bed-sediment $D_{50}$ in the subestuary in question is first calculated, and then the lookup table of erosion depths is selected from at the closest corresponding value.

**Figure 7**

Erosion depth (m) of bed sediments in subestuary 9 (Meola) by the end of the resuspension day.



#### 5.6.1.2 R5 and R5SUSP

*R5* and *R5SUSP* were determined for each of four $D_{con}$ constituent particle sizes (12, 40, 125 and 180 μm) and two sets of environmental conditions. The environmental conditions were exactly the same as those used in the calculation of *ED50* (Table 6).

In fact, *ED50* , *R5* and *R5SUSP* for any given environmental condition were all calculated from the one DHI model run. Specifying the set of $D_{50}$ particle sizes to be the same as the set of $D_{con}$ constituent particle sizes allowed this convenience.

For each combination of $D_{50}$ ($D_{con}$), environmental condition and "origin" subestuary, a separate DHI model run was required.

For each model run, all subestuaries except the origin subestuary were "concreted". That is, only the bed sediment in the estuary in question was allowed to erode. (If the DHI model were able to simultaneously track sediments from different origin areas in the harbour then this would not be necessary.) The DHI model was run for two complete tidal cycles. Model runs started at high tide and ended at high tide. High tide corresponds to slackwater.

For the purposes of this explanation, assume the origin subestuary is subestuary #1 and there are three subestuaries in total in the model domain. At the end of the model run, a sediment budget is constructed (Table 7 shows an example), consisting of:

- Term 1: the mass of sediment eroded from the bed of the origin subestuary by the end of the model run (a negative number, eg, -100 kg).
- Term 2: the mass of sediment deposited in all the other subestuaries except the origin subestuary at the end of the model run (positive numbers, eg, 20 kg for subestuary #2 and 40 kg subestuary #3).
- Term 3: the mass of sediment remaining in suspension in all subestuaries including the origin subestuary at the end of the model run (positive numbers, eg, 20, 10 and 10 kg for subestuaries #1, #2 and #3, respectively).

**Table 7**
Example calculation of *ED50*, *R5* and *R5SUSP*.

| Subestuary | kg sediment on bed | kg sediment in suspension | *ED50* | *R5* | *R5SUSP* |
|---|---|---|---|---|---|
| 1 (origin) | -100 (1) | 20 (3) | 100/(area × density) | 0 | 20/100 |
| 2 | 20 (2) | 10 (3) | | 20/100 | 10/100 |
| 3 | 40 (2) | 10 (3) | | 40/100 | 10/100 |

The sediment budget, defined as the sum of all terms, necessarily sums to zero, meaning that all of the sediment eroded from the origin subestuary is accounted for.

- Term (1) is converted to *ED50* by *ED50* = (-1.0 × term (1))/(origin subestuary area × density of settled sediment), where the density of settled sediment is assumed to be 1200 kg $m^{-3}$.
- *R5* is calculated as term (2)/(-1.0 × term (1)) for each subestuary.
- *R5SUSP* is calculated as term (3)/(-1.0 × term (1)) for each subestuary.

Appendix 3 shows the fraction of sediment that is resuspended from each origin subestuary and deposited (*R5*) and left in suspension (*R5SUSP*) by the end of the resuspension day in each destination subestuary when it is not raining.

Appendix 4 shows the fraction of sediment that is resuspended from each origin subestuary and deposited (*R5*) and left in suspension (*R5SUSP*) by the end of the resuspension day in each destination subestuary when it is raining.

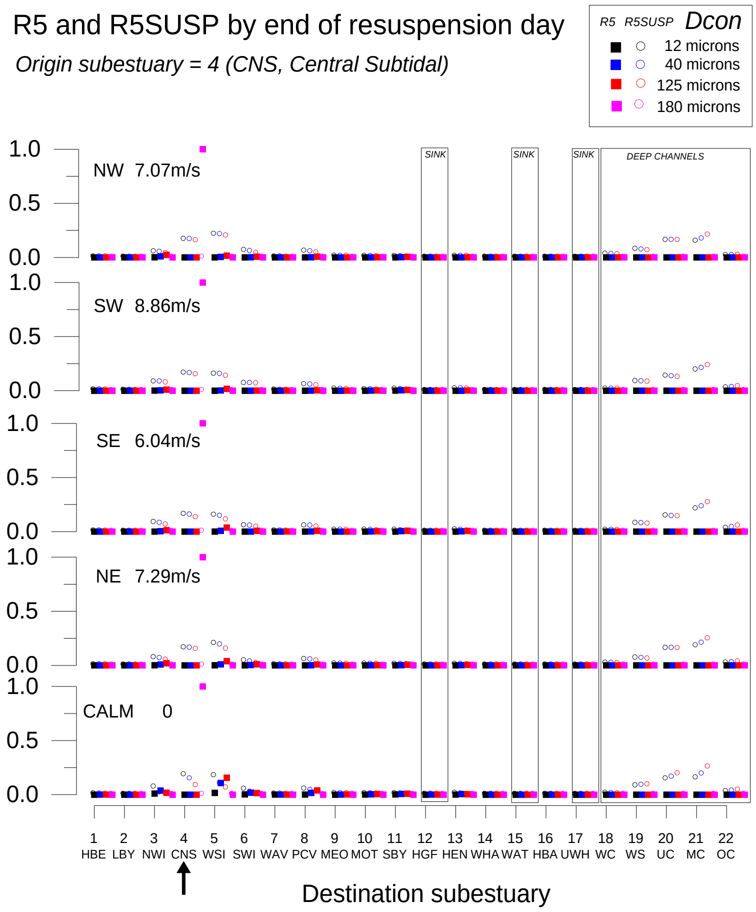
An example of *R5* and *R5SUSP* is shown in Figure 8. Sediment resuspended from subestuary 4 (Central Subtidal) is seen to spread to subestuaries in the immediate vicinity by the end of the resuspension day (Northwestern Intertidal, Western Subtidal) and a substantial amount of sediment finds its way into the deep channels in the upper sector of the harbour. More of the 12 µm sediment remains in suspension at the end of the suspension day compared to the coarser fractions, which is expected. The different wind directions do not seem to have much effect on the dispersal patterns, presumably because the origin subestuary is centrally located in the main body of the harbour.

Note:

- The **amount** of sediment resuspended in each origin subestuary is given by *ED50*. Sediment may be resuspended only in subestuaries 1 to 11 (*ED50* may be nonzero). Sediment may not be resuspended in all other subestuaries (*ED50* is zero).
- If the destination subestuary corresponds to a deep channel, then *R5* is forced to 0, since sediments are not allowed to settle to the bed in deep channels.
- Sediment may deposit in the same subestuary from which it is resuspended, but this is not reflected in values for *R5*. Instead, *ED50* naturally accounts for this. As a result, $R5_{kestorigin,kestdestination}$ = 0 when *kestorigin* = *kestdestination*. $R5SUSP_{kestorigin,kestdestination}$ may be nonzero when *kestorigin* = *kestdestination*.

**Figure 8**

*R5* and *R5SUSP* (dimensionless) showing the dispersal of estuarine bed sediment resuspended from subestuary 4 (Central Subtidal – shown the arrow) by the end of the resuspension day.




## 5.6.2 Injection into the harbour of sediments and contaminants when it rains

### 5.6.2.1 RTC

*RTC* was determined for the three cases where a sub-catchment discharges into a subestuary that is defined as a tidal creek. These are given in Table 8.

**Table 8**

The three cases where a sub-catchment discharges into a subestuary that is defined as a tidal creek.

| Sub-catchment that discharges into a tidal creek | Subestuary that is the tidal creek discharged into |
|---|---|
| 1 Hobsons Bay (HBY) | 16 Hobsons Bay (HBA) |
| 9 Whau River (WHR) | 14 Whau River (WHA) |
| 10 Hendersons Creek (HEK) | 13 Hendersons Creek (HEN) |

*RTC* was determined for each of four $D_{con}$ constituent particle sizes (12, 40, 125 and 180 μm) and one set of environmental conditions.

Freshwater input was chosen to vary (Table 6) because it is the primary control on tidal creek dynamics, which in turn affects export of land-derived sediment into the main body of the harbour. Table 9 shows the freshwater inputs associated with each of 7 rainfall bands addressed in the *RTC* simulations. The freshwater run-off from each sub-catchment in each rainfall band was established using the TP108 approach (ARC, 1999).

**Table 9**

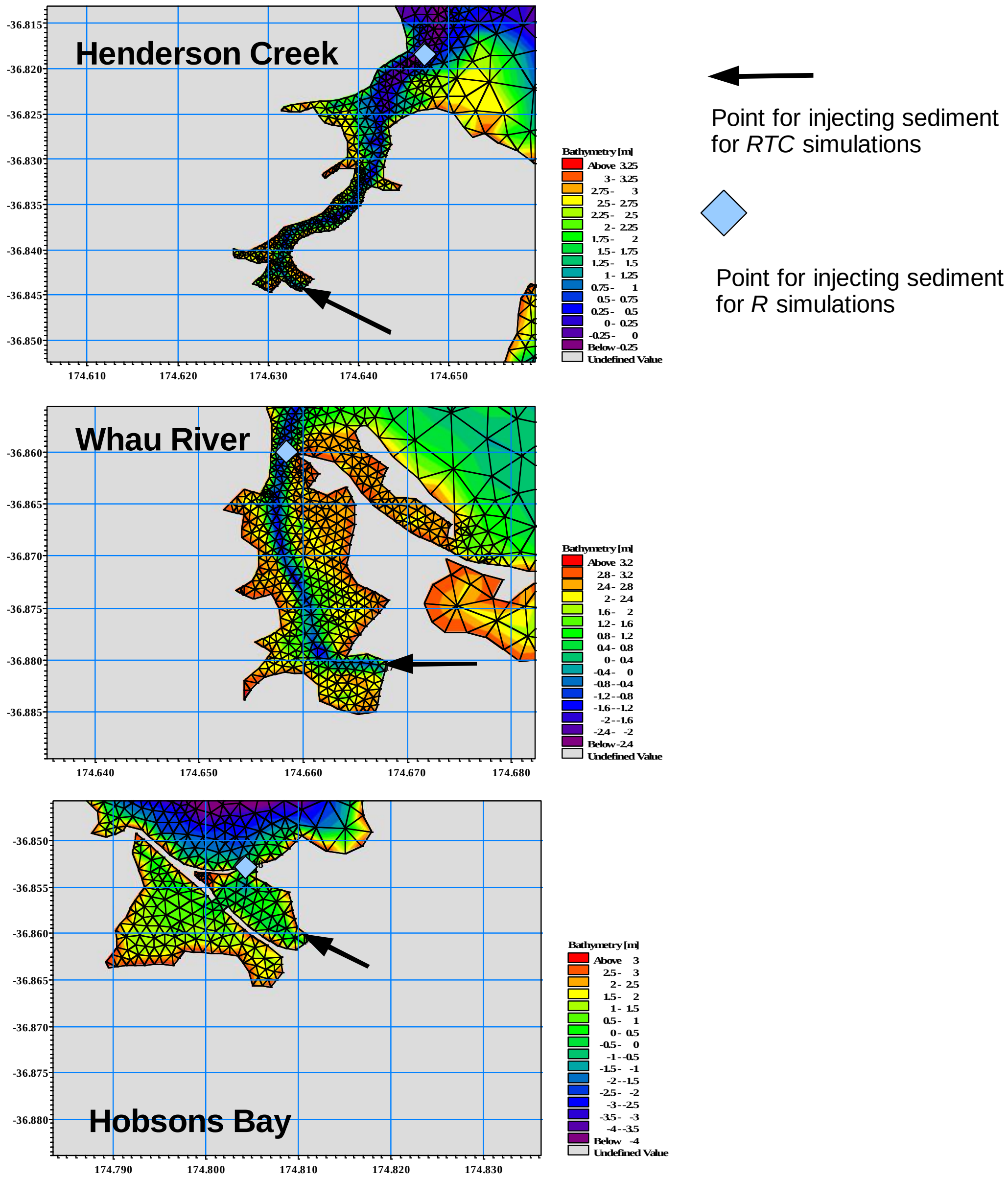
Freshwater inputs ($m^3\ s^{-1}$) associated with each of 7 rainfall bands addressed in the *RTC* simulations.

| Sub-catchment | Rainfall (mm) | | | | | | |
|---|---|---|---|---|---|---|---|
| | 0.9–4.6 | 4.6–10.3 | 10.3–18.8 | 18.8–30.0 | 30–60 | 60–100 | >100 |
| 15 - SBN | 0.07 | 0.30 | 0.80 | 1.61 | 3.13 | 6.71 | 15.28 |
| 14 - SBE | 0.02 | 0.11 | 0.30 | 0.59 | 1.13 | 2.37 | 5.25 |
| 13 - LSB | 0.01 | 0.06 | 0.18 | 0.38 | 0.79 | 1.81 | 4.39 |
| 12 - UWH | 9.12 | 17.21 | 23.10 | 26.05 | 29.48 | 33.44 | 37.74 |
| 11 - HBV | 0.01 | 0.06 | 0.15 | 0.30 | 0.58 | 1.27 | 2.98 |
| 10 - HEK | 0.25 | 1.02 | 3.15 | 7.23 | 16.32 | 41.28 | 108.67 |
| 9 - WHR | 0.14 | 0.72 | 1.94 | 3.89 | 7.63 | 16.64 | 38.76 |
| 8 - OAK | 0.07 | 0.35 | 0.93 | 1.84 | 3.56 | 7.59 | 17.31 |
| 7 - MEK | 0.04 | 0.21 | 0.55 | 1.07 | 2.04 | 4.32 | 9.84 |
| 6 - MOK | 0.02 | 0.11 | 0.28 | 0.56 | 1.09 | 2.33 | 5.30 |
| 5 - COB | 0.03 | 0.13 | 0.35 | 0.71 | 1.40 | 3.07 | 7.11 |
| 4 - WSB | 0.02 | 0.08 | 0.22 | 0.45 | 0.86 | 1.83 | 4.10 |
| 3 - CST | 0.02 | 0.08 | 0.22 | 0.42 | 0.78 | 1.57 | 3.33 |
| 2 - SST | 0.01 | 0.07 | 0.19 | 0.38 | 0.73 | 1.57 | 3.61 |
| 1 - HBY | 0.06 | 0.28 | 0.76 | 1.53 | 3.00 | 6.54 | 15.21 |

A unit load of land-derived sediment was injected into the head of each tidal creek in suspension (Figure 9). The sediment was injected continuously over the first 24 hours of each simulation. The injected sediment was tracked until "equilibrium" was attained. This was defined as the time when all (99 %) of the injected sediment could be accounted for by settlement to the bed (anywhere in the harbour where deposition is permitted) or loss to a sink. *RTC* is defined as the ratio of sediment exported from the tidal creek by the end of the simulation to the amount of sediment injected into the tidal creek.

**Figure 9**

Sediment injection point for the *RTC* simulations. Also shown is the injection point for the *R* simulations.

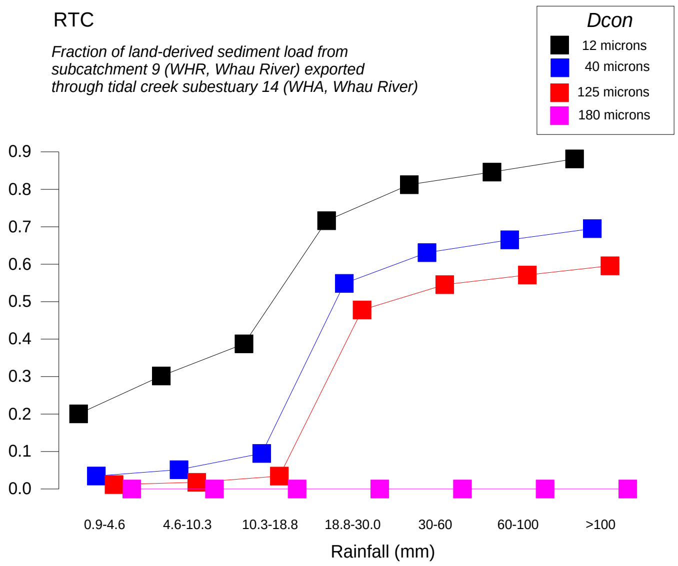



Appendix 5 shows values for *RTC* as the fraction of the land-derived sediment load exported from each tidal creek under the different freshwater inputs.

An example of *RTC* is shown in Figure 10. Compared to larger particle sizes, a greater portion of the 12 µm sediment load is exported from the Whau River into the main body of the harbour. As rainfall and the corresponding freshwater discharge increase, a greater portion of the sediment load (all particle sizes) is flushed from the tidal creek.

In that regard, there is a step increase in the amount of sediment exported (all particle sizes), between about 20 and 30 mm rainfall.

**Figure 10**
*RTC* for attenuating the land-derived sediment load from sub-catchment 9 (Whau River) as it passes through the Whau River tidal creek (subestuary 14, Whau River).




As part of the Coastal Receiving Environment Assessment (CREA), detailed modelling studies of the Whau River tidal creek and Hobsons Bay were conducted by Croucher et al. (2005a) and Croucher et al. (2005b), respectively. In both cases, contaminant (sediment, zinc) accumulation models were developed, underpinned by the RMA-2 depth-averaged, finite-element hydrodynamic model (King, 2004). Eight different size classes of sediment were simulated, and "deposition fractions" for each size class for each of a number of representative storms were calculated. Some mention is made of how much sediment and zinc is predicted to escape the respective basins versus how much is retained. 28 % of the zinc discharged from outfalls into the Whau River is predicted to escape to the Waitemata Harbour. This is an average for three representative storms with "total mean flow range" <0.116 $m^3$ $s^{-1}$, 0.116 – 0.165 $m^3$ $s^{-1}$ and >0.165 $m^3$ $s^{-1}$. Comparing these numbers with the freshwater inputs in Table 9 suggests that the CREA simulations were biased towards relatively small rainstorms, in which case the *RTC* estimates for the Whau River are similar to the CREA results. It is difficult to provide a more precise comparison of the model results, since no corresponding amount of sediment that is predicted by the CREA modelling to escape to the Waitemata Harbour is given, and it is not explained how the figure of 28 % is broken down across size classes.

In contrast to the Whau River, the CREA modelling predicted that a high proportion (77 %) of the zinc discharged through outfalls into Hobsons Bay escapes to the Waitemata Harbour and Hauraki Gulf. This was explained by the highly energetic flow at the mouth of the Bay, which sweeps up and widely disperses particles that leave the Bay through its two narrow entrances. The *RTC* simulations show a similar large loss of 12 µm sediment from Hobsons Bay, across all freshwater inputs, but with relatively greater retention of the larger particle sizes in Hobsons Bay (Appendix 5). Again, it is difficult to make a more precise comparison of the model predictions given the way this information has been reported in the CREA study.

#### 5.6.2.2 R and RSUSP

*R* and *RSUSP* were determined for each of four $D_{con}$ constituent particle sizes (12, 40, 125 and 180 µm) and one set of environmental conditions (Table 6). In each set of environmental conditions there are five winds. Wind was chosen to vary as the principal control on dispersal of land-derived sediment in the main body of the harbour on the day of injection. The winds applied were the same winds applied during the calculation of *ED50*, *R5* and *R5SUSP* for the case when it is raining.

The tide range and the freshwater inputs were fixed in each set of environmental conditions. Freshwater discharge has little effect on the wider circulation patterns in main body of harbour, so it was fixed. Tide range does have an effect on the wider circulation patterns in the main body of harbour, but tide range was fixed nevertheless for practicality.

For each combination of $D_{con}$,, environmental condition and origin sub-catchment, a separate DHI model run was required.

For each model run, a unit load of suspended sediment was injected in suspension over 24 hours at the sub-catchment outfall in question. For the three sub-catchments that discharge into subestuaries that are designated as tidal creeks, the injection point was at the mouth of the corresponding tidal creek (see Figure 9). For all other sub-catchments, the injection point was the element in the harbour model closest to the sub-catchment outlet. The injected sediment was tracked as the simulation proceeded. All subestuaries in the harbour were "concreted". That is, bed sediment in subestuaries was not allowed to erode. However, land-derived sediment was able to settle and be resuspended from subestuaries, as dictated by the hydrodynamics. The DHI model was run for two complete tidal cycles. Model runs started at high tide and ended at high tide. High tide corresponds to slackwater.

For the purposes of this explanation, assume the origin sub-catchment is sub-catchment #1 and there are three subestuaries in total in the model domain. At the end of the model run, a sediment budget is constructed (Table 10), consisting of the amount of sediment deposited in each subestuary by the end of the injection day, and the amount of sediment remaining in suspension in each subestuary by the end of the injection day. *R* and *RSUSP* are calculated from the sediment budget as shown in Table 10.

**Table 10**
Example calculation of *R* and *RSUSP*.

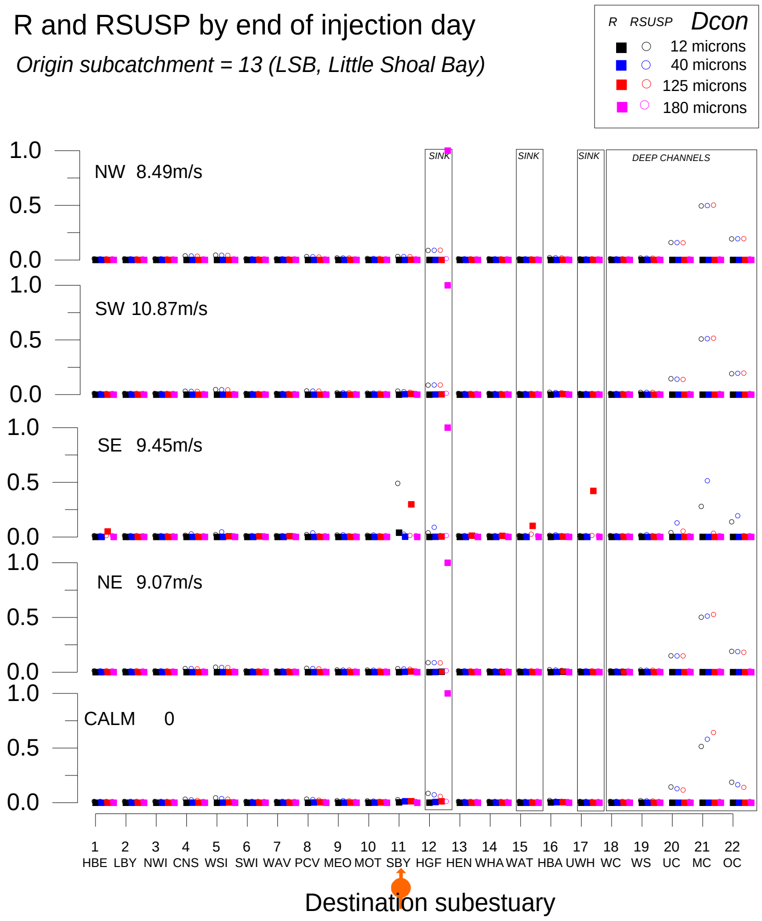
| Sub-catchment | kg sediment injected | Subestuary | kg sediment deposited | *R* | kg sediment in suspension | *RSUSP* |
|---|---|---|---|---|---|---|
| 1 | 1000 | 1 | 100 | 100/1000 | 0 | 0/1000 |
| | | 2 | 200 | 200/1000 | 500 | 500/1000 |
| | | 3 | 300 | 300/1000 | 0 | 0/1000 |

Appendix 6 shows the fraction of sediment that is injected from each origin sub-catchment and that deposits (*R*) and that is left in suspension (*RSUSP*) by the end of the injection day in each subestuary.

An example of *R* and *RSUSP* is shown in Figure 11. Land-derived sediment injected from Little Shoal Bay sub-catchment is largely dispersed into the deep channels of the harbour by the end of the injection day. With the exception of under a southeasterly wind, little of the land-derived sediment remains in Little Shoal Bay subestuary at the end of the injection day.

**Figure 11**

*R* and *RSUSP* (dimensionless) showing the dispersal of land-derived sediment injected from sub-catchment 13 (Little Shoal Bay – shown the arrow) by the end of the injection day.




Note: If the destination subestuary corresponds to a deep channel, then R is forced to 0, since sediments are not allowed to settle to the bed in deep channels.

### 5.6.3 Dispersal of sediment on days following resuspension/injection day

#### 5.6.3.1 RFS

*RFS* was determined for each of four $D_{con}$ constituent particle sizes (12, 40, 125 and 180 µm) and two sets of environmental conditions (Table 6). In each set of environmental conditions the wind was fixed and the freshwater inputs were fixed. Tide range was chosen to vary because this has the greatest effect on sediment dispersal over the longer term (ie, more than one-day). Tide range was varied by varying the starting point in the spring-neap cycle, as shown in Table 6.

For each combination of $D_{con}$, environmental condition and origin subestuary, a separate DHI model run was required.

A unit load (1000 kg) of sediment was placed in suspension in the origin subestuary at hand at the start of each model run, and tracked until "equilibrium" was attained. This was defined as the time when all (99 %) of the suspended sediment could be accounted for by settlement to the bed (anywhere in the harbour where deposition is permitted) or loss to a sink.

At the end of each model run, a sediment budget is constructed, and *RFS* calculated accordingly. Table 11 shows an example.

**Table 11**
Example calculation of *RFS*.

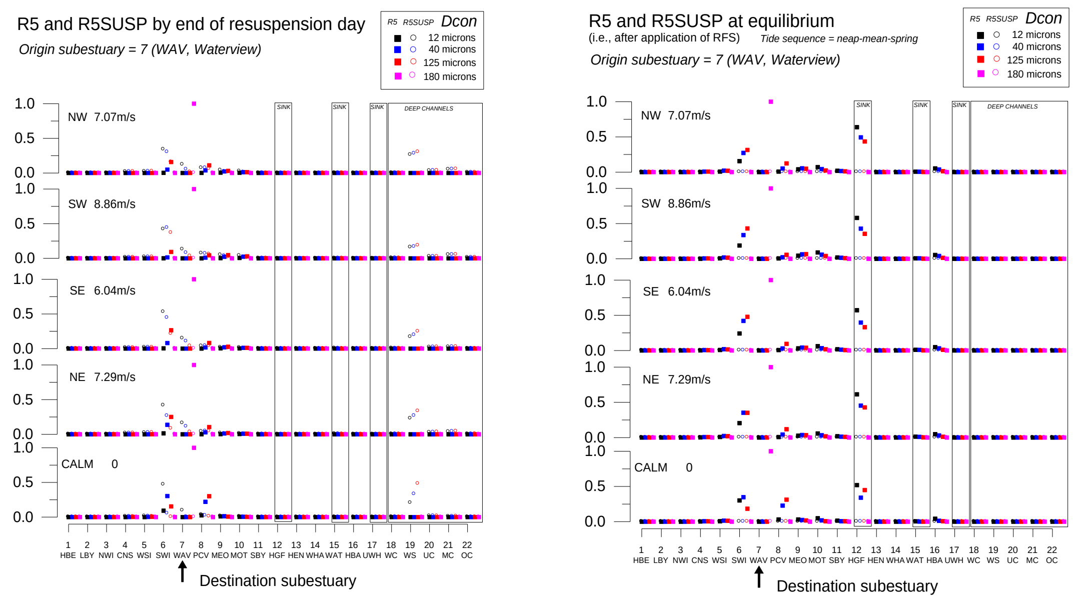
| Subestuary | kg sediment in suspension at start of DHI model run | kg sediment in suspension at end of DHI model run | *RFS* |
|---|---|---|---|
| 1 (origin) | 1000 | 200 | 200/1000 |
| 2 | 0 | 500 | 500/1000 |
| 3 | 0 | 300 | 300/1000 |

Appendix 7 shows the fraction of sediment that is resuspended from each origin subestuary on a day when it is not raining and deposited (*R5*) and left in suspension (*R5SUSP*) in each destination subestuary at equilibrium, ie, after application of the RFS term. The results of the four different tide sequences that were considered are shown. Note that after application of *RFS* no sediment is left suspended anywhere in the model domain. Hence, there is no sediment in the deep channels, since sediment in deep channels can only be in suspension.

Figure 12 shows a comparison between *R5* at the end of the resuspension day and *R5* at equilibrium (ie, after applying *RFS*) for estuarine sediment resuspended from the Waterview Flats subestuary. The 12 µm particle size is seen to disperse more widely than the larger particle sizes on the days following resuspension. Note, for instance, the arrival of the 12 µm particle size in adjacent subestuaries 9, 10 and 11, and the fact that a greater proportion of the 12 µm particle size deposits in those subestuaries compared to the larger particle sizes. The loss of all particle sizes to the Hauraki Gulf (subestuary 12) is increased on the days following resuspension, with the 12 µm particle size experiencing the greatest loss, which is expected.

**Figure 12**

Comparison between *R5* at the end of the resuspension day and *R5* at equilibrium (ie, after applying *RFS*) for estuarine sediment eroded from the Waterview Flats subestuary.



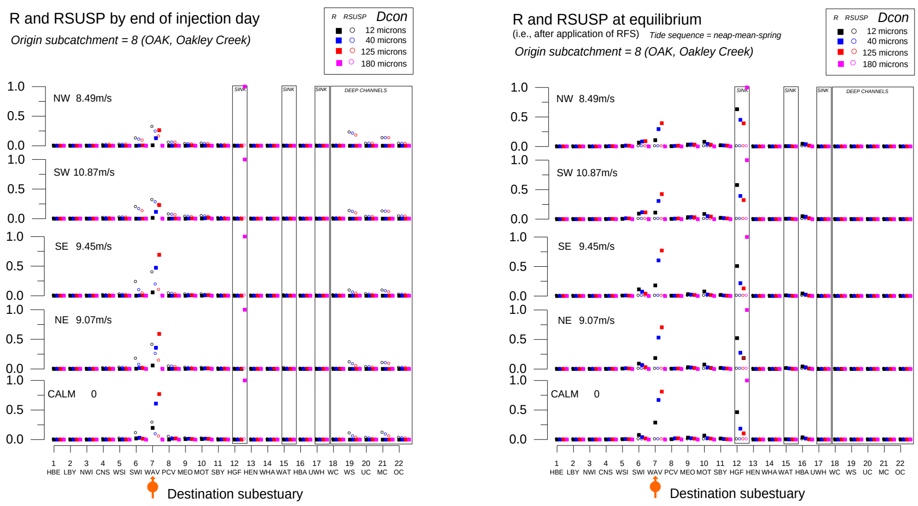

Appendix 8 shows the fraction of sediment that is resuspended from each origin subestuary on a day when it is raining and deposited (*R5*) and left in suspension (*R5SUSP*) in each destination subestuary at equilibrium, ie, after application of the RFS term. The results of the four different tide sequences that were considered are shown. Note that after application of *RFS* no sediment is left suspended anywhere in the model domain. Hence, there is no sediment in the deep channels, since sediment in deep channels can only be in suspension.

Appendix 9 shows the fraction of sediment that is injected from each origin sub-catchment and that deposits (*R*) and that is left in suspension (*RSUSP*) in each subestuary at equilibrium, ie, after application of the *RFS* term. The results of the four different tide sequences that were considered are shown. Note that after application of *RFS* no sediment is left suspended anywhere in the model domain. Hence, there is no sediment in the deep channels, since sediment in deep channels can only be in suspension.

Figure 13 shows a comparison between *R* at the end of the injection day and *R* at equilibrium (ie, after applying *RFS*) for land-derived sediment injected from the Oakley Creek (sub-catchment 8) outfall. The 12 μm particle size is seen to disperse more widely than the larger particle sizes on the days following injection. Note, for instance, the arrival of the 12 μm particle size in adjacent subestuaries 9 and 10. The loss of all particle sizes to the Hauraki Gulf (subestuary 12) is increased on the days following injection, with the 12 μm particle size experiencing the greatest loss, which is expected.

**Figure 13**

Comparison between *R* at the end of the injection day and *R* at equilibrium (ie, after applying *RFS*) for land-derived sediment injected from the Oakley Creek (sub-catchment 8) outfall.




## 5.7 Calculation of heavy metal concentration in surface mixed layer

Mixing on the one hand moves sediments (and attached heavy metals) near the surface of the sediment column deeper into the sediment column, and on the other hand moves sediments deeper in the sediment column towards the surface. Mixing therefore has the net effect of reducing gradients in heavy metal concentrations in the bed sediment. For example, a recently deposited layer carrying heavy metals at a concentration greater than in the underlying bed sediment will get mixed downwards, obliterating the concentration gradient between the recently deposited layer and the underlying bed sediment, and slightly raising the concentration in the surface mixed layer (which now includes the recently deposited layer) as a whole. If the recently deposited layer carries metal at a concentration less than the underlying bed sediment, then concentration in the surface mixed layer will be reduced.

For the application of the USC-3 model in the Central Waitemata Harbour, mixing is assumed to act uniformly from the surface down to a depth of *MIXDEPTH*.

After mixing, the concentration of heavy metal in the surface mixed layer is given by the ratio of the total amount of heavy metal (attached to all particle sizes) in the surface mixed layer to the total amount of sediment (ie, all particle sizes) in the surface mixed layer:

$$HEAVYMETALCONCSML =$$

$$\sum_{iparticle=1}^{nparticle} HEAVYMETALMASSSML_{iparticle} \Big/ \sum_{iparticle=1}^{nparticle} SEDIMENTMASSSML_{iparticle}$$

Hence, heavy metal concentration is expressed as mass of heavy metal per mass of sediment.  Furthermore, heavy metal concentrations are "total-sediment" concentrations.

- Note that *HEAVYMETALCONCSML* is the primary output of the USC-3 model.

For the implementation of the USC-3 model in the Central Waitemata Harbour, sediment and heavy metals are taken from the (layered) bed sediment column each time the heavy metal concentration is to be evaluated, as follows:

$$HEAVYMETALCONCSML =$$

$$\sum_{ilayer=1}^{nlayersmixed} \sum_{iparticle=1}^{nparticle} HEAVYMETALMASSSML_{iparticle,ilayer} / SEDIMENTMASSSML_{iparticle,ilayer}$$

where there are *nlayersmixed* layers in the bed sediment column corresponding to the mixing depth *MIXDEPTH*.

As noted previously, if it is not raining, the heavy metal concentration is made to apply at the end of the resuspension day ( ie, the day the sediment was resuspended), even though *RFS* acts beyond that day to fully disperse and deposit resuspended sediment. Similarly, if is it raining, the heavy metal concentration is made to apply at the end of the day it was raining, even though *RFS* acts beyond that day to fully disperse and deposit both the injected land-derived sediments and the resuspended estuarine bed sediments.

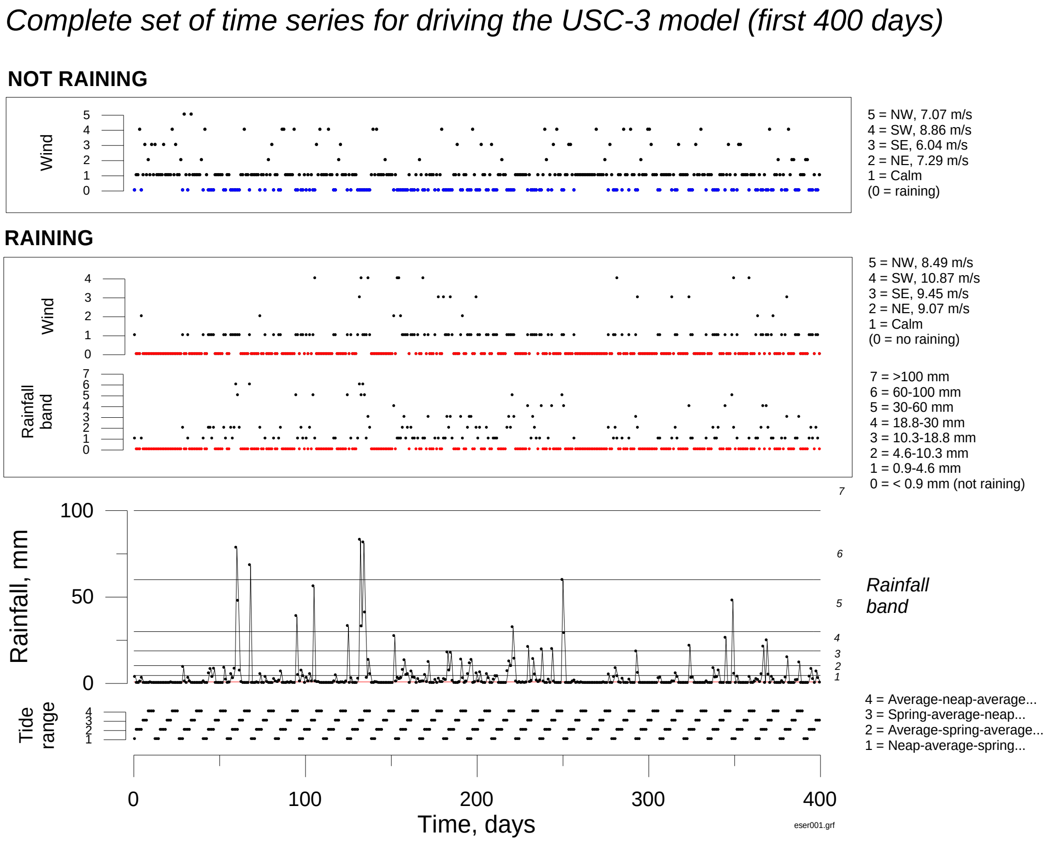
## 5.8 Completion of the time series for driving the USC-3 model

The scheme for evaluating the land-derived sediment and contaminant loads at BOC (described previously) resulted in a 100-year time series of daily rainfall and corresponding 100-year time series of sediment run-off emanating from the bottom of each sub-catchment.  The daily timestep of these series matches the daily timestep of the USC-3 model, and are used to drive the USC-3 model.

Further daily time series are required to drive the model.  These are the rainfall band, the wind, and the tide range.  These are used to choose the various parameters in the model that get applied on a daily basis (for example, see Table 6).

An example of a complete set of time series (all with a daily timestep) for driving the USC-3 model is shown in Figure 14.

**Figure 14**
A complete set of time series, all with a daily timestep, for driving the USC-3 model.




## 5.8.1 Rainfall band

The rainfall band on each day is evaluated from the daily rainfall time series. Rainfall bands are shown in Table 6. Furthermore:

- If the daily rainfall is less than 0.9 mm it is said to be “not raining”.
- If the daily rainfall is greater than 0.9 mm it is said to be “raining”.

A threshold of 0.9 mm rainfall was chosen as the rainfall required across the catchment to have any significant effect on freshwater inflows and sediment delivery to the harbour.

Rainfall bands above the 0.9 mm threshold (Table 6) were chosen to span extreme events.

## 5.8.2 Wind

The wind on each day is randomly chosen:

- If it is raining, one of the 5 winds shown in Table 6 for days it is raining is chosen.

- If it is not raining, one of the 5 winds shown in Table 6 for days it is not raining is chosen.

In both cases, the random choice is constructed so that calm winds occur 80 % of the time. Here, "calm" means wind speed less than 4 m $s^{-1}$, which is not sufficient to raise any significant wave activity in the harbour. The "non-calm" wind speeds (Table 6) were chosen to represent more extreme wind events, which in turn is intended to depict larger and "more effective" sediment resuspension and transport episodes

If it is not calm, then:

- winds from the northeast are chosen 6 % of the time;
- winds from the southeast are chosen 6 % of the time;
- winds from the southwest are chosen 7 % of the time; and
- winds from the northwest are chosen 1 % of the time.

This scheme yields wind speeds and directions at frequencies that correspond to frequencies that emerge from analysis of three-hourly wind data from Auckland Airport for the period 1980–2005.

### 5.8.3 Tide range

The tide range is "deterministic", meaning that it can be predicted exactly in advance. For each of the *N* model simulations in a Monte Carlo "package", the tide range at the starting point in the simulation at hand is chosen randomly.

## 5.9 Mixing depth

Various estimates of mixing depth in bed sediments of the Central Waitemata Harbour have been reported by Swales et al. (2008b), based on measurements of radioisotope activity, x-ray images of sediment cores, and inferences from sediment fauna. Further comments on mixing, based on measurements of zinc and copper concentrations in sediment cores, are provided by Ahrens et al. (2008).

The bioturbation index reported by Swales et al. shows the potential for bioturbation to 10 cm depth or more in the Central Waitemata Harbour. The index was 120–970 at sites in the subtidal central basin and 2300–5600 at intertidal sites ringing the subtidal basin. The substantially lower values for the index in the subtidal sites reflect lower densities and smaller sizes of animals, which suggests that sediment mixing is less intense than at intertidal sites.

In contrast, Swales et al. also described $^{7}Be$ and $^{210}Pb$ profiles preserved in sediment cores that show that surface sediments in subtidal and intertidal sites alike are well-mixed to 1–5 cm depth in a surface mixed layer and to ≥ 3 cm depth in 60 % of the sites sampled. These are direct observations of mixing, and so are preferred over the indirect inferences from the bioturbation index.

An important observation was that the surface mixed layer inferred from the $^{7}Be$ data corresponded almost exactly with the surface mixed layer inferred from the $^{210}Pb$ data, from which Swales et al. concluded that most of the mixing occurred over periods of <100 days. This indicates that mixing is primarily due to physical processes, as opposed to bioturbation. Bioturbation, which operates over a longer timescale than physical mixing, would result in a deeper $^{210}Pb$ surface mixed layer compared to the $^{7}Be$ surface mixed layer, which is not the case here. That homogenisation does not occur below the 5 cm deep surface mixed layer indicated by the radioisotope data does not preclude deeper mixing by animals, but does indicate that the rate of mixing is low below 5 cm depth.

Placing more weight on the direct (radioisotope and x-ray) observations, and given that the mixing depth in the USC-3 model is physically equivalent to the depth of the surface mixed layer, the mixing depth in the model was set to 5 cm. Furthermore, the mixing depth was set to that value uniformly throughout the model domain.

The mixing depth in the USC-3 model applies to the sediment column as a whole (ie, to all constituent particle sizes). This is consistent with Swales et al.'s conclusion that mixing is primarily due to physical processes, which, at least to first order, can be expected to overturn the bed sediment *en masse*. That contrasts the case of bioturbation, where mixing could be particle-dependent as a result of biological selection, eg, feeding processes. The three cores that were analysed by Ahrens et al. (2008) for metals also do not support particle-dependent mixing.

# 6 Model Behaviour

The harbour can be viewed simply as a bucket that contains sediment and metal, and sediment and metal from another bucket – the catchment – gets tipped into the harbour bucket as the simulation proceeds. At the start of the simulation, metal is present in the harbour bucket at some average concentration. If metal is present in the catchment bucket at the same concentration, then the concentration in the harbour bucket will not change as the simulation proceeds. On the other hand, if metal is present in the sub-catchment at a greater (lesser) concentration, then the concentration in the harbour bucket will increase (decrease) as the simulation proceeds. If there is enough time and if the metal concentration in the catchment bucket does not change, then the concentration in the harbour bucket will attain the same concentration as in the catchment bucket, which is termed "equilibrium".

Figure 15 demonstrates the equilibrium principle: subestuary 13, which is a sink and which therefore monotonously accumulates sediments (Figure 16), attains equilibrium just before the end of the simulation. However, subestuary 2, which is not a sink and which therefore experiences erosion and deposition as the simulation proceeds (Figure 16), does not reach equilibrium. Notice how the changes in metal concentration that do occur in subestuary 2 correspond with periods when the sediment column is in an accreted state.

**Figure 15**

Change in metal concentration over time: initial metal concentration in estuary bed sediment = 50 mg $kg^{-1}$; metal concentration in sediment run-off from catchment = 90 mg $kg^{-1}$.

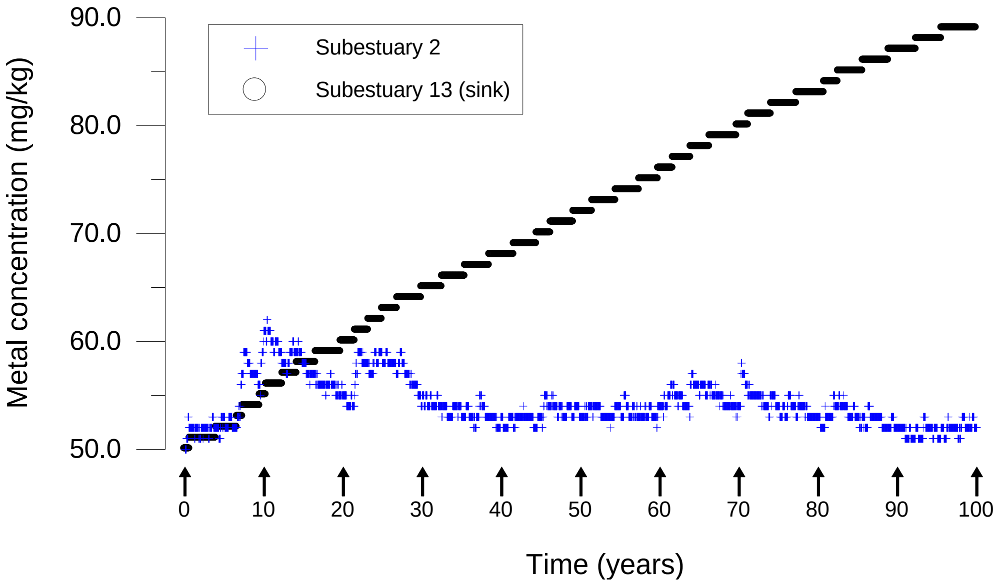
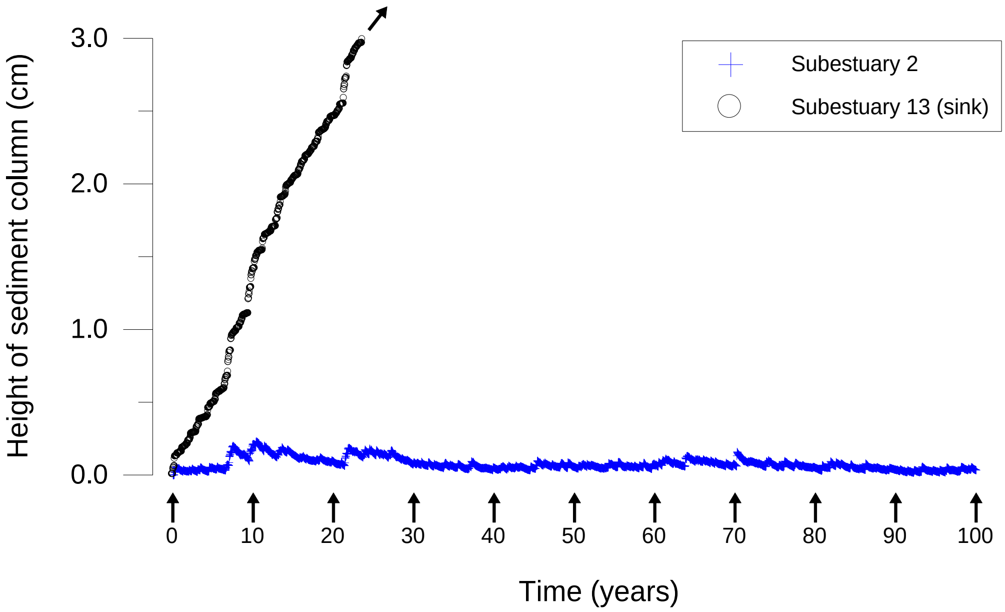


**Figure 16**

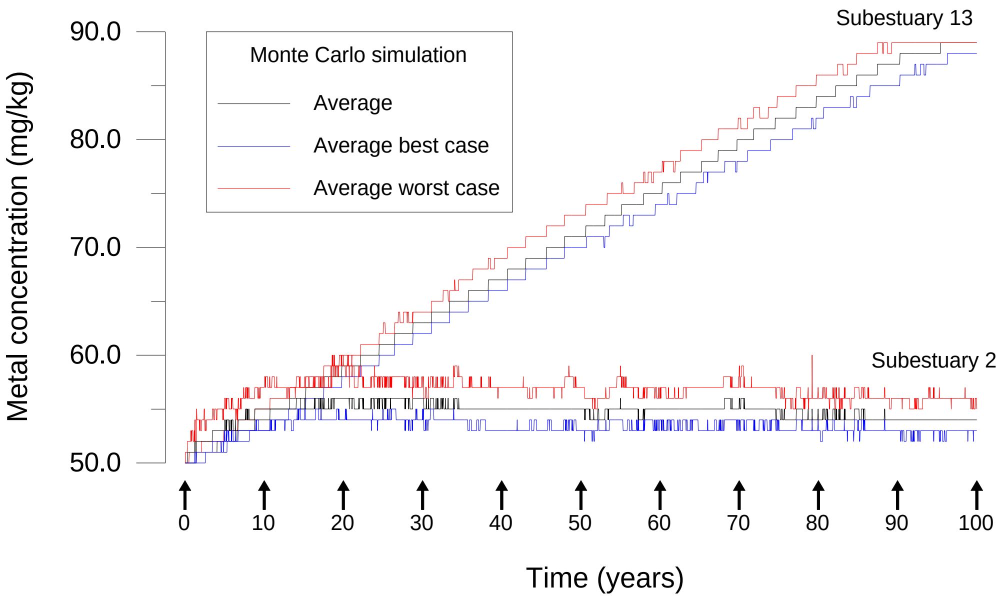
Change over time in height of the sediment column above the starting level of 0 cm. Subestuary 13 is a sink.




The equilibrium principle is also shown in Figure 17, this time from a Monte Carlo simulation consisting of 50 model runs, in which the rural (GLEAMS) sediment loads were randomly varied, as described previously. The "average" referred to in Figure 17 is the average over all of the 50 runs that comprised the Monte Carlo simulation. The "average worst case" is the average positive deviation from the "average". The "average best case" is the average negative deviation from the "average". The average worst case corresponds to larger-than-average rural sediment inputs, which deliver correspondingly more (natural) metal to the harbour, thus driving the estuary bucket more quickly to equilibrium. Conversely, the average best case corresponds to smaller-than-average rural sediment inputs, which deliver correspondingly less (natural) metal to the harbour, thus driving the estuary bucket more slowly to equilibrium.

**Figure 17**

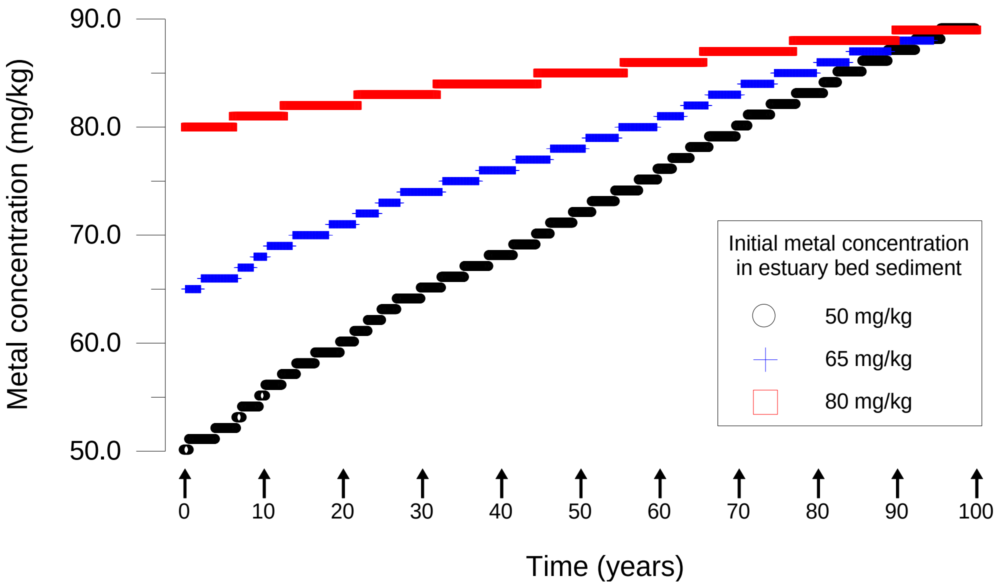
Change in metal concentration over time: initial metal concentration in estuary bed sediment = 50 mg kg$^{-1}$; metal concentration in sediment run-off from catchment = 90 mg kg$^{-1}$. Results from a Monte Carlo simulation consisting of 50 individual model runs.




All other things being equal, the rate at which equilibrium is approached varies directly with how far from equilibrium the harbour is, that is, the difference between the metal concentration in the harbour and the metal concentration in sediment from the catchment. This is evident in Figure 15, which shows the rate of change of concentration reducing through time, and it is also more explicitly demonstrated in Figure 18.

**Figure 18**

Change in metal concentration over time: initial metal concentration in estuary bed sediment = 50 mg kg$^{-1}$, 65 mg kg$^{-1}$ and 80 mg kg$^{-1}$; metal concentration in sediment run-off from catchment = 90 mg kg$^{-1}$.



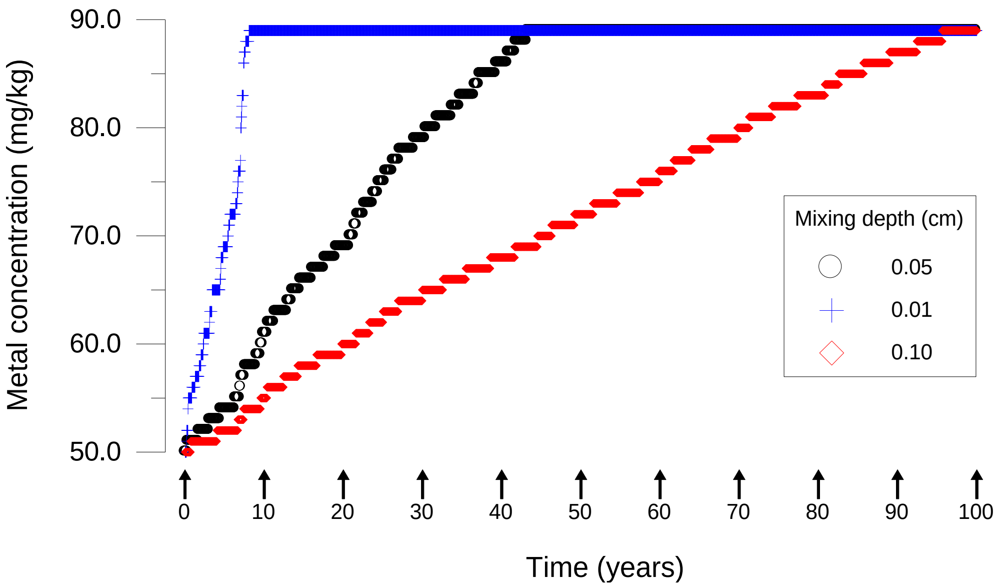

Metal concentrations are evaluated in the model over the surface mixed layer. For the purposes of this discussion, assume a single layer of sediment and attached metal is deposited between applications of mixing.

If the mixing depth is less than the thickness of the deposited layer, then the metal concentration in the new surface mixed layer will immediately jump to the metal concentration in the deposited layer.

On the other hand, if the mixing depth is greater than the thickness of the deposited layer, which will nearly always be the case, then the new surface mixed layer will incorporate all of the deposited layer as well as some of the pre-existing sediment. In that case, metal concentration in the new surface mixed layer will lie somewhere between the metal concentration in the deposited layer and the metal concentration in the pre-existing sediment. The greater the mixing depth relative to the thickness of the deposited layer, the more pre-existing sediment will be incorporated in the new surface mixed layer, and the smaller will be the change in metal concentration in the new surface mixed layer as a result. This equates to a slower change in metal concentration in the surface mixed layer over time under repeated deposition events. The converse of all of that is: the smaller the mixing depth relative to the thickness of the deposited layer, the quicker the change in metal concentration in the surface mixed layer over time under repeated deposition events. This is demonstrated in Figure 19, which shows the rise, under three different mixing depths, in metal concentration in the surface mixed layer towards an equilibrium value imposed by run-off from the catchment.

**Figure 19**

Change in metal concentration over time: initial metal concentration in estuary bed sediment = 50 mg $kg^{-1}$; metal concentration in sediment run-off from catchment = 90 mg $kg^{-1}$.




Given a particular set of sediment and heavy metal inputs from the catchment, the model predictions of heavy metal concentration in the surface mixed layer of the estuary bed sediments are most sensitive to variations in the mixing depth. The reason for this dependence has just been explained; in effect, the mixing depth determines the "inertia" of the system. Figure 19 gives some indication of the extent of the sensitivity.

With this simple explanation of how the system being modelled works, model calibration is now described.

# 7 Model Calibration

The USC-3 model was run for the historical period 1940 to 2001, with sediment and metal inputs from the catchment appropriate to that period. The aim of the calibration process was to adjust various terms in the USC-3 model so that its hindcasts ("backward-looking predictions") during the historical period came to match observations from that same period.

The parameters that may be adjusted to achieve model calibration are:

- the area over which deposition in each subestuary may occur;
- the rate at which sediments and metals are lost to both pre-defined and "dynamic" sinks; and
- a so-called "metal retention factor", which is the fraction of the metal load emanating from each sub-catchment that is attached to the corresponding sediment particulate load and that therefore gets discharged into the harbour.

The model with those adjusted terms then constitutes the calibrated model.

For model calibration, the USC-3 model was run in a Monte Carlo package, which consisted of 50 individual USC-3 model runs. The average of the 50 individual model outputs was used in the calibration process.

## 7.1 Land use – historical period

The method applied to develop a description of the land use for the historical period, and the land use so derived, are documented in Parshotam and Wadhwa (2008a).

## 7.2 Sediment inputs – historical period

The total sediment run-off from the catchment into the harbour is the sum of the sediment run-off from rural areas, which is hindcast by GLEAMS, and the sediment run-off from urban areas, which is hindcast by the CLM.

The implementation of GLEAMS for the Central Waitemata Harbour Contaminant Study is documented by Parshotam and Wadhwa (2008b). The GLEAMS historical-period hindcasts are presented in detail by Parshotam and Wadhwa (2008a).

The implementation of the CLM for the Central Waitemata Harbour Contaminant Study is documented by Timperley and Reed (2008a). The CLM historical-period hindcasts are also presented there in some detail.

Note: for the historical period only, the GLEAMS hindcasts were of sediment run-off from rural areas plus sediment run-off from greenfields bare earth (earthworks) in urban areas. Correspondingly, the CLM hindcasts were of sediment run-off from urban areas not including sediment run-off from greenfields bare earth (earthworks).

### 7.2.1 Sediment inputs from rural sources

Fifty time series, each covering the period 1940–2001, of daily rural sediment run-off from each sub-catchment are required (one time series for each USC-3 model run in the Monte Carlo package). Each of these 50 time series was constructed by block sampling of hindcasts from GLEAMS.

GLEAMS was run for six historical land uses, these corresponding to the years 1945, 1964, 1975, 1987, 1996 and 2001. Each of these runs was driven by a 50-year rainfall time series covering the period 1 January 1954 to 31 December 2003.

For the purposes of the block sampling, these land uses, and the corresponding GLEAMS hindcasts of rural sediment run-off, were deemed to apply for the following periods of time:

- 1945 land use applies to the period 1940–1961.
- 1964 land use applies to the period 1962–1972.
- 1975 land use applies to the period 1973–1984.
- 1987 land use applies to the period 1985–1993.
- 1996 land use applies to the period 1994–1997.
- 2001 land use applies to the period 1998–2001.

The block sampling scheme has been described in Chapter 5 of this report. Because it is a random scheme, each of the 50 time series of daily rural sediment run-off may be unique.

The split of the rural sediment load amongst the constituent particle sizes (12, 40, 125 and 180 µm) is shown in Table 12, which was based on suspended-sediment sampling at various sites in the Auckland region. Further details are given in Parshotam and Wadhwa (2008b). This split was applied to the rural sediment load from every sub-catchment.

**Table 12**
Split of rural sediment load amongst the constituent particle sizes (12, 40, 125 and 180 µm) that was applied to every sub-catchment for the historical period.

| Constituent particle size (µm) | Fraction of rural sediment load |
|---|---|
| 12 | 0.5 |
| 40 | 0.3 |
| 125 | 0.2 |
| 180 | 0.0 |

### 7.2.2 Sediment inputs from urban sources

Fifty time series, each covering the period 1940–2001, of daily urban sediment run-off from each sub-catchment are also required (as before, one time series for each USC-3 model run in the Monte Carlo package).

The CLM was used to produce a hindcast of annual (not daily) urban sediment run-off from each sub-catchment for the period 1940–2001. The 50 required time series of daily urban sediment run-off (one time series for each USC-3 model run in the Monte Carlo package, with each time series covering the period 1940–2001) were constructed by distributing the urban sediment run-off for each year in proportion to the corresponding daily GLEAMS sediment loads for that same year. This scheme has also been described in Chapter 5 of this report.

The split of the urban sediment load from each sub-catchment amongst the constituent particle sizes (12, 40, 125 and 180 µm) was calculated by the CLM (Table 13).

**Table 13**
Fraction of urban sediment load assigned to each constituent particle size (12, 40, 125 and 180 µm) during the historical period, calculated by the CLM.

| Sub-catchment | Constituent particle size (µm) | | | |
|---|---|---|---|---|
| | 12 | 40 | 125 | 180 |
| 1 – HBY | 0.36 | 0.34 | 0.30 | 0.00 |
| 2 – SST | 0.36 | 0.34 | 0.30 | 0.00 |
| 3 – CST | 0.37 | 0.34 | 0.30 | 0.00 |
| 4 – WSM | 0.36 | 0.34 | 0.30 | 0.00 |
| 5 – COB | 0.36 | 0.34 | 0.30 | 0.00 |
| 6 – MOK | 0.37 | 0.34 | 0.30 | 0.00 |
| 7 – MEK | 0.36 | 0.34 | 0.30 | 0.00 |
| 8 – OAK | 0.36 | 0.34 | 0.30 | 0.00 |

| Sub-catchment | Constituent particle size (μm) | | | |
|---|---|---|---|---|
| | 12 | 40 | 125 | 180 |
| 9 – WHR | 0.36 | 0.34 | 0.30 | 0.00 |
| 10 – HEK | 0.36 | 0.34 | 0.30 | 0.00 |
| 11 – HBV | 0.36 | 0.34 | 0.30 | 0.00 |
| 12 – UWH | – | – | – | – |
| 13 – LSB | 0.36 | 0.34 | 0.30 | 0.00 |
| 14 – SBN | 0.36 | 0.34 | 0.30 | 0.00 |
| 15 – SBE | 0.37 | 0.34 | 0.30 | 0.00 |

### 7.2.3 Sediment inputs from the Upper Waitemata Harbour

Since it can be viewed simply as a source of metals and sediments to the Central Waitemata Harbour, the Upper Waitemata Harbour is treated in the USC-3 model as a sub-catchment of the CWH.

The sediment inputs from the Upper Waitemata Harbour (sub-catchment 12) were not derived from either GLEAMS or the CLM. Instead, these were derived from USC-2 model hindcasts performed as part of the 2004 Upper Waitemata Harbour Contaminant Study. Specifically, sediment inputs from the UWH to the CWH were set equal to the loss of sediments from the UWH to the CWH as hindcast by the USC-2 model in a similar exercise to the one being done here, which was aimed at calibrating the USC-2 model over the historical period 1950–2000. Further details are given in Green et al. (2004). The USC-2 model as it was implemented for the UWH did not distinguish between sediments of rural and urban origin. It is not possible to "back calculate" this split.

The sediment load split shown in Table 12 was applied to sediment inputs from the UWH.

### 7.2.4 Total (rural plus urban) sediment inputs

The daily rural and daily urban sediment run-offs were added to give daily total sediment run-offs. This results in 50 daily time series (one time series for each USC-3 model run in the Monte Carlo package, with each time series covering the period 1940–2001).

Note that the rural component of the total sediment run-off may vary from time series to time series, since this is constructed from random sampling of the GLEAMS outputs. The sum over each year of the urban component of the total sediment run-off will be the same for every time series, since these derive from the hindcast by the CLM of annual urban sediment loads. However, the **distribution** of the daily urban sediment run-off throughout the year may vary from time series to time series, as this depends on the daily rural (GLEAMS) sediment run-off.

Table 14 and Figure 20 show some statistics of the total (urban plus rural) sediment run-off.

- Sub-catchment 10 – HEK (Henderson Creek) is the principal sediment source to the harbour.
- Sub-catchment 9 – WHR (Whau River) is the next largest source.
- The larger rainfall events deliver more sediment to the harbour than the smaller rainfall events. However, summed over the duration of the simulation, medium-size events deliver more sediment than both smaller and larger events. Small-size events occur more frequently than medium-size events, but they deliver less sediment per event. Large-size events deliver more sediment per event than medium-size events, but they occur less frequently.

Figure 21 shows the annual sediment run-off.

- For all sub-catchments, the proportion of the total sediment run-off from rural sources decreased over time in the historical period, and the proportion of the sediment run-off from urban sources correspondingly increased. This, of course, reflects the increasing urbanisation of the catchment through the historical period.
- For most of the historical period, sediment from rural sources dominated run-off from sub-catchment 10 – HEK (Henderson Creek), which is the principal source of sediment to the harbour.
- Early in the historical period, sediment from rural sources dominated sediment run-off from sub-catchment 9 – WHR (Whau River), which is the next largest source of sediment to the harbour. Later in the historical period, sediment from rural sources dwindled.
- For some sub-catchments (eg, 9 – WHR, 8 – OAK and 1 – HBY), sediment from rural sources reduced virtually to zero by halfway through the historical period, reflecting almost complete urbanisation of the respective sub-catchments. For others (eg, 3 – CST and 4 – WSM), the historical period began with the sub-catchment virtually completely urbanised.
- In the late 1980s and early 1990s there was a spike in rural sediment inputs, which was due to a surge in greenfields development, and accompanying bare earth (earthworks).

Figure 22 shows daily total (rural plus urban) sediment run-off plotted against rainfall. The large variability in the response of the catchment to rainfall is apparent, which is due to GLEAMS capturing the effects on sediment generation of antecedent rainfall and rainfall intensity on the day of generation.

**Table 14**

Statistics of the total (rural plus urban) sediment run-off. These statistics are for the sum of all particle sizes, and are for just one USC-3 model run in the Monte Carlo package of 50 USC-3 model runs.

| Sub-catchment | Average per year (kg) | Sum over simulation (kg) |
|---|---|---|
| 1 – HBY | 1,474,382 | 91,411,696 |
| 2 – SST | 309,626 | 19,196,820 |
| 3 – CST | 178,484 | 11,066,016 |
| 4 – WSM | 245,011 | 15,190,665 |
| 5 – COB | 500,582 | 31,036,090 |
| 6 – MOK | 359,956 | 22,317,272 |
| 7 – MEK | 767,381 | 47,577,596 |
| 8 – OAK | 1,306,047 | 80,974,920 |
| 9 – WHR | 3,471,705 | 215,245,696 |
| 10 – HEK | 8,560,855 | 530,772,992 |
| 11 – HBV | 336,437 | 20,859,100 |
| 12 – UWH | 1,651,838 | 102,413,968 |
| 13 – LSB | 481,904 | 29,878,046 |
| 14 – SBN | 1,157,694 | 71,777,016 |
| 15 – SBE | 329,951 | 20,456,984 |

**Figure 20**

Statistics of the total (rural plus urban) sediment run-off. These statistics are for the sum of all particle sizes, and are for just one USC-3 model run in the Monte Carlo package of 50 USC-3 model runs.

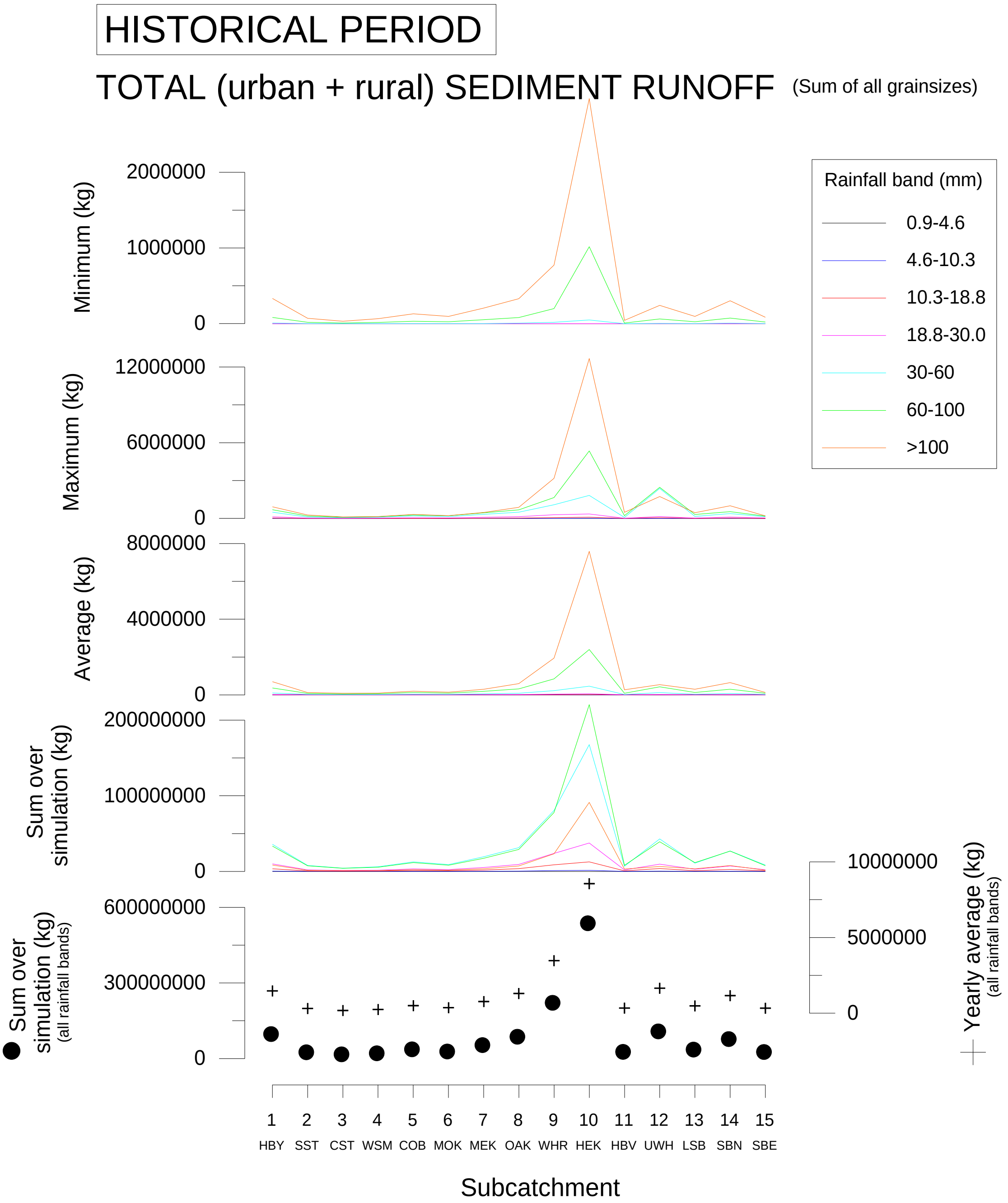


**Figure 21**

Annual sediment run-off. This is the sum of all particle sizes, as it appears for just one USC-3 model run in the Monte Carlo package of 50 USC-3 model runs. This figure shows the urban component of the total load, and the total load. The rural component of the total load is the difference between those two. Year 1 is 1940 and year 62 is 2001.

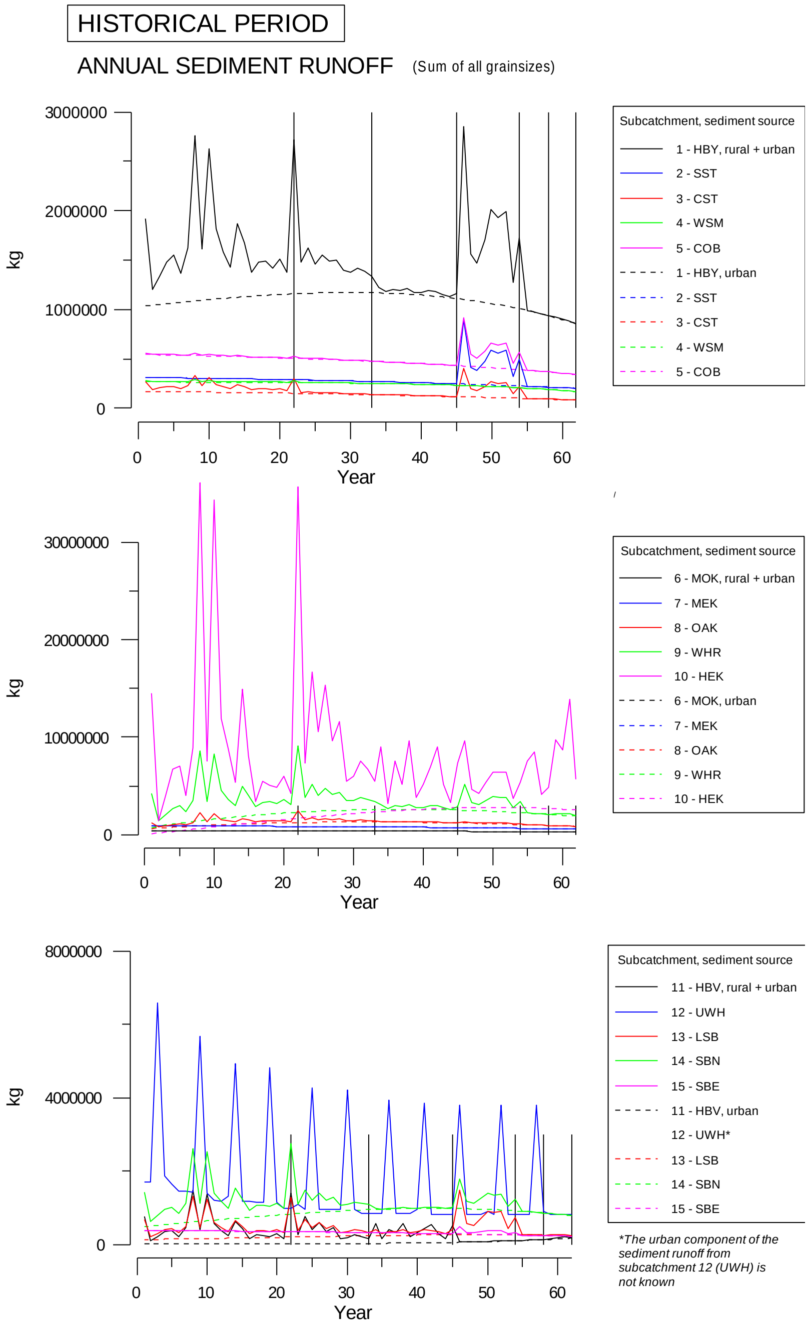
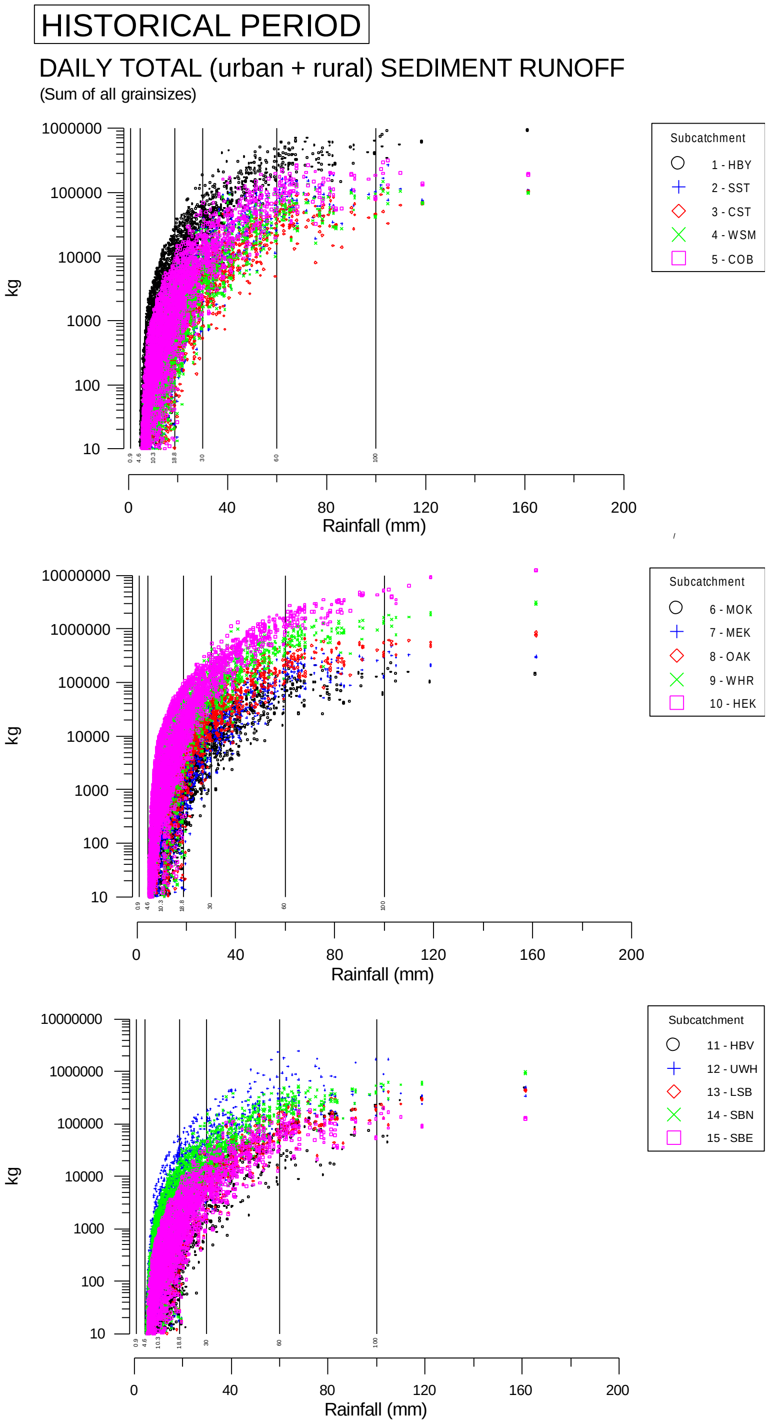


**Figure 22**

Daily total (rural plus urban) sediment run-off plotted against daily rainfall. This is the sum of all particle sizes, as it appears for just one USC-3 model run in the Monte Carlo package of 50 USC-3 model runs.



## 7.3 Metal inputs – historical period

### 7.3.1 Natural metal inputs

Table 15 shows the concentration at which zinc is carried on soils in the sub-catchments of the Central Waitemata Harbour, which is taken from Reed (2007). Table 16 shows the concentration at which copper is carried on soils in the sub-catchments of the Central Waitemata Harbour, also from Reed (2007).

To calculate daily inputs of natural metals to the harbour:

- The 12 µm fraction of the daily total (urban plus rural) sediment load was multiplied by the <25 µm concentration and the resulting metal load was carried in the USC-3 model by the 12 µm sediment constituent particle size.
- The 40 µm fraction of the daily total (urban plus rural) sediment load was multiplied by the 25–63 µm concentration and the resulting metal load was carried in the USC-3 model by the 40 µm sediment constituent particle size.
- The 125 µm fraction of the daily total (urban plus rural) sediment load was multiplied by the 63–250 µm concentration and the resulting metal load was carried in the USC-3 model by the 125 µm sediment constituent particle size.
- The 180 µm fraction of the daily total (urban plus rural) sediment load was multiplied by the 63–250 µm concentration and the resulting metal load was carried in the USC-3 model by the 180 µm sediment constituent particle size.

Natural metal inputs from the Upper Waitemata Harbour (sub-catchment 12) were treated differently, as described below.

**Table 15**

Concentration (mg $kg^{-1}$) at which zinc is carried on soils in the sub-catchments of the Central Waitemata Harbour, from Reed (2007).

| Sub-catchment | <25 µm | 25–63 µm | 63–250 µm |
|---|---|---|---|
| 1 – HBY | 72.4 | 62.9 | 57.7 |
| 2 – SST | 86.3 | 104 | 80.5 |
| 3 – CST | 86.3 | 104 | 80.5 |
| 4 – WSM | 86.3 | 104 | 80.5 |
| 5 – COB | 87.2 | 81.3 | 37.2 |
| 6 – MOK | 121 | 115 | 78.9 |
| 7 – MEK | 47.3 | 39.7 | 28.9 |
| 8 – OAK | 72.6 | 79 | 39.5 |
| 9 – WHR | 68 | 57.8 | 43 |
| 10 – HEK | 68 | 57.8 | 43 |
| 11 – HBV | 68 | 57.8 | 43 |
| 12 – UWH | – | – | – |
| 13 – LSB | 47.3 | 39.7 | 28.9 |
| 14 – SBN | 47.3 | 39.7 | 28.9 |
| 15 – SBE | 86.3 | 104.0 | 80.5 |

**Table 16**

Concentration (mg/kg) at which copper is carried on soils in the sub-catchments of the Central Waitemata Harbour, from Reed (2007).

| Sub-catchment | <25 µm | 25–63 µm | 63–250 µm |
|---|---|---|---|
| 1 – HBY | 20 | 18 | 14.8 |
| 2 – SST | 27.6 | 30.7 | 25.2 |
| 3 – CST | 27.6 | 30.7 | 25.2 |
| 4 – WSM | 27.6 | 30.7 | 25.2 |
| 5 – COB | 26 | 24.9 | 12.9 |
| 6 – MOK | 37.7 | 36.3 | 26.7 |
| 7 – MEK | 10.9 | 9.8 | 7.4 |
| 8 – OAK | 44.1 | 40.4 | 28.3 |
| 9 – WHR | 32.5 | 31.1 | 26.6 |
| 10 – HEK | 32.5 | 31.1 | 26.6 |
| 11 – HBV | 32.5 | 31.1 | 26.6 |
| 12 – UWH | – | – | – |
| 13 – LSB | 10.9 | 9.8 | 7.4 |
| 14 – SBN | 10.9 | 9.8 | 7.4 |
| 15 – SBE | 27.6 | 30.7 | 25.2 |

### 7.3.2 Anthropogenic metal inputs

The CLM was used to produce a hindcast of annual anthropogenic zinc and copper loads at the bottom of each sub-catchment, split by sediment constituent particle size that carries that load, for each year during the historical period.

The implementation of the CLM for the Central Waitemata Harbour Contaminant Study is documented in Timperley and Reed (2008b). The CLM historical-period hindcasts are also presented there in some detail.

Figure 23 shows the anthropogenic zinc loads, and Table 17 shows how the zinc load is carried on the sediment constituent particle sizes.

Figure 24 shows the anthropogenic copper loads, and Table 18 shows how the copper load is carried on the sediment constituent particle sizes.

Anthropogenic metal inputs from the Upper Waitemata Harbour (sub-catchment 12) were treated differently, as described below.

**Figure 23**

Anthropogenic zinc loads (total carried by all sediment constituent particle sizes). Year 1 is 1940 and year 62 is 2001.

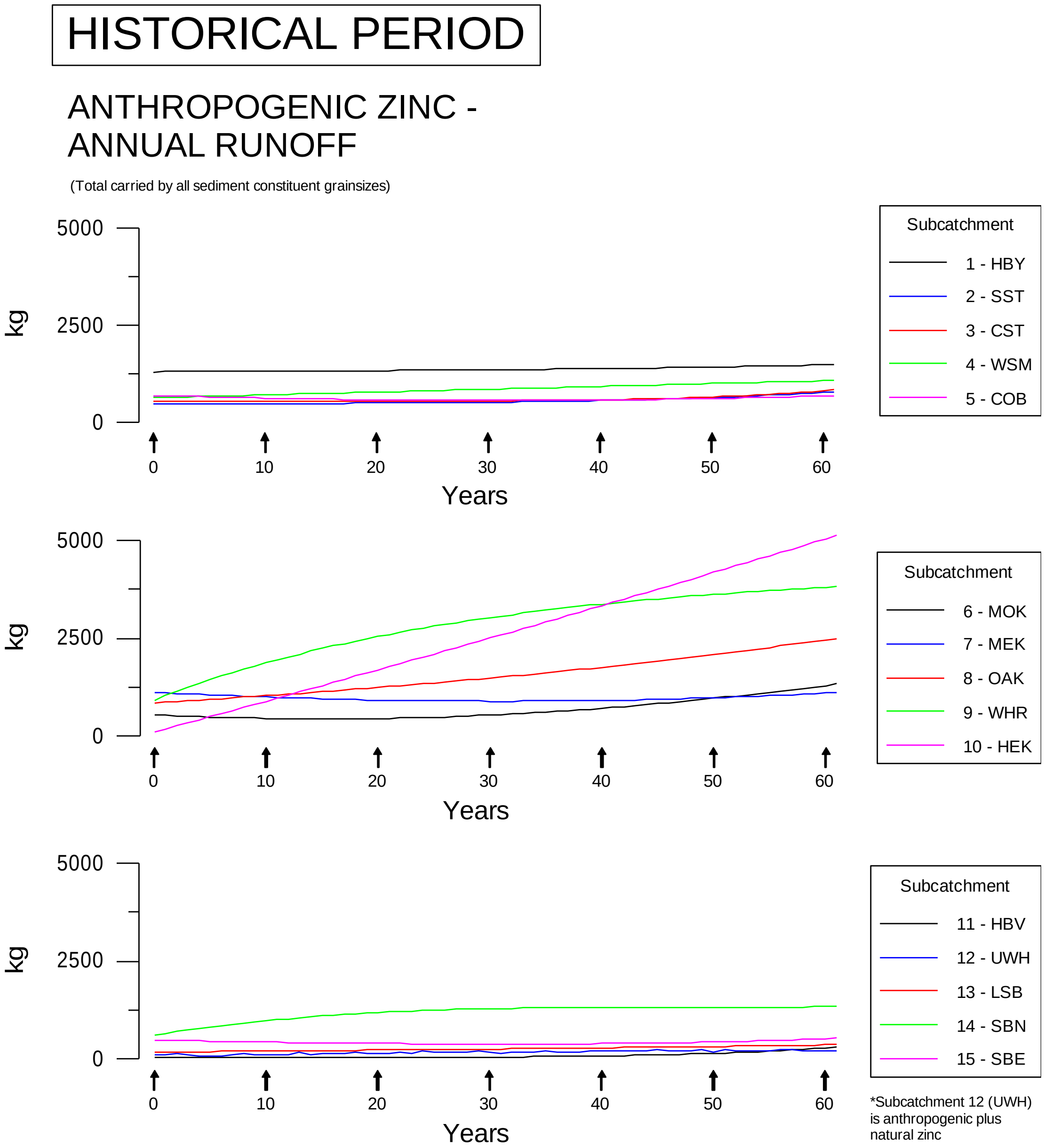


**Figure 24**

Anthropogenic copper loads (total carried by all sediment constituent particle sizes). Year 1 is 1940 and year 62 is 2001.

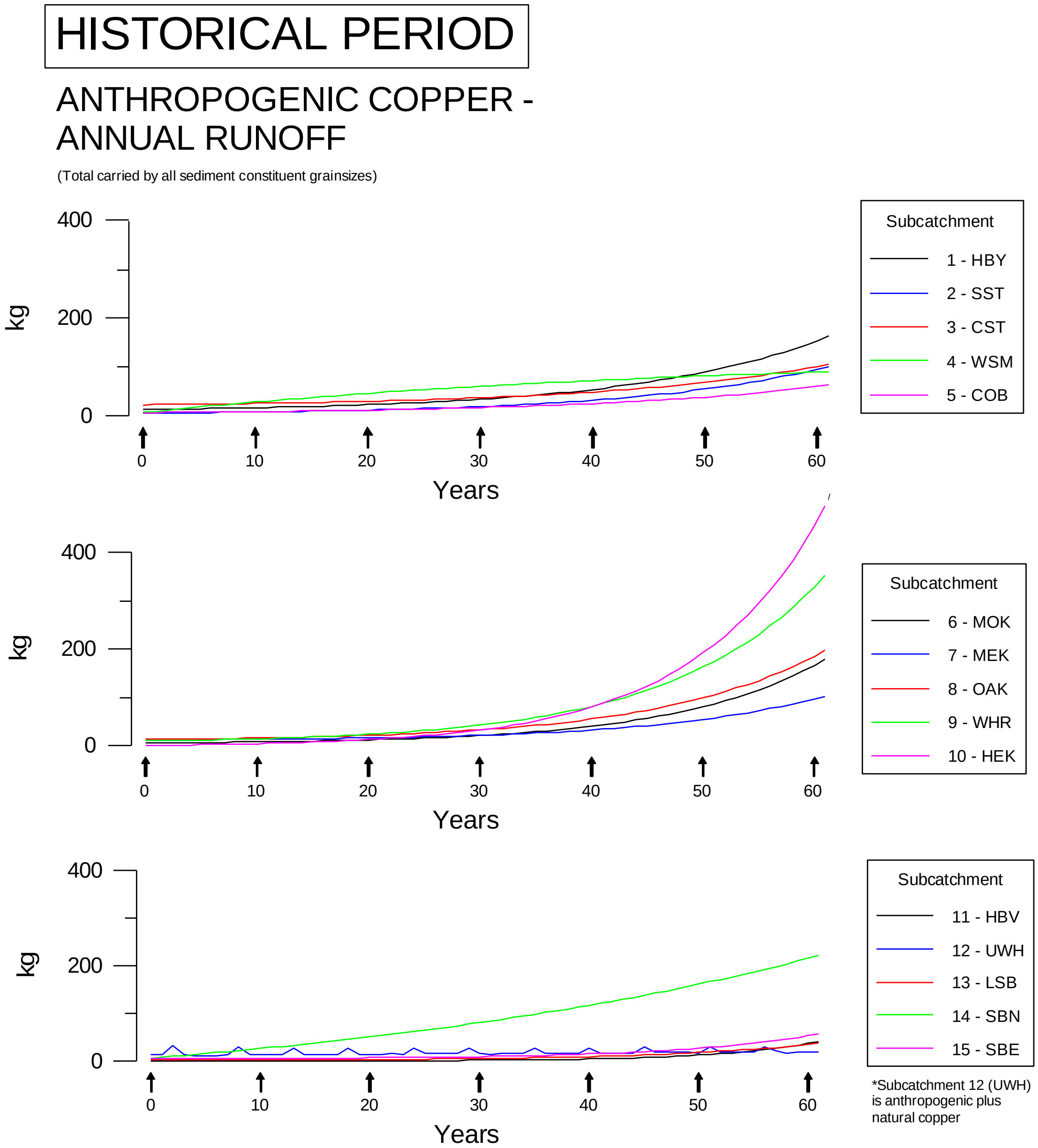


**Table 17**

Fraction of anthropogenic zinc load carried by each sediment constituent particle size (12, 40, 125 and 180 µm), hindcast by the CLM.

| Sub-catchment | Sediment constituent particle size (µm) | | | |
|---|---|---|---|---|
| | 12 | 40 | 125 | 180 |
| 1 – HBY | 0.54 | 0.28 | 0.17 | 0.0 |
| 2 – SST | 0.53 | 0.29 | 0.18 | 0.0 |
| 3 – CST | 0.52 | 0.29 | 0.19 | 0.0 |
| 4 – WSM | 0.53 | 0.29 | 0.18 | 0.0 |
| 5 – COB | 0.55 | 0.28 | 0.17 | 0.0 |
| 6 – MOK | 0.52 | 0.29 | 0.19 | 0.0 |
| 7 – MEK | 0.55 | 0.28 | 0.17 | 0.0 |
| 8 – OAK | 0.54 | 0.28 | 0.18 | 0.0 |
| 9 – WHR | 0.54 | 0.29 | 0.18 | 0.0 |
| 10 – HEK | 0.53 | 0.30 | 0.17 | 0.0 |
| 11 – HBV | 0.52 | 0.29 | 0.19 | 0.0 |
| 12 – UWH | – | – | – | – |
| 13 – LSB | 0.54 | 0.29 | 0.17 | 0.0 |
| 14 – SBN | 0.52 | 0.29 | 0.19 | 0.0 |
| 15 – SBE | 0.55 | 0.28 | 0.17 | 0.0 |

**Table 18**

Fraction of anthropogenic copper load carried by each sediment constituent particle size (12, 40, 125 and 180 µm), hindcast by the CLM.

| Sub-catchment | Sediment constituent particle size (µm) | | | |
|---|---|---|---|---|
| | 12 | 40 | 125 | 180 |
| 1 – HBY | 0.41 | 0.33 | 0.26 | 0.0 |
| 2 – SST | 0.40 | 0.33 | 0.27 | 0.0 |
| 3 – CST | 0.40 | 0.33 | 0.27 | 0.0 |
| 4 – WSM | 0.40 | 0.33 | 0.27 | 0.0 |
| 5 – COB | 0.41 | 0.33 | 0.26 | 0.0 |
| 6 – MOK | 0.39 | 0.33 | 0.28 | 0.0 |
| 7 – MEK | 0.41 | 0.33 | 0.26 | 0.0 |
| 8 – OAK | 0.40 | 0.33 | 0.27 | 0.0 |
| 9 – WHR | 0.43 | 0.32 | 0.26 | 0.0 |
| 10 – HEK | 0.42 | 0.32 | 0.26 | 0.0 |
| 11 – HBV | 0.40 | 0.33 | 0.26 | 0.0 |
| 12 – UWH | – | – | – | – |

| Sub-catchment | Sediment constituent particle size (µm) | | | |
|---|---|---|---|---|
| | 12 | 40 | 125 | 180 |
| 13 – LSB | 0.42 | 0.32 | 0.26 | 0.0 |
| 14 – SBN | 0.40 | 0.33 | 0.26 | 0.0 |
| 15 – SBE | 0.40 | 0.33 | 0.26 | 0.0 |

### 7.3.3 Metal inputs from the Upper Waitemata Harbour

As was the case for sediments, metal inputs from the Upper Waitemata Harbour (sub-catchment 12) were derived from USC-2 model hindcasts performed as part of the 2004 Upper Waitemata Harbour Contaminant Study. Specifically, total (anthropogenic plus natural) metal inputs from the UWH to the CWH were set equal to the loss of total metals from the UWH to the CWH as hindcast by the USC-2 model in a similar exercise to the one being done here, which was aimed at calibrating the USC-2 model over the historical period 1950–2000. Further details are given in Green et al. (2004). The USC-2 model as it was implemented for the UWH did not distinguish between anthropogenic and natural metals. It is not possible to "back calculate" this split.

An average split, calculated from Tables 17 (for zinc) and 18 (for copper), was used to specify how the total zinc and copper loads emanating from the Upper Waitemata Harbour were carried by the sediment constituent particle sizes.

### 7.3.4 Total (anthropogenic plus natural) metal inputs

As explained in Chapter 5 of this report, each annual anthropogenic load of metal is fully distributed over the days in that year such that no part of the annual load is "carried over" into a succeeding year. Specifically, the annual anthropogenic heavy metal load emanating from each sub-catchment is broken down into daily loads over that same year in proportion to the daily GLEAMS sediment loads.

The daily anthropogenic metal loads so formed were added to the daily natural metal loads to form the daily total metal loads. Table 19 and Table 20 show the total (anthropogenic plus natural) metal loads, and how those total loads are constituted between anthropogenic and natural sources.

For zinc:

- Sub-catchment 9 – WHR (Whau River) and sub-catchment 10 – HEK (Henderson Creek) are the principal sources of zinc to the harbour. Sub-catchment 8 – OAK (Oakley Creek) contributes the next largest load.
- 17 % of the zinc load from sub-catchment 10 – HEK is from natural sources, which is the second highest proportion (23 % of the zinc load from sub-catchment 11 – HBV, Hobsonville, is from natural sources). For all of the other sub-catchments, natural zinc contributes less than 10 % to the total zinc load.

For copper:

- Sub-catchment 9 – WHR (Whau River), sub-catchment 10 – HEK (Henderson Creek) and sub-catchment 14 – SBN (Shoal Bay North) are the principal sources of copper to the harbour.
- The proportion of the total copper load that is due to natural sources is typically much greater than the proportion of the total zinc load that is due to natural sources. For two of the sub-catchments with the highest loads (9 – WHR and 10 – HEK), natural copper makes up greater than 60 % of the total load.

**Table 19**
Total (anthropogenic plus natural) zinc loads and how those total loads are constituted between anthropogenic and natural sources. These figures are for the total zinc carried by all sediment constituent particle sizes, and are for just one USC-3 model run in the Monte Carlo package of 50 USC-3 model runs.

| Sub-catchment | Sum over simulation of anthropogenic zinc (kg) | Sum over simulation of total (anthropogenic plus natural) zinc (kg) | Percentage of total due to anthropogenic | Percentage of total due to natural |
|---|---|---|---|---|
| 1 – HBY | 83,960 | 90,049 | 0.93 | 0.07 |
| 2 – SST | 33,546 | 35,282 | 0.95 | 0.05 |
| 3 – CST | 35,829 | 36,830 | 0.97 | 0.03 |
| 4 – WSM | 52,221 | 53,595 | 0.97 | 0.03 |
| 5 – COB | 36,922 | 39,263 | 0.94 | 0.06 |
| 6 – MOK | 41,443 | 43,916 | 0.94 | 0.06 |
| 7 – MEK | 59,524 | 61,491 | 0.97 | 0.03 |
| 8 – OAK | 96,061 | 101,559 | 0.95 | 0.05 |
| 9 – WHR | 174,857 | 187,759 | 0.93 | 0.07 |
| 10 – HEK | 159,215 | 191,029 | 0.83 | 0.17 |
| 11 – HBV | 4300 | 5550 | 0.77 | 0.23 |
| 12 – UWH | – | – | – | – |
| 13 – LSB | 15,296 | 16,531 | 0.93 | 0.07 |
| 14 – SBN | 72,576 | 75,544 | 0.96 | 0.04 |
| 15 – SBE | 25,447 | 27,297 | 0.93 | 0.07 |

**Table 20**
Total (anthropogenic plus natural) copper loads and how those total loads are constituted between anthropogenic and natural sources. These figures are for the total copper carried by all sediment constituent particle sizes, and are for just one USC-3 model run in the Monte Carlo package of 50 USC-3 model runs.

| Sub-catchment | Sum over simulation of anthropogenic copper (kg) | Sum over simulation of total (anthropogenic plus natural) copper (kg) | Percentage of total due to anthropogenic | Percentage of total due to natural |
|---|---|---|---|---|
| 1 – HBY | 3223 | 4902 | 0.66 | 0.34 |
| 2 – SST | 1912 | 2451 | 0.78 | 0.22 |
| 3 – CST | 2884 | 3194 | 0.90 | 0.10 |
| 4 – WSM | 3561 | 3987 | 0.89 | 0.11 |
| 5 – COB | 1452 | 2168 | 0.67 | 0.33 |
| 6 – MOK | 2641 | 3424 | 0.77 | 0.23 |
| 7 – MEK | 2035 | 2505 | 0.81 | 0.19 |
| 8 – OAK | 3435 | 6660 | 0.52 | 0.48 |
| 9 – WHR | 5266 | 11,917 | 0.44 | 0.56 |
| 10 – HEK | 5892 | 22,293 | 0.26 | 0.74 |
| 11 – HBV | 402 | 1046 | 0.38 | 0.62 |
| 12 – UWH | – | – | – | – |
| 13 – LSB | 599 | 894 | 0.67 | 0.33 |
| 14 – SBN | 5774 | 6482 | 0.89 | 0.11 |
| 15 – SBE | 981 | 1555 | 0.63 | 0.37 |

## 7.4 Concentration at which metals are delivered to the harbour – historical period

The concentrations at which total (anthropogenic plus natural) metals are delivered to the harbour over the historical period are shown in Figures 25 and 26.

Concentrations generally increase through the historical period, as rural sediment loads fall and anthropogenic metal loads rise, both of which reflect increasing urbanisation of the catchment of the CWH. The exception is the late 1980s and early 1990s, when there was a spike in rural sediment inputs, which was due to a surge in greenfields development, and accompanying bare earth (earthworks). Note the greater variability in concentration early in the historical period associated with catchments with a high rural sediment load (eg, 8 – OAK, 9 – WHR and 10 – HEK). This is due to GLEAMS capturing the effects on rural sediment generation of antecedent rainfall and rainfall intensity on the day of generation.

The concentrations at which total metals have been delivered to the harbour over the historical period are typically much higher than the present day concentrations in the estuarine bed sediments (to be described). The discrepancy is due to bed-sediment mixing in the harbour which confers an "inertia" to the system. This occurs, as previously explained, through mixing of highly contaminated sediments that arrive during rainstorms from the catchment down into the "ballast" of less contaminated estuarine sediments. This has the effect of reducing metal concentrations in the surface mixed layer compared to the concentrations at which metals left the catchment.

**Figure 25**

Concentrations at which total (anthropogenic plus natural) zinc is delivered to the harbour over the historical period. Concentration is defined here as the total (anthropogenic plus natural) metal carried by all sediment particle sizes divided by the total (rural plus urban) sediment summed over all particle sizes. These figures are for just one USC-3 model run in the Monte Carlo package of 50 USC-3 model runs.

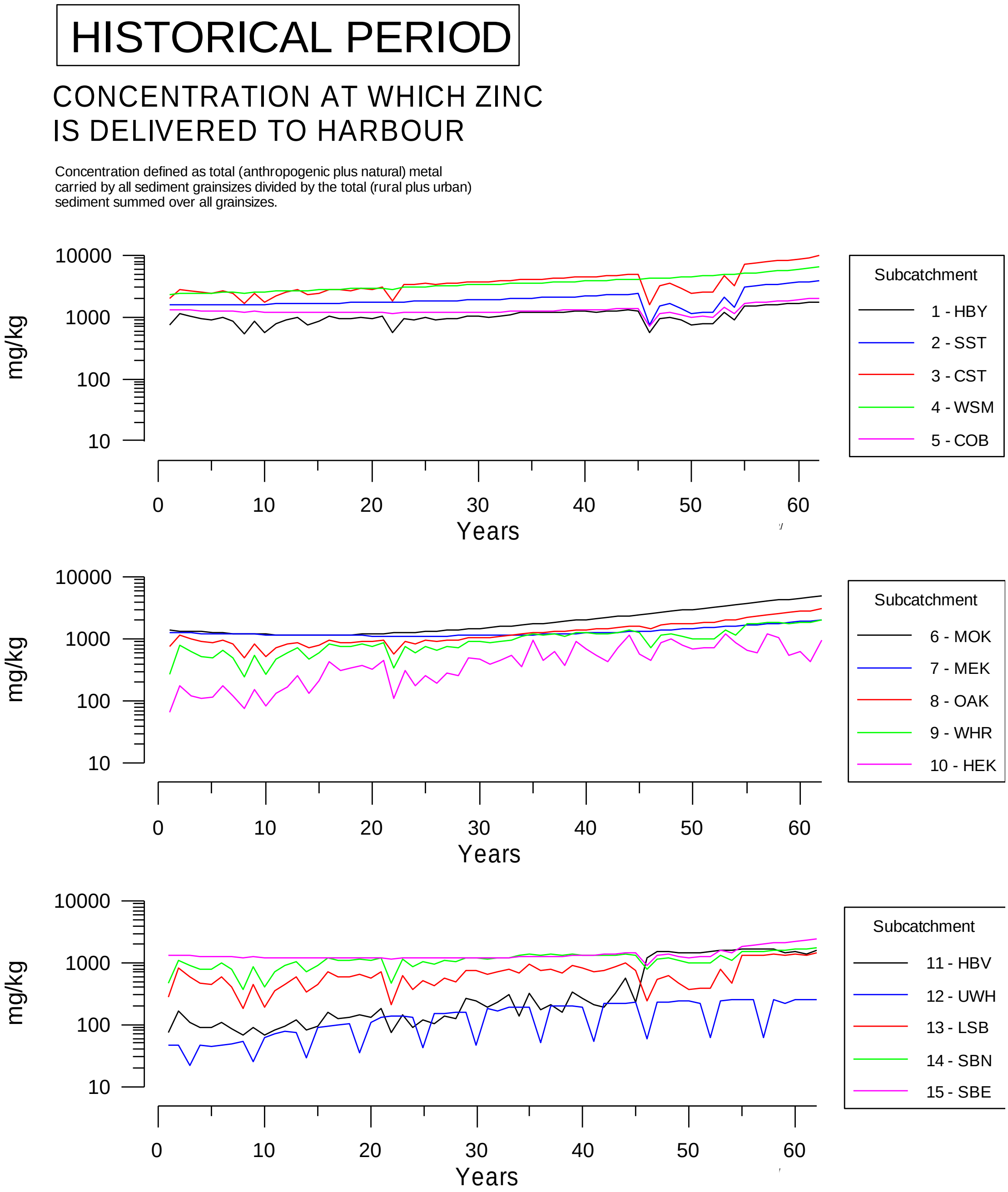
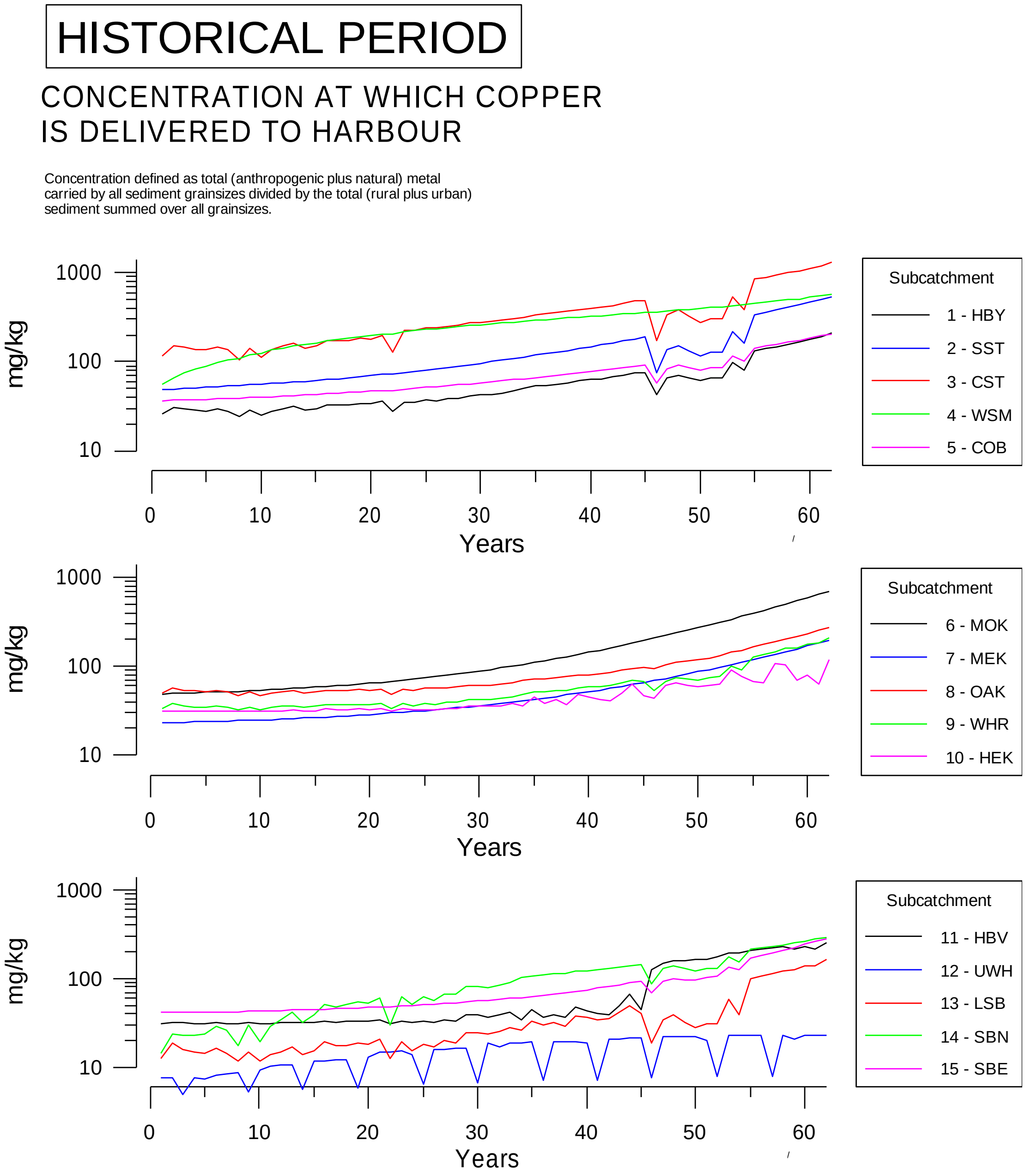


**Figure 26**

Concentrations at which total (anthropogenic plus natural) copper is delivered to the harbour over the historical period. Concentration is defined here as the total (anthropogenic plus natural) metal carried by all sediment particle sizes divided by the total (rural plus urban) sediment summed over all particle sizes. These figures are for just one USC-3 model run in the Monte Carlo package of 50 USC-3 model runs.



## 7.5 Estuarine bed sediments at the start of the historical period

The split of the bed sediment in each subestuary amongst the constituent particle sizes needs to be specified at the start of the historical period. Without any better information available, the particle size distribution of the present day estuarine bed sediments, which has been described by Swales et al. (2008b) as part of the Central Waitemata Harbour Contaminant Study, was used to specify this split for the start of the historical period.

Swales et al. provided maps of percent clay and fine silt (<25 µm), percent medium silt (25–62.5 µm) and percent very fine sand (62.5–125 µm). The <25 µm particle size class was equated with the 12 µm constituent particle size in the USC-3 model; the 25–62.5 µm particle size class was equated with the 40 µm constituent particle size; and the 63–125 µm particle size class was equated with the 125 µm constituent particle size. The percentages for the three particle size classes reported by Swales et al. do not add up to 100 %, which suggests the presence of a coarser mode. The presence of a fraction coarser than 125 µm is confirmed by looking at Swales et al.'s maps of median and mean particle size, which typically exceed 125 µm. The 180 µm fraction in the USC-3 model was assigned so that the resulting D50 in the USC-3 model matched Swales et al.'s observed median particle size. The results of this analysis are shown in Table 21. As noted above, the particle size split shown in that table is for the present day, but, without any better information, it was applied in the USC-3 model at the start of the historical period for the purposes of model calibration.

**Table 21**
Present day split of estuarine bed sediments amongst constituent particle sizes, derived from Swales et al.'s (2007) data, and applied at the start of the historical period for the USC-3 model calibration.

| Subestuary | Fraction of bed sediment composed of 12 µm particle size | Fraction of bed sediment composed of 40 µm particle size | Fraction of bed sediment composed of125 µm particle size | Fraction of bed sediment composed of 180 µm particle size | Bed sediment D50 (µm) |
|---|---|---|---|---|---|
| 1 -HBE | 0.05 | 0.04 | 0.45 | 0.46 | 141 |
| 2 - LBY | 0.03 | 0.05 | 0.30 | 0.62 | 151 |
| 3 - NWI | 0.02 | 0.03 | 0.55 | 0.40 | 142 |
| 4 - CNS | 0.02 | 0.10 | 0.35 | 0.53 | 144 |
| 5 - WSI | 0.02 | 0.03 | 0.40 | 0.55 | 150 |
| 6 - SEI | 0.06 | 0.15 | 0.60 | 0.19 | 116 |
| 7 - WAV | 0.03 | 0.10 | 0.25 | 0.62 | 147 |
| 8 - PCV | 0.01 | 0.02 | 0.30 | 0.67 | 159 |
| 9 - MEO | 0.01 | 0.02 | 0.35 | 0.62 | 156 |
| 10 - MOT | 0.01 | 0.02 | 0.35 | 0.62 | 156 |
| 11 - SBY | 0.07 | 0.20 | 0.60 | 0.13 | 107 |

| Subestuary | Fraction of bed sediment composed of 12 µm particle size | Fraction of bed sediment composed of 40 µm particle size | Fraction of bed sediment composed of125 µm particle size | Fraction of bed sediment composed of 180 µm particle size | Bed sediment D50 (µm) |
|---|---|---|---|---|---|
| 12 - HGF | – | – | – | – | – |
| 13 - HEN | 0.40 | 0.40 | 0.15 | 0.05 | 49 |
| 14 - WHA | 0.40 | 0.40 | 0.15 | 0.05 | 49 |
| 15 - WAT | 0.40 | 0.40 | 0.15 | 0.05 | 49 |
| 16 - HBA | 0.40 | 0.40 | 0.15 | 0.05 | 49 |
| 17 - UWH | – | – | – | – | – |

## 7.6 Results – Part 1

The first part of the calibration process consisted of adjusting (1) the areas over which sediments may deposit and (2) the various *R*, *R5*, *RSUSP*, *R5SUSP* and *RFS* terms, until realistic sedimentation rates and patterns of sediment dispersal were obtained.

(1) The first adjustment reduces the deposition area in each subestuary relative to the total area, which increases sedimentation per unit mass of sediment deposited. The calibration process was started by assuming that deposition occurs over the entire area of each subestuary (Table 4). These areas may be adjusted as the calibration proceeds.

(2) The *R*, *R5*, *RSUSP*, *R5SUSP* and *RFS* terms, which all together describe the movement and fate of sediments and heavy metals in the harbour under the influence of freshwater plumes, tidal currents and waves, were determined by a number of independent (that is, separate) runs of the DHI model suite. These same terms, when implemented in the USC-3 model, describe, in effect, the strength and direction of "connections" between subestuaries. The connections may form a complex network, with multiple cross-connections or interactions possible. Because of these interactions, any small errors associated with the connection strengths and directions may also interact, and grow as a result.

For instance, a particular run of the DHI model may indicate a small net loss of sediment from one subestuary (#1) and the transfer of that sediment to a neighbouring subestuary (#2), resulting in a small net gain in subestuary #2 by the end of the model run. A problem may occur in the USC-3 model when that small loss/gain pair is repeatedly applied over many timesteps, in which case any small error in the estimate of the connection may become magnified. This problem may be exacerbated when subestuaries are connected to each other in "chains", for instance, in the case of subestuary #1 losing sediment to subestuary #2 which in turn loses sediment to subestuary #3. In that case, any small errors will be passed along the chain, getting magnified as they go. This kind of problem is unavoidable in any scheme that seeks to extrapolate error-prone calculations beyond the scale at which the calculations are first performed. In the case of the USC-3 model, a scale-up of patterns of sediment dispersal that apply at a roughly daily timescale, to a final timescale that is order $10^4$ times larger than daily, is attempted.

In general, the main body of the Central Waitemata Harbour will be "dispersive", meaning that sediments will be passed more-or-less randomly in all directions between subestuaries, which should minimise the growth of errors as described. However, that notion cannot be entirely true, since there obviously will be preferred sediment-transport routes, particularly into the pre-defined sinks, which (by definition) do not give up sediments back to the larger system. In addition to the pre-defined sinks, there may also be "dynamic" sinks, which arise from the behaviour of the system. In fact, any subestuary in the model domain may act as a sink, even if not defined as such when the USC-3 model is set up. This is an important feature of the model, and will arise from the particular connections (strengths and directions) between subestuaries.

There may be a need to adjust the various *R*, *R5*, *RSUSP*, *R5SUSP* and *RFS* terms in the calibration process in order to correct for small errors that affect the rate of sediment transfer into both pre-defined and dynamic sinks in the domain. In principle, any such adjustment may be specific to the particular sequence of weather being used to drive the USC-3 model, since the weather sequence, in general terms, controls the rate at which sediments move around the harbour, and therefore the rate at which they are lost to sinks. In practice here, however, this is not expected to be an issue.

The first part of the calibration was finally achieved by:

- Setting the area over which sediments may deposit in each subestuary as one-half of the respective total subestuary area reported in Table 4.
- Adjusting the *R*, *R5*, *RSUSP*, *R5SUSP* and *RFS* terms so that the loss of sediments to the Hauraki Gulf was reduced to one-quarter of the loss that would have resulted with the original set of terms.

The intent of these two adjustments was to increase sedimentation rates throughout the harbour, which is in line with observations (described below). The first adjustment reduces the deposition area in each subestuary relative to the total area, which increases sedimentation per unit mass of sediment deposited. The second adjustment reduces the overall loss of sediment from the CWH to the Hauraki Gulf, which increases sedimentation outright.

A set of adjustments to the *R*, *R5*, *RSUSP*, *R5SUSP* and *RFS* terms had to be made to stabilise a large dynamic sink that arose in the model with the original terms. This involved weakening the connections between subestuary 10 and each of subestuaries 7, 8 and 9, which otherwise caused subestuary 10 to accumulate sediment too rapidly at the expense of those other three subestuaries.

Patterns of sediment dispersal hindcast by the calibrated model are shown in Table 22, which shows the fate of sediment from each sub-catchment, and in Table 23, which shows the origin of sediment deposited in each subestuary. The sedimentation rate in each subestuary averaged over the entire historical period and hindcast by the calibrated model is shown in Table 24.

Referring to Table 22 (sediment fate):

- Sediment from the Hobsons Bay sub-catchment (1 – HBY) deposits almost exclusively in Hobsons Bay subestuary (16 – HBA), which is at the base of that same sub-catchment. The sediment that does escape from Hobsons Bay subestuary is entirely lost to the Hauraki Gulf. This seems reasonable, given the proximity of the mouth of Hobsons Bay subestuary to the entrance of the Hauraki Gulf.
- About one-third of the sediment load from the Stanley Street sub-catchment (2 – SST) turns the corner and deposits in the adjacent Hobsons Bay subestuary (16 – HBA), with the remainder being lost to the Hauraki Gulf. Sediment from the two sub-catchments that drain to the south shore of the harbour throat a little further to the west (3 – CST and 4 – WSM) evidently does not turn that same corner to the same extent, and as a result is almost entirely lost to the Hauraki Gulf.
- It is noteworthy that none of the sediment from the four sub-catchments that drain to the southern shore of the harbour throat crosses the harbour to deposit in Shoal Bay subestuary (11 – SBY). The significance of this will become clear shortly.

There is a distinct change of pattern moving further to the west into the transition zone between the harbour throat and the main body of the harbour, where the Coxs Bay (5 – COB), Motions Creek (6 – MOK) and Meola Creek (7 – MEK) sub-catchments enter into the harbour.

- A significant fraction of the sediment from each of these sub-catchments is now seen to cross the harbour and deposit in Shoal Bay subestuary (11 – SBY), and similar significant fractions are lost to the Hauraki Gulf. Each of these sub-catchments drains to the west of the natural constriction in the harbour that is crossed by the Harbour Bridge. The constriction might act to mix and steer ebb flows and associated suspended sediments across the harbour to where they may enter and deposit in Shoal Bay subestuary.
- Sediment from each of these sub-catchments is also dispersed widely to the west into the main body of the harbour, at least as far as the Western Intertidal (5 – WSI) subestuary.
- Sediment from Coxs Bay (5 – COB) and Motions Creek (6 – MOK) sub-catchments also deposits locally in Motions subestuary (10 – MOT).
- Sediment from Meola Creek sub-catchment (7 – MEK) also deposits locally in Meola subestuary (9 – MEO) and the adjacent Point Chevalier subestuary (8 – PCV).
- The fraction of the load from Meola Creek sub-catchment (7 – MEK) that deposits locally in Meola subestuary (9 – MEO) seems low (7 %) compared to the fraction of the load (42 %) from Motions Creek sub-catchment (6 – MOK) that deposits locally in Motions subestuary (10 – MOT). It was in this area that small adjustments to the *R*, *R5*, *RSUSP*, *R5SUSP* and *RFS* terms had to be made to stabilise a large dynamic sink, as noted previously. As a result, this is probably the least trustworthy area of the model.

The Oakley Creek (8 – OAK), Whau River (9 – WHR), Henderson Creek (10 – HEK), Hobsonville (11 – HBV) and Upper Waitemata Harbour (12 – UWH) sub-catchments drain into the main body of the harbour.

- It is noteworthy, again, that a significant fraction of the sediment from all of these sub-catchments is seen to cross the harbour and deposit in Shoal Bay subestuary (11 – SBY), and similar significant fractions are lost to the Hauraki Gulf (This was also the case for the sub-catchments that drained to the harbour in the transition zone between the harbour throat and the main body.). This suggests that Shoal Bay intercepts a large fraction of the sediment that originates from all sub-catchments to the west of Shoal Bay, which (presumably) would otherwise be lost to the Hauraki Gulf. The obvious conclusion to draw is that Shoal Bay experiences a relatively large sedimentation rate, which does in fact turn out to be the case (to be described shortly).
- A significant fraction of sediment from Oakley Creek sub-catchment (8 – OAK) does not escape the Waterview Embayment subestuary (15 – WAT), which is the enclosed embayment through which that sub-catchment discharges. Apart from that, sediment from Oakley creek is dispersed widely in the southwestern sector of the main body amongst the Point Chevalier (8 – PCV), Waterview Flats (7 – WAV), Southwestern Intertidal (6 – WSI), and Western Intertidal (5 – WSI) subestuaries.
- A significant fraction of sediment from the Whau River sub-catchment (9 – WHR) accumulates in the Whau River subestuary (14 – WHA), which is the tidal creek at the base of that sub-catchment. Apart from that, sediment from the Whau River disperses widely in the western sector of the main body amongst the Southwestern Intertidal (6 – WSI), and Western Intertidal (5 – WSI) subestuaries.
- A significant fraction of sediment from the Henderson Creek sub-catchment (10 – HEK) accumulates in the Henderson Creek subestuary (13 – HEN), which is the tidal creek at the base of that sub-catchment. Apart from that, sediment from Henderson Creek disperses widely in the southwestern, western and northwestern sectors of the main body amongst the Southwestern Intertidal (6 – WSI), Western Intertidal (5 – WSI), Central Subtidal (4 – CNS) and Northwestern Intertidal (3 – NWI) subestuaries. Sediment from Henderson Creek is also deposited in Limeburners Bay subestuary (2 – LBY), which is in a sheltered position at the mouth of Henderson Creek.
- Sediment from the Hobsonville Creek sub-catchment (11 – HBV) is also distributed widely in the southwestern, western and northwestern sectors of the main body, in a very similar way to the dispersal of sediments from Henderson Creek sub-catchment. The outlets of these two sub-catchments are nearby to each other.
- Sediment emanating from the Upper Waitemata Harbour (12 – UWH) spreads widely throughout the entire main body of the Central Waitemata Harbour, with the interception of a significant fraction of its load by Shoal Bay subestuary (11 – SBY) along the path to the Hauraki Gulf.

Little Shoal Bay sub-catchment (13 – LSB) drains to the north shore of the harbour throat, immediately to the west of the natural constriction in the harbour that is crossed by the Harbour Bridge, and to the west of Shoal Bay subestuary (11 – SBY). The Shoal Bay North (14 – SBN) and Shoal Bay East (15 – SBE) sub-catchments both discharge directly into Shoal Bay subestuary.

- About two-thirds of the sediment from Little Shoal Bay sub-catchment is lost to the Hauraki Gulf, with the other third turning the corner to the east and getting trapped in Shoal Bay. Those fractions are reversed for Shoal Bay North and Shoal Bay East sub-catchments, both of which drain directly into Shoal Bay: about two-thirds of the sediment from each sub-catchment is deposited in Shoal Bay, and the remaining third is lost to the Hauraki Gulf.

The analysis of the fate of sediments from the sub-catchments surrounding the Central Waitemata Harbour paints a fairly convincing picture, which adds to the confidence in the calibrated USC-3 model. The area that is least convincing is that around Motions, Meola, Point Chevalier and Waterview Flats intertidal flats.

Referring now to Table 23 (sediment sources):

- Sediment in the Hobsonville subestuary (1 – HBE), situated on the northwest shore of the main body of the harbour, originates primarily from the adjacent Hobsonville sub-catchment. This suggests that this is a relatively sheltered part of the main body, with minimal transfer of sediment into this part of the harbour from other parts.
- The same is true for Limeburners Bay subestuary (2 – LBY), which is in a sheltered position at the mouth of Henderson Creek and, as a result primarily receives sediment from Henderson Creek sub-catchment.
- Sediment deposited in the Northwestern Intertidal subestuary (3 – NWI) and in the Central Subtidal subestuary (4 – CNS) is also sourced almost exclusively from the Henderson Creek sub-catchment. These are exposed areas, and unlikely to be sheltered in the same sense as Hobsonville and Limeburners Bay subestuaries. It is more likely that the (very large) Henderson Creek sub-catchment is the exclusive source of sediments to the Central Subtidal and Northwestern Intertidal subestuaries because that sub-catchment supplies the largest loads of sediment to the harbour. In other words, 3 – NWI and 4 – CNS are immediately adjacent to the largest (by far) sediment supply, and so are dominated by that supply. In that regard it is noteworthy that 4 – CNS, which is further from Henderson Creek outlet and further out in the main body of the harbour, does show sediments arriving from a slightly wider range of sources.
- The Western Intertidal (5 – WSI) and Southwestern Intertidal (6 – SWI) subestuaries are much further from the outlet of Henderson Creek and so are less dominated by sediments from Henderson Creek sub-catchment. They are also reasonably exposed. As a result, both of these subestuaries receive sediment from a correspondingly wide range of sources, from the north (Upper Waitemata Harbour and Hobsonville sub-catchment), the northwest (Henderson Creek sub-catchment),

the southwest (Whau River sub-catchment), the southeast (Oakley Creek sub-catchment) and the east (Meola Creek sub-catchment).

- The Waterview Flats subestuary (7 – WAV) is dominated by sediments from the adjacent Oakley Creek sub-catchment. Although this is in a reasonably sheltered part of the main body of the harbour it does in fact also receive sediments from sub-catchments to the west (Whau River and Henderson Creek sub-catchments) and the east (Meola Creek sub-catchment).
- That same pattern is seen in the three adjacent subestuaries to the east (8 – PCV, 9 – MEO and 10 – MOT). In all of these subestuaries, sediment principally derives from the respective adjacent source, but there are also contributions from sources to the west and east. The easternmost source is Coxs Bay sub-catchment; further to the east sub-catchments drain directly into the harbour throat, which loses sediment readily to the Hauraki Gulf.
- Shoal Bay subestuary (11 – SBY) receives sediment from all sub-catchments except those four that drain to the south shore of the harbour throat, as previously described. Henderson Creek sub-catchment is the principal source, presumably because it is a far larger source than the local sources 14 – SBN and 15 – SBE.
- Sediment that deposits in the Henderson Creek subestuary (13 – HEN) and the Whau River subestuary (14 – WHA), both of which are tidal creeks, originates virtually exclusively from the sub-catchment that drains into the respective tidal creek headwaters. This is also the case for the Waterview Embayment subestuary (15 – WAT), which acts like a sink at the base of the Oakley Creek sub-catchment.
- In contrast, sediment that deposits in Hobsons Bay subestuary (16 – HBA) is captured from virtually every sub-catchment around the harbour, which is by virtue of its position at the harbour mouth. The majority, however, comes from the local Hobsons Bay sub-catchment.

The analysis of the sources of sediments depositing in the subestuaries also paints a fairly convincing picture, which further adds to the confidence in the calibrated USC-3 model.

By radioisotopic dating of sediment cores, Swales et al. (2008b) determined an average sedimentation rate over the past 50 years or so of 3.2 mm year$^{-1}$ for intertidal sites in the Central Waitemata Harbour (range 0.7 – 6.8 mm year$^{-1}$), and 3.3 mm year$^{-1}$ for subtidal sites (range 2.2 – 5.3 mm year$^{-1}$). Sedimentation rates were more variable at intertidal sites compared to subtidal sites. A map showing locations of the cores that Swales et al. analysed is given in Figure 27, which also shows the radioisotopic sedimentation rates. Swales et al. also produced a conceptual model of sedimentation in the Central Waitemata Harbour, from a consideration of the radioisotopic sedimentation rates. This is reproduced in Figure 28.

The hindcast sedimentation rates are generally smaller than the radioisotopic sedimentation rates, however the patterns of sedimentation are similar in several respects.

The highest radioisotopic sedimentation rate outside of tidal creeks (6.8 mm $year^{-1}$ $^{210}Pb$; 4.0 mm $year^{-1}$ $^{137}Cs$) is in Shoal Bay. The highest hindcast sedimentation rate outside of tidal creeks, with one exception, is also Shoal Bay (11 – SBY) (2.2 mm $year^{-1}$). As noted previously, Shoal Bay receives sediment from all sub-catchments except those four that drain on the south shore of the harbour throat, and a high sedimentation rate was anticipated as a result. The exception is Limeburners Bay (2 – LBY) (3.3 mm $year^{-1}$). Limeburners Bay may be viewed as an extension of the Henderson Creek tidal creek, which drains directly into Limeburners Bay, and which Limeburners Bay primarily receives sediments from.

The hindcast sedimentation rates are lower in the Point Chevalier, Waterview Flats, Meola and Motions subestuaries compared to hindcast sedimentation rates on the intertidal flats in the western main body of the harbour (Southwestern Intertidal, Western Intertidal, Northwestern Intertidal subestuaries). This is broadly in line with Swales et al. who designated the Point Chevalier/Motions area as a "temporary sink", with relatively lower sedimentation rates.

The radioisotopic sedimentation rates on the intertidal flats in the western main body of the harbour are quite variable compared to the hindcast sedimentation rates for the same areas (Southwestern Intertidal, Western Intertidal and Northwestern Intertidal subestuaries). Swales et al. designated the "Whau Flats" as a temporary sink, and the "Central Basin" as a sink. The hindcast sedimentation rates do not show that distinction. Instead, they show a lower sedimentation rate in the subtidal Central Subtidal subestuary (4 – CNS) compared to the adjacent intertidal flats to the west. Swales et al. shows that same pattern (lower radioisotopic sedimentation rate towards the subtidal zone compared to up on the adjacent intertidal flat) a little further to the south (0.7 mm $year^{-1}$ $^{210}Pb$ and 0.6 mm $year^{-1}$ $^{137}Cs$ for core WH-I2 low on an intertidal flat, compared to 2.2 mm $year^{-1}$ $^{210}Pb$ and 2.3 mm $year^{-1}$ $^{137}Cs$ for core WH-I1 high on the adjacent intertidal flat).

Finally, the hindcast sedimentation rates in the three tidal creeks (Henderson Creek, Whau River and Hobsons Bay) exceeded the hindcast sedimentation rates at all places outside of the tidal creeks. This concurs with previous observations of sedimentation in tidal creeks in the Auckland region (eg, Vant et al. 1993; Oldman and Swales, 1999; Swales et al. 1997; Swales et al. 2008a).

**Table 22**

Fate of sediment from each sub-catchment (read the table across the page): percentage of total sediment load from each sub-catchment deposited in each subestuary. Hindcast by the calibrated USC-3 model; average over 50 model runs in a Monte Carlo package.

| Sub-catchment | Subestuary | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 HBE | 2 LBY | 3 NWI | 4 CNS | 5 WSI | 6 SWI | 7 WAV | 8 PCV | 9 MEO | 10 MOT | 11 SBY | 12 HGF | 13 HEN | 14 WHA | 15 WAT | 16 HBA | 17 UWH |
| Hobsons Bay | | | | | | | | | | | | | | | | | |
| 1 – HBY | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 13 | 0 | 0 | 0 | 87 | 0 |
| South Shore of throat | | | | | | | | | | | | | | | | | |
| 2 – SST | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 65 | 0 | 0 | 0 | 34 | 0 |
| 3 – CST | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 94 | 0 | 0 | 0 | 4 | 0 |
| 4 – WSM | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 95 | 0 | 0 | 0 | 4 | 0 |
| Transition between throat and main body | | | | | | | | | | | | | | | | | |
| 5 – COB | 0 | 0 | 0 | 0 | 4 | 3 | 0 | 1 | 0 | 44 | 27 | 20 | 0 | 0 | 0 | 2 | 0 |
| 6 – MOK | 0 | 0 | 0 | 0 | 5 | 3 | 0 | 2 | 0 | 42 | 30 | 16 | 0 | 0 | 0 | 2 | 0 |
| 7 – MEK | 0 | 0 | 0 | 0 | 9 | 7 | 0 | 7 | 7 | 3 | 44 | 21 | 0 | 0 | 0 | 2 | 0 |
| Main body | | | | | | | | | | | | | | | | | |
| 8 – OAK | 0 | 0 | 0 | 0 | 9 | 19 | 5 | 3 | 0 | 3 | 23 | 12 | 0 | 0 | 23 | 3 | 0 |
| 9 – WHR | 0 | 0 | 1 | 0 | 15 | 26 | 0 | 0 | 0 | 1 | 11 | 9 | 0 | 35 | 0 | 2 | 0 |
| 10 – HEK | 0 | 9 | 21 | 3 | 11 | 5 | 0 | 0 | 0 | 1 | 16 | 9 | 24 | 0 | 0 | 2 | 0 |
| 11 – HBV | 7 | 16 | 4 | 0 | 17 | 8 | 0 | 1 | 0 | 1 | 30 | 14 | 0 | 0 | 0 | 1 | 0 |
| 12 – UWH | 1 | 2 | 8 | 1 | 16 | 16 | 1 | 2 | 1 | 3 | 33 | 12 | 1 | 0 | 0 | 4 | 0 |
| Shoal Bay | | | | | | | | | | | | | | | | | |
| 13 – LSB | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 30 | 61 | 0 | 0 | 0 | 6 | 0 |
| 14 – SBN | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 71 | 25 | 0 | 0 | 0 | 4 | 0 |
| 15 – SBE | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 69 | 26 | 0 | 0 | 0 | 4 | 0 |

**Table 23**

Source of sediment in each subestuary (read the table across the page): percentage of total sediment load deposited in each subestuary originating from each sub-catchment. Hindcast by the calibrated USC-3 model; average over 50 model runs in a Monte Carlo package.

| Subestuary | Sub-catchment | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 HBY | 2 SST | 3 CST | 4 WSM | 5 COB | 6 MOK | 7 MEK | 8 OAK | 9 WHR | 10 HEK | 11 HBV | 12 UWH | 13 LSB | 14 SBN | 15 SBE |
| Northwest shore of main body | | | | | | | | | | | | | | | |
| 1 – HBE | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 13 | 62 | 25 | 0 | 0 | 0 |
| 2 – LBY | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 90 | 6 | 4 | 0 | 0 | 0 |
| Main body | | | | | | | | | | | | | | | |
| 3 – NWI | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 91 | 1 | 7 | 0 | 0 | 0 |
| 4 – CNS | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 90 | 0 | 8 | 0 | 0 | 0 |
| 5 – WSI | 0 | 0 | 0 | 0 | 1 | 1 | 4 | 6 | 26 | 45 | 3 | 14 | 0 | 0 | 0 |
| 6 – SWI | 0 | 0 | 0 | 0 | 1 | 1 | 3 | 13 | 46 | 21 | 1 | 14 | 0 | 0 | 0 |
| Transition between throat and main body | | | | | | | | | | | | | | | |
| 7 – WAV | 0 | 0 | 0 | 0 | 1 | 1 | 4 | 60 | 7 | 13 | 1 | 14 | 0 | 0 | 0 |
| 8 – PCV | 0 | 0 | 0 | 0 | 2 | 5 | 27 | 18 | 7 | 21 | 2 | 18 | 0 | 0 | 0 |
| 9 – MEO | 0 | 0 | 0 | 0 | 2 | 2 | 57 | 6 | 5 | 14 | 1 | 12 | 0 | 0 | 0 |
| 10 – MOT | 0 | 0 | 0 | 0 | 40 | 27 | 5 | 6 | 4 | 8 | 0 | 8 | 0 | 0 | 0 |
| Shoal Bay | | | | | | | | | | | | | | | |
| 11 – SBY | 0 | 0 | 0 | 0 | 3 | 2 | 8 | 7 | 9 | 30 | 2 | 12 | 3 | 18 | 5 |
| Hauraki Gulf | | | | | | | | | | | | | | | |
| 12 – HGF | 6 | 6 | 5 | 7 | 3 | 2 | 5 | 5 | 9 | 22 | 1 | 6 | 9 | 9 | 3 |
| Tidal creeks/sinks | | | | | | | | | | | | | | | |
| 13 – HEN | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 99 | 0 | 1 | 0 | 0 | 0 |
| 14 – WHA | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 100 | 0 | 0 | 0 | 0 | 0 | 0 |
| 15 – WAT | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 99 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| 16 – HBA | 69 | 6 | 0 | 1 | 1 | 0 | 1 | 2 | 3 | 8 | 0 | 4 | 2 | 2 | 1 |
| Upper Waitemata Harbour | | | | | | | | | | | | | | | |
| 17 – UWH | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 48 | 0 | 0 | 51 | 0 | 0 |

**Table 24**
Sedimentation rate in each subestuary over the historical period. These are hindcasts by the calibrated USC-3 model, run 50 times in a Monte Carlo package. "Average" is the average over 50 model runs, "Low" is the average negative deviation from "Average" and "High" is the average positive deviation from "Average".

| Subestuary | Sedimentation rate, mm year$^{-1}$ | | |
|---|---|---|---|
| | Low | Average | High |
| 1 – HBE | 0.1 | 0.1 | 0.1 |
| 2 – LBY | 2.9 | 3.3 | 3.5 |
| 3 – NWI | 1.8 | 2.1 | 2.3 |
| 4 – CNS | 0.2 | 0.2 | 0.2 |
| 5 – WSI | 1.2 | 1.3 | 1.5 |
| 6 – SWI | 1.1 | 1.1 | 1.2 |
| 7 – WAV | 0.3 | 0.3 | 0.3 |
| 8 – PCV | 0.3 | 0.3 | 0.3 |
| 9 – MEO | 0.3 | 0.3 | 0.3 |
| 10 – MOT | 1.3 | 1.3 | 1.4 |
| 11 – SBY | 2.2 | 2.2 | 2.3 |
| 12 – HGF | – | – | – |
| 13 – HEN | 5.3 | 5.7 | 6.1 |
| 14 – WHA | 3.6 | 3.7 | 3.8 |
| 15 – WAT | 0.9 | 0.9 | 1.0 |
| 16– HBY | 4.8 | 4.9 | 5.1 |
| 17 – UWH | – | – | – |

**Figure 27**
Location of the cores that Swales et al. (2008) subjected to radioisotopic dating to determine sedimentation rates. The sedimentation rates so determined (average over the past 50 years or so) are shown in red on the figure. The first figure is the Pb-210 estimate and the second figure (in brackets) is the Cs-137 estimate.

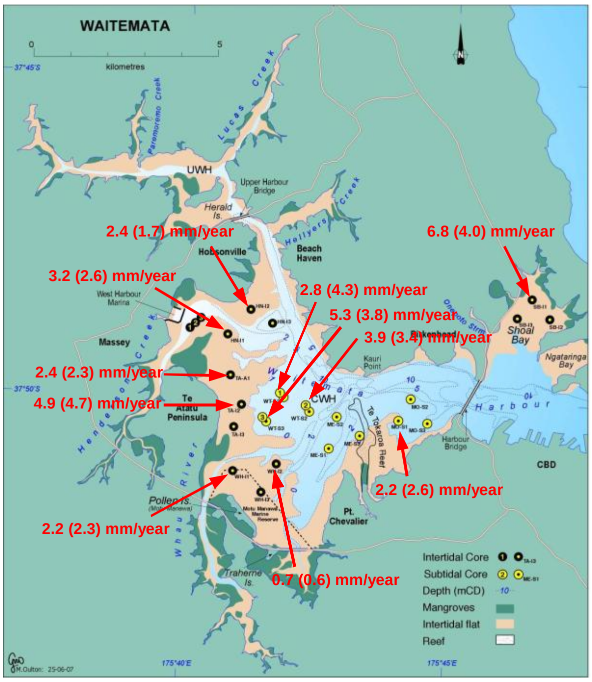
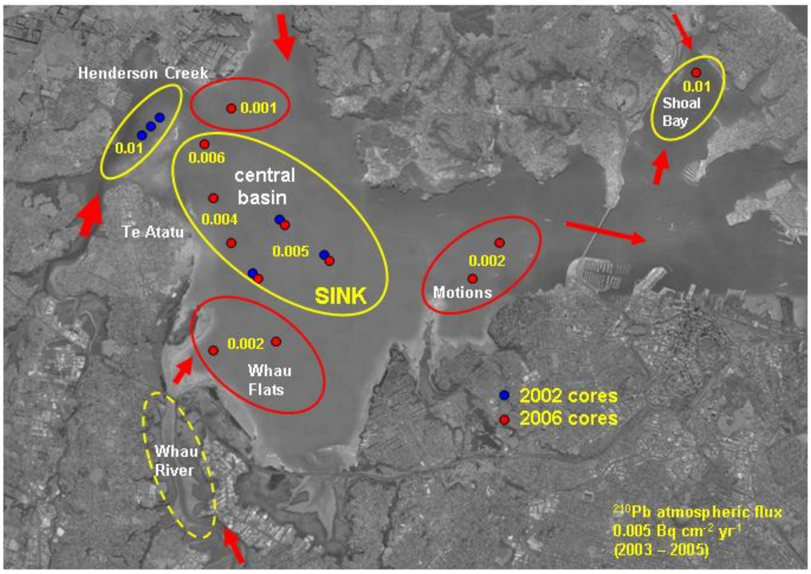



**Figure 28**
The conceptual model of sedimentation in the Central Waitemata Harbour, from a consideration of radioisotopic sedimentation rates, reproduced from Swales et al. (2008b). Long-term sediment sinks are shown by yellow ellipses. Temporary sinks are shown by red ellipses. Red arrows represent the relative size of sediment inputs and transfers.



## 7.7 Results – Part 2

The second part of the calibration process consisted of adjusting the metal retention factor until a good match was obtained between hindcast and observed metal concentrations in estuarine bed sediments at the end of the historical period. The observed metal concentrations, which became the "target" of the calibration process, were taken from an analysis of cores conducted by Ahrens et al. (2008). Downcore metal (zinc and copper) concentrations were determined in three cores: HN-I1 (which was taken from subestuary 3 – NWI, Northwestern Intertidal); WT-S3 (which was taken from subestuary 5 – WSI, Western Intertidal); and SB-I1 (which was taken from subestuary 11 – SBY, Shoal Bay). These subestuaries (3, 5 and 11) became the "test" subestuaries. For the purposes of the calibration, the metal concentration reported from the bottom of each core is assumed to be the surface mixed layer concentration at 1940 (the beginning of the historical period), and the metal concentration reported from the top of each core is assumed to be the surface mixed layer concentration at the end of the historical period.

The USC-3 simulation was begun at the start of the historical period with metal concentrations in the surface mixed layer of each test subestuary (3, 5 and 11) set equal to the metal concentrations at the base of each respective core. Ahrens et al. reported the concentration of metal associated with each of three sediment particle size classes: <25 µm, 25–63 µm, and 63–250 µm. The <25 µm particle size class was equated with the 12 µm constituent particle size in the USC-3 model; the 25–63 µm particle size class was equated with the 40 µm constituent particle size; and the 63–250 µm particle size class was equated with both the 125 and 180 µm constituent particle sizes.

Metal concentrations at the start of the historical period must also be specified for the remainder of the subestuaries, since these may exchange sediments (and associated metals) with the test subestuaries during the historical-period simulation. For the purposes of the calibration exercise, the metal concentrations in the remainder of the subestuaries were set to averages of Ahrens et al.'s base-of-core values. Table 25 shows the zinc concentrations in each subestuary applied in the USC-3 model at the start of the historical period, and Table 26 likewise shows the copper concentrations. Also shown in Tables 25 and 26 is total metal concentration, which is defined as the metal carried on all sediment particle sizes divided by the total (sum of all particle sizes) sediment. To calculate this, the estuarine bed-sediment particle size split shown in Table 21 was used.

**Table 25**

Zinc concentrations in each subestuary applied in the USC-3 model at the start of the historical period. The concentrations in test subestuaries 3, 5 and 11 are Ahrens et al.'s respective base-of-core values. The way Ahrens et al.'s particle sizes were equated with the constituent particle sizes in the USC-3 model is explained in the text. The concentrations in the remainder of the subestuaries are averages of Ahrens et al.'s base-of-core values. The total metal concentration is calculated from the constituent concentrations (this table) and the split of the bed sediment amongst the constituent particle sizes (Table 21).

| Subestuary | Metal concentration on 12 µm constituent particle size (mg kg-1) | Metal concentration on 40 µm constituent particle size (mg kg-1) | Metal concentration on 125 µm constituent particle size (mg kg-1) | Metal concentration on 180 µm constituent particle size (mg kg-1) | Total metal concentration (mg kg-1) |
|---|---|---|---|---|---|
| 1 -HBE | 50 | 35 | 30 | 30 | 31 |
| 2 - LBY | 50 | 35 | 30 | 30 | 31 |
| 3 - NWI | 67 | 40 | 25 | 25 | 26 |
| 4 - CNS | 50 | 35 | 30 | 30 | 31 |
| 5 - WSI | 52 | 30 | 38 | 38 | 38 |
| 6 - SEI | 50 | 35 | 30 | 30 | 32 |
| 7 - WAV | 50 | 35 | 30 | 30 | 31 |
| 8 - PCV | 50 | 35 | 30 | 30 | 30 |
| 9 - MEO | 50 | 35 | 30 | 30 | 30 |
| 10 - MOT | 50 | 35 | 30 | 30 | 30 |
| 11 - SBY | 50 | 24 | 12 | 12 | 17 |
| 12 - HGF | – | – | – | – | – |
| 13 - HEN | 50 | 35 | 30 | 30 | 40 |
| 14 - WHA | 50 | 35 | 30 | 30 | 40 |
| 15 - WAT | 50 | 35 | 30 | 30 | 40 |
| 16 - HBA | 50 | 35 | 30 | 30 | 40 |
| 17 - UWH | – | – | – | – | – |

**Table 26**

Copper concentrations in each subestuary applied in the USC-3 model at the start of the historical period. The concentrations in test subestuaries 3, 5 and 11 are Ahrens et al.'s respective base-of-core values. The way Ahrens et al.'s particle sizes were equated with the constituent particle sizes in the USC-3 model is explained in the text. The concentrations in the remainder of the subestuaries are averages of Ahrens et al.'s base-of-core values. The total metal concentration is calculated from the constituent concentrations (this table) and the split of the bed sediment amongst the constituent particle sizes (Table 21).

| Subestuary | Metal concentration on 12 µm constituent particle size (mg $kg^{-1}$) | Metal concentration on 40 µm constituent particle size (mg $kg^{-1}$) | Metal concentration on 125 µm constituent particle size (mg $kg^{-1}$) | Metal concentration on 180 µm constituent particle size (mg $kg^{-1}$) | Total metal concentration (mg $kg^{-1}$) |
|---|---|---|---|---|---|
| 1 -HBE | 14 | 6 | 4 | 4 | 5 |
| 2 - LBY | 14 | 6 | 4 | 4 | 4 |
| 3 - NWI | 17 | 8 | 4 | 4 | 4 |
| 4 - CNS | 14 | 6 | 4 | 4 | 4 |
| 5 - WSI | 14 | 6 | 6 | 6 | 6 |
| 6 - SEI | 14 | 6 | 4 | 4 | 5 |
| 7 - WAV | 14 | 6 | 4 | 4 | 5 |
| 8 - PCV | 14 | 6 | 4 | 4 | 4 |
| 9 - MEO | 14 | 6 | 4 | 4 | 4 |
| 10 - MOT | 14 | 6 | 4 | 4 | 4 |
| 11 - SBY | 9 | 4 | 3 | 3 | 3 |
| 12 - HGF | – | – | – | – | – |
| 13 - HEN | 14 | 6 | 4 | 4 | 9 |
| 14 - WHA | 14 | 6 | 4 | 4 | 9 |
| 15 - WAT | 14 | 6 | 4 | 4 | 9 |
| 16 - HBA | 14 | 6 | 4 | 4 | 9 |
| 17 - UWH | – | – | – | – | – |

The USC-3 model was run for the historical period, with sediment and metal inputs appropriate to that period, and initial conditions (ie, at the start of the historical period) as described. At the end of the simulation, a comparison is made between the hindcast metal concentration in the surface mixed layer in each test subestuary and the respective target concentrations. The target concentration was the total metal concentration, which was calculated from Ahrens et al.'s top-of-core concentrations and the present day split of the bed sediment amongst the constituent particle sizes (Table 21). The metal retention factor, which will be explained shortly, was adjusted to achieve a good match between hindcast and target concentrations at the end of the historical period.

The model was calibrated firstly for zinc. The performance of the finally calibrated model is shown in Figure 29. This was achieved with a metal retention factor of approximately 40 % applied to the zinc load discharged from every sub-catchment. A good calibration was obtained. The same metal retention factor was then applied to the historical copper simulations without further change. The results, which are reasonable, are shown in Figure 30.

Based on these results, for future application of the model to both zinc and copper, a metal retention factor of 0.4 was chosen to apply to the zinc and copper loads discharged from every sub-catchment.

A discussion of the calibration results follows.

## 7.8 Discussion

The metal retention factor, which is denoted by the symbol *MRF*, was used to set the fraction of the daily metal load emanating from each sub-catchment that gets attached to the daily sediment particulate load, which then gets injected into and dispersed throughout the harbour. Specifically, the fraction of the metal load that gets attached to the sediment particulate matter at the bottom of the catchment is equal to *MRF*. The fraction of the load that does not get attached to sediment particulate matter, and which therefore in effect does not even enter into the harbour domain, is equal to (1 – *MRF*). Applying *MRF* has the effect of reducing the concentration at which metals are delivered to the harbour in the model. This reduces the disequilibrium between the input metal concentrations and the concentrations at which metals are present in the pre-existing estuarine bed sediments, which retards the rate at which metal concentrations change in the estuarine bed sediments. *MRF* is, of course, a calibration factor: it is chosen, in the calibration process, to yield a time-rate-of-change of metal concentrations over the historical period that ends in the target concentrations being achieved.

On the one hand, the metal retention factor may be accounting for any number of uncertainties in the USC-3 model and the underlying models (GLEAMS, the CLM, and the DHI model suite), which provide inputs and parameters to the USC-3 model. This includes uncertainties in inputs, uncertainties in initial conditions, deficiencies in depiction of known processes, and lack of representation of other processes.

On the other hand, it is significant that one value of the metal retention factor applied to every sub-catchment yielded good results for zinc for each of the test subestuaries, and that the metal retention factor derived from the zinc calibration performed reasonably well for the historical copper simulations. This shows that metal loads are being delivered to the harbour in the model at uniformly too-high concentrations, which points at a physical interpretation of the metal retention factor, *viz.*, (1 – *MRF*) represents the proportion of the metal load emanating from the catchment that:

- gets lost to a dissolved phase and which does not accumulate (by definition) in the estuary bed sediments;
- gets attached to very fine particles that never settle or only settle very slowly; and
- gets attached to loosely-bound aggregates (or "flocs") of particles, the settling speed of which is significantly smaller than the settling speed of the particles the aggregate is composed of.

None of these processes is explicitly accounted for in the USC-3 model. The metal retention factor can be seen as implicitly accounting for these processes.

It is notable that subsequent experimental work by Ellwood et al. (2008) confirmed a large loss of zinc to the dissolved phase as it transited the Whau River tidal creek in the freshwater run-off. Specifically, ~70 % of the zinc load associated with the particulate phase discharged in freshwater was recycled into the dissolved phase (average over a large range of metal input loads and concentrations). This measured loss was similar to (1 – *MRF*) determined by calibration. Hence, the calibration is not implausible.

**Figure 29**

Performance of the finally calibrated model for zinc. The starting concentrations are shown by the filled circles at year 1 and the target concentrations are shown by the filled circles at year 62.

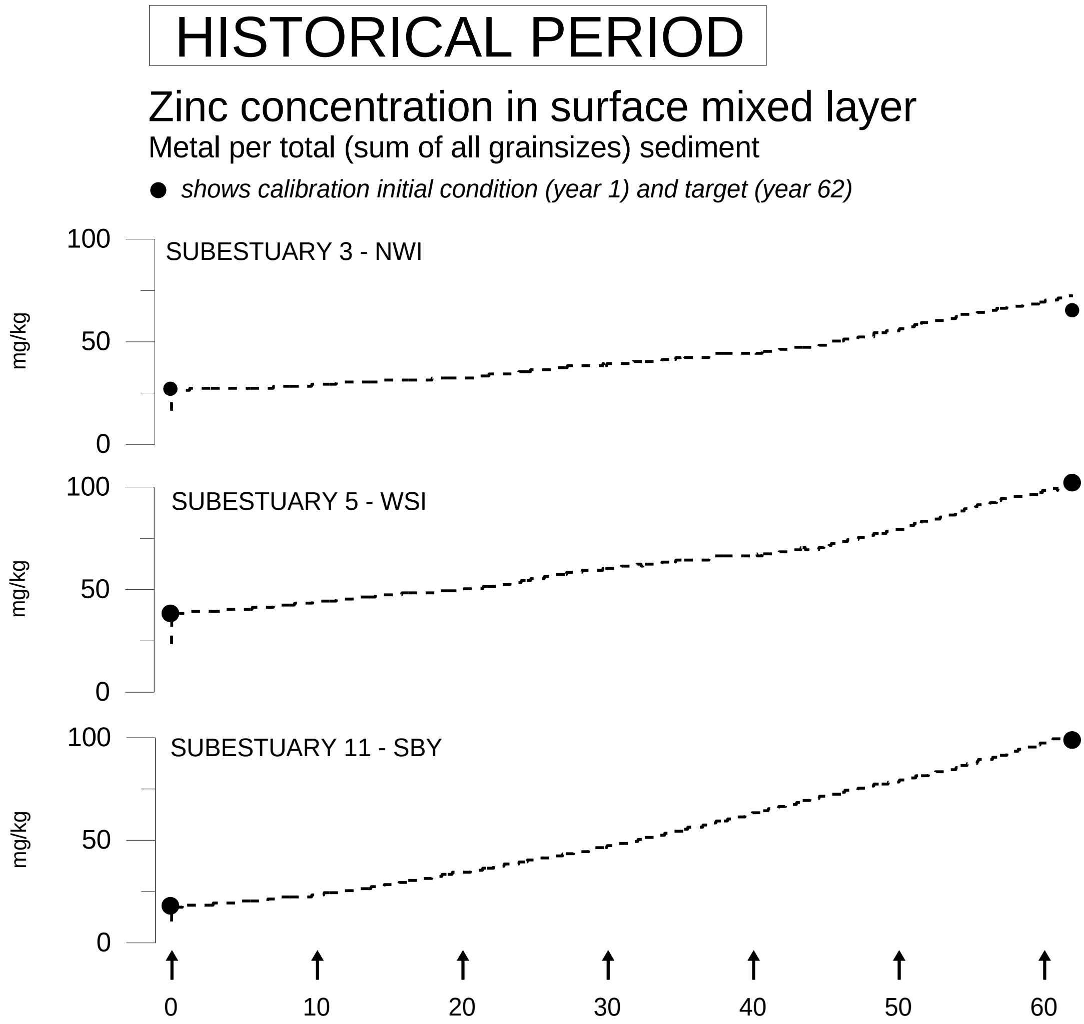
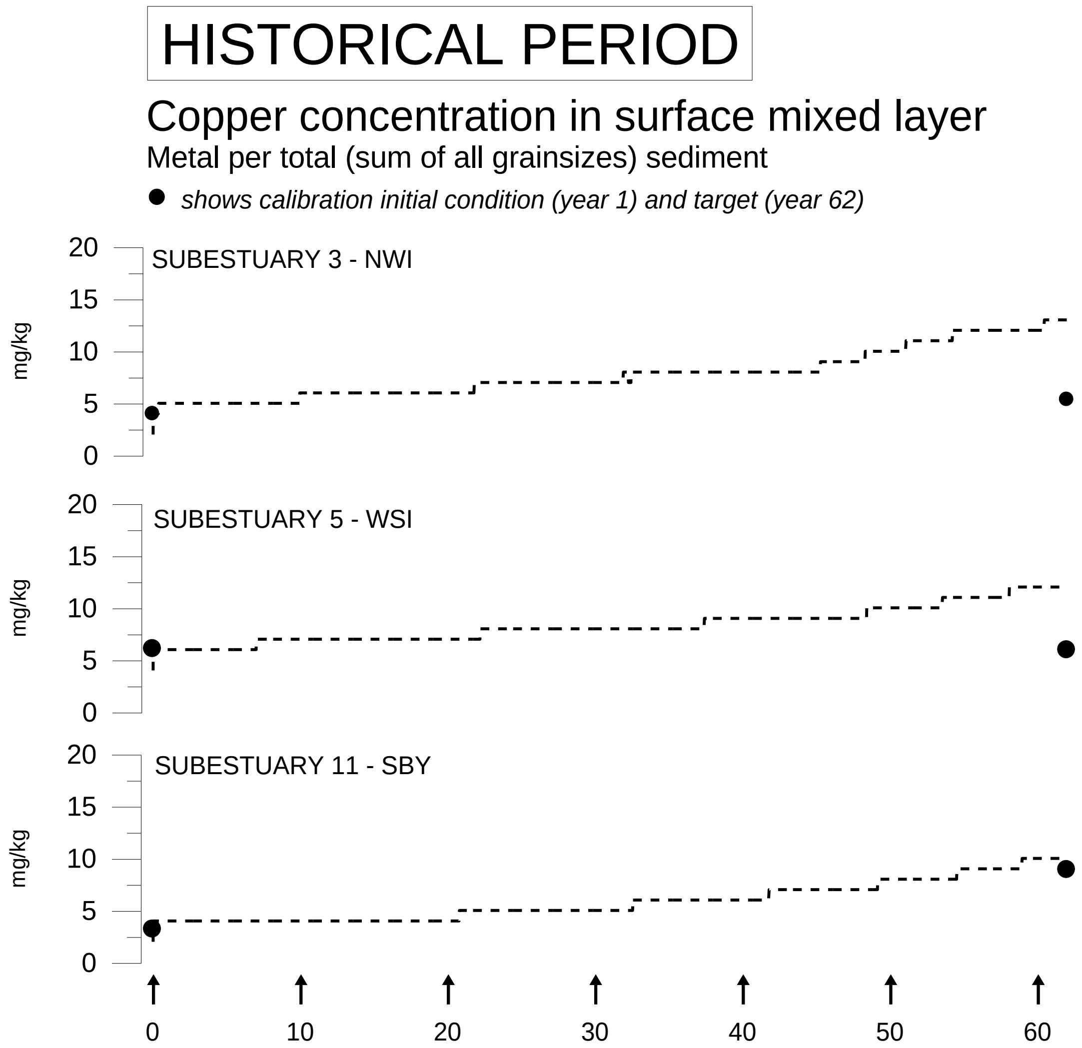


**Figure 30**
Performance of the finally calibrated model for copper. The starting concentrations are shown by the filled circles at year 1 and the target concentrations are shown by the filled circles at year 62.



# 8 Conclusions

The USC-3 model has been implemented for the Central Waitemata Harbour, and calibrated through a simulation of the historical period 1940 to 2001. The calibration involved adjusting the area over which deposition in each subestuary may occur, the behaviour of certain dynamic sinks in the model, and the metal retention factor.

The analysis of the fate of sediments from the sub-catchments surrounding the Central Waitemata Harbour paints a fairly convincing picture. T he analysis of the sources of sediments depositing in the subestuaries also paints a fairly convincing picture, which further adds to the confidence in the calibrated USC-3 model.

The metal retention factor, which is the fraction of the metal load emanating from each sub-catchment that is attached to the corresponding sediment particulate load, was used to reduce the concentration at which metals are delivered to the harbour in the model. A value for the factor was chosen to yield a time-rate-of-change of metal concentrations over the historical period that ended in the target concentrations being achieved. The term (1 – metal retention factor) may be interpreted as representing the loss of metal to a dissolved phase, attachment of metal to very fine sediment, and/or attachment of metal to aggregates ("flocs") of sediment, none of which is explicitly accounted for in the USC-3 model. Subsequent work has provided experimental confirmation of the value of the metal retention factor determined in the calibration.

The USC-3 model is now ready to make predictions for future catchment development scenarios.

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# 10 Appendix 1: ED50, Not Raining

**Figure 31**

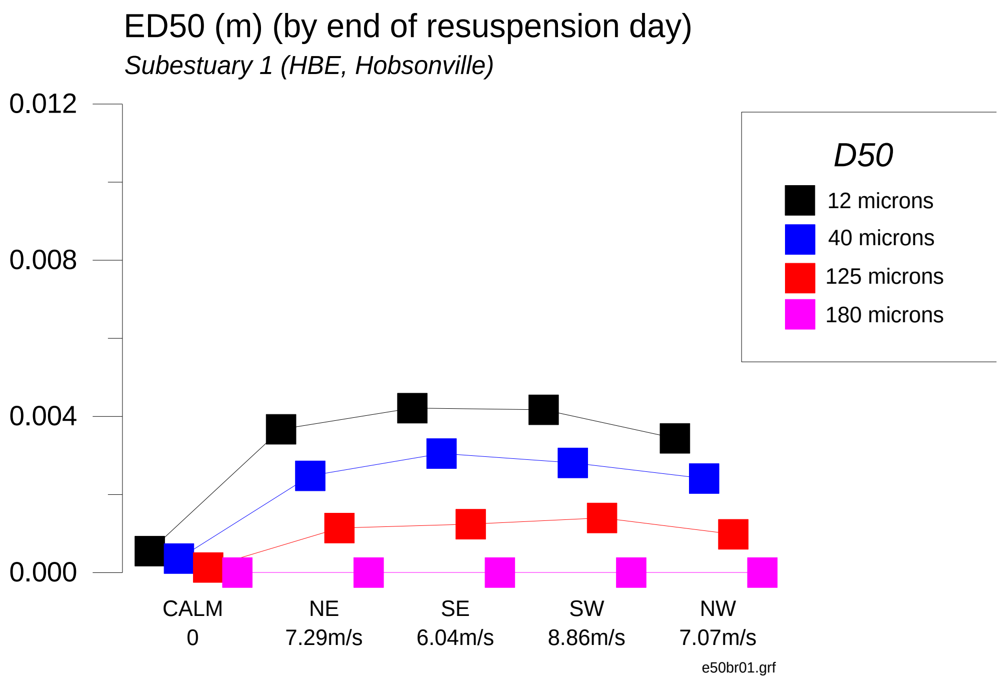


Figure 32

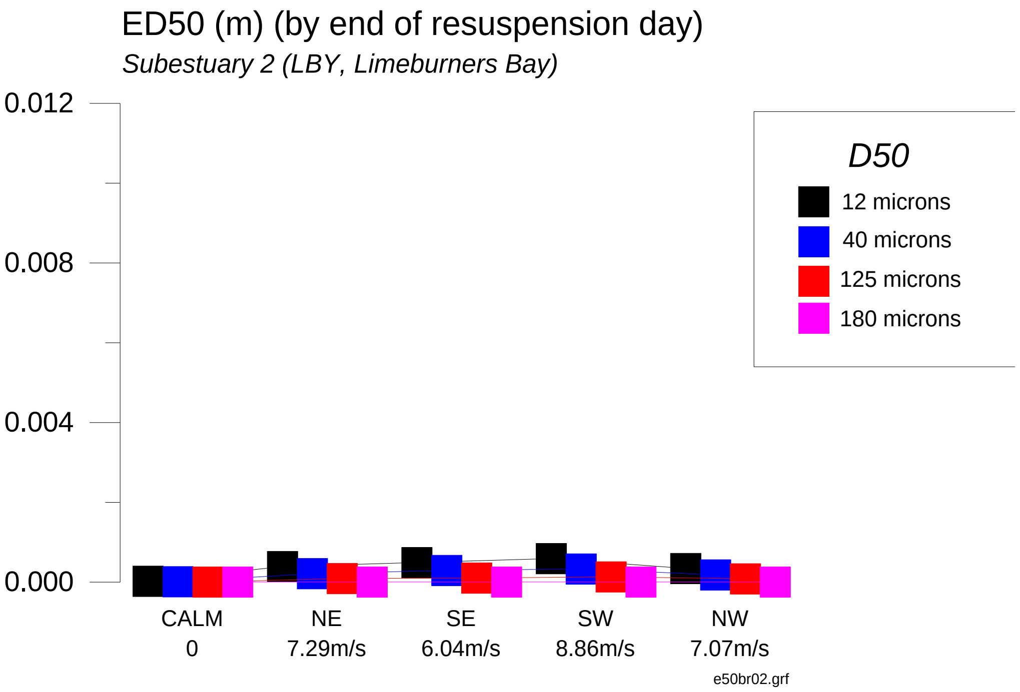



Figure 33

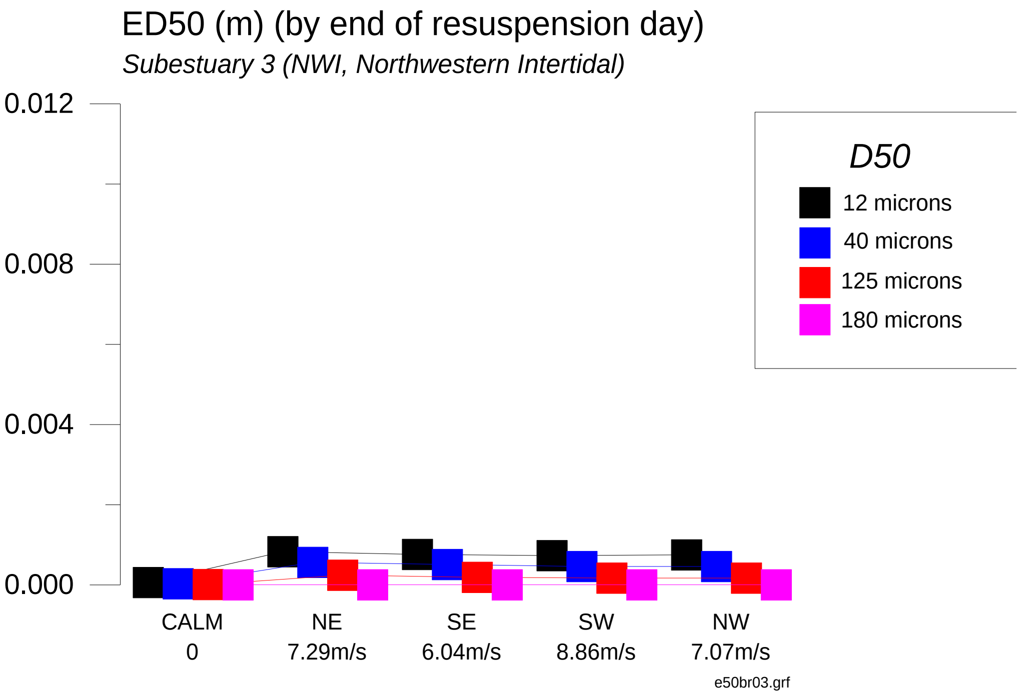


**Figure 34**

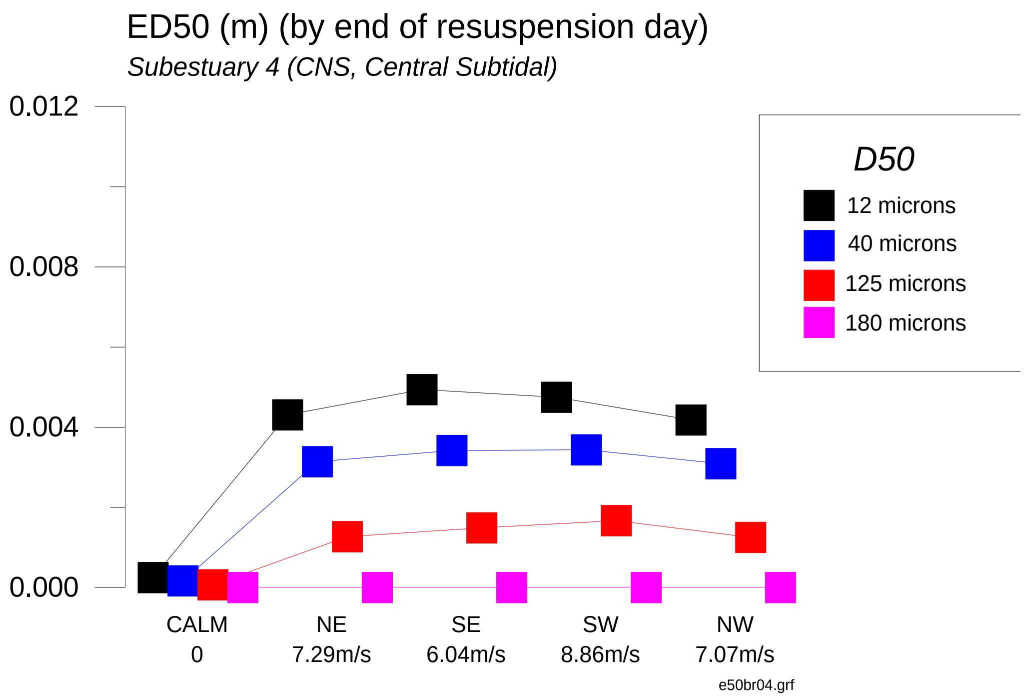



**Figure 35**

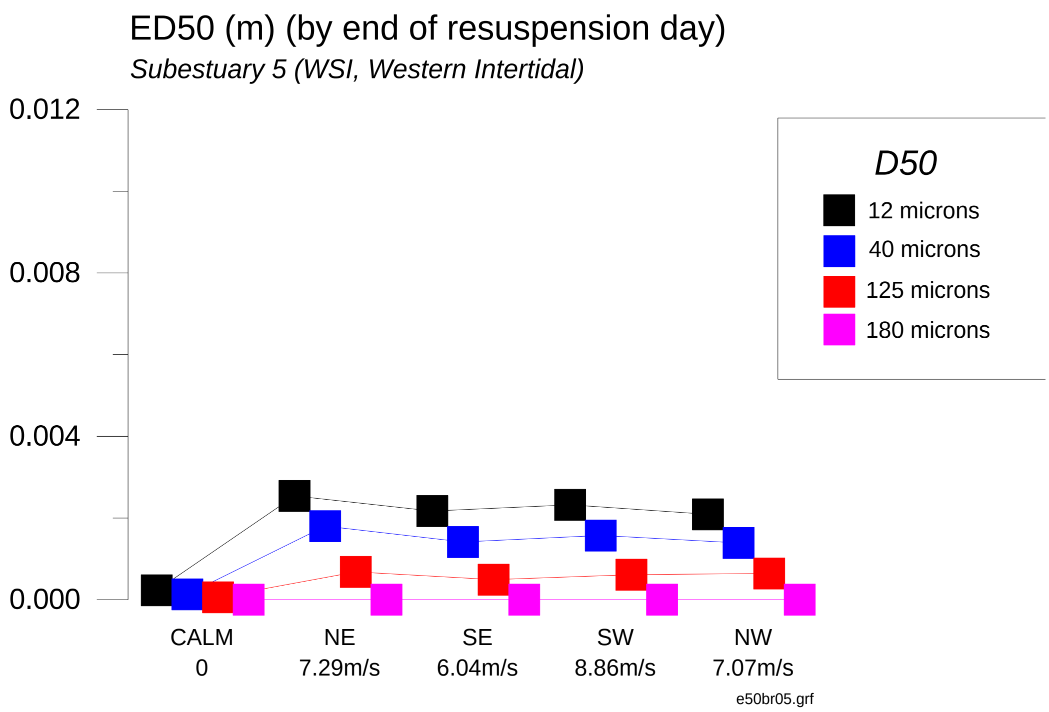


Figure 36

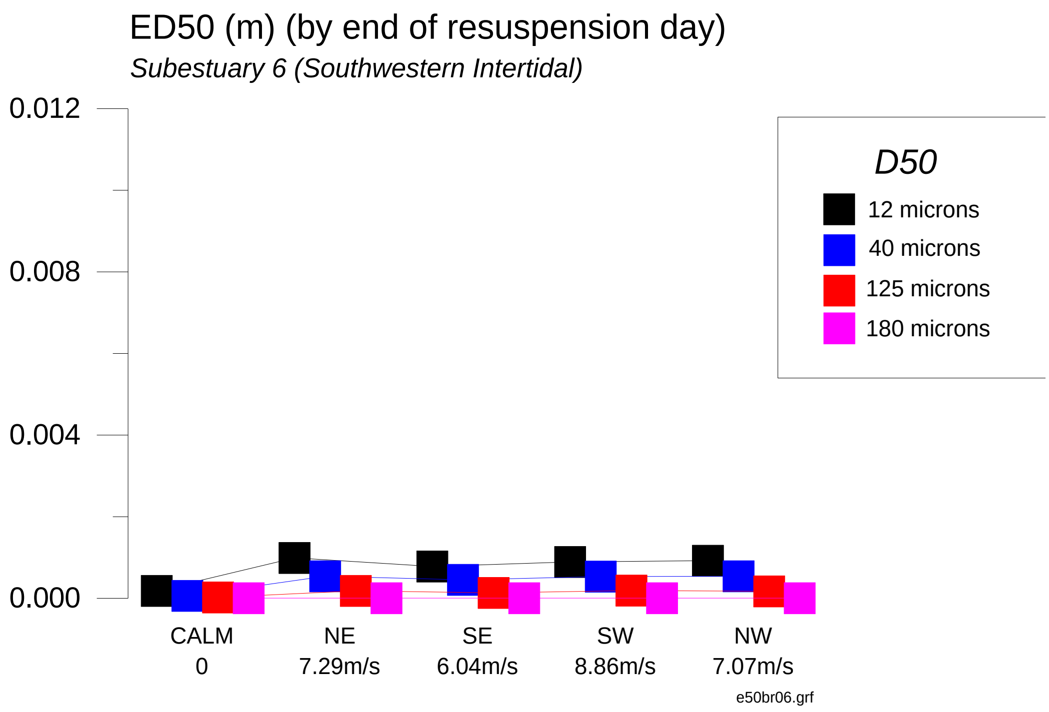



Figure 37

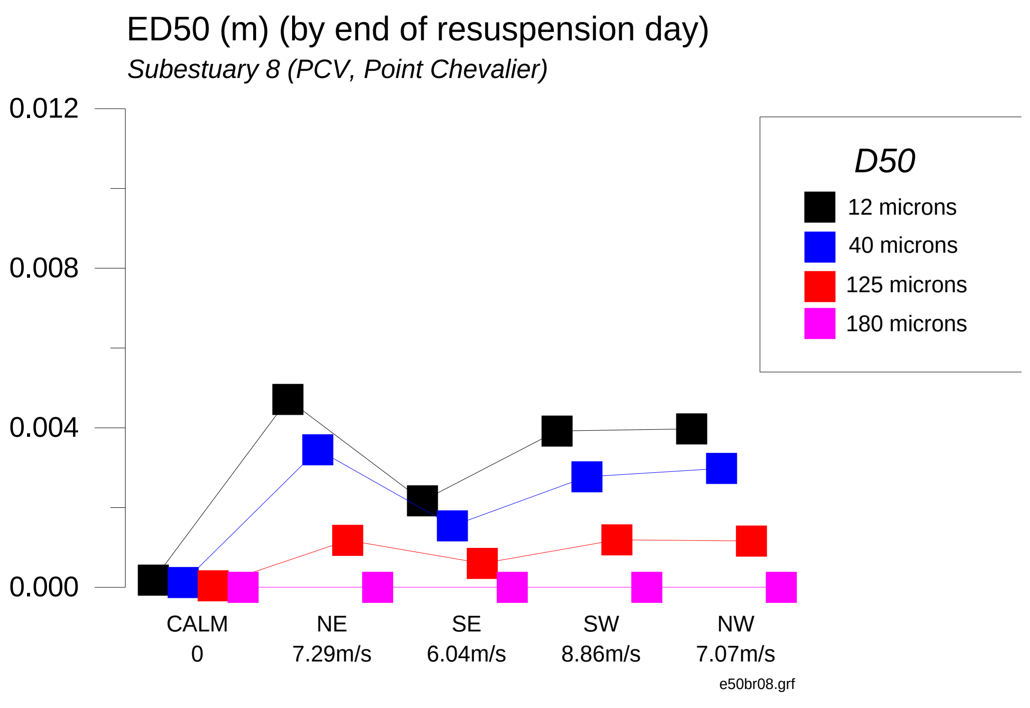


Figure 38

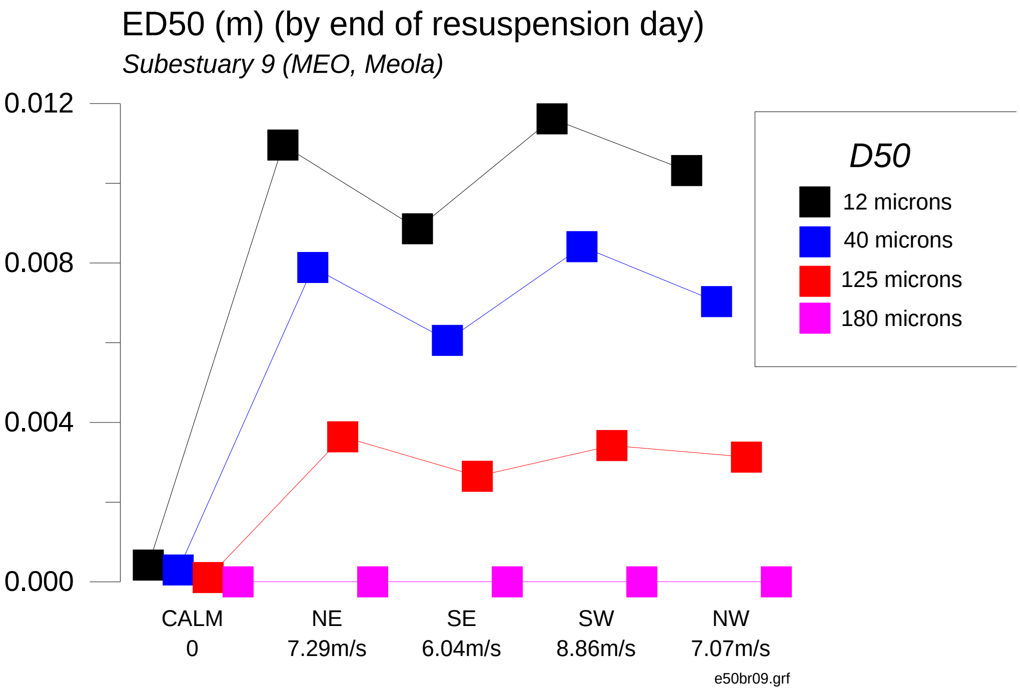



Figure 39

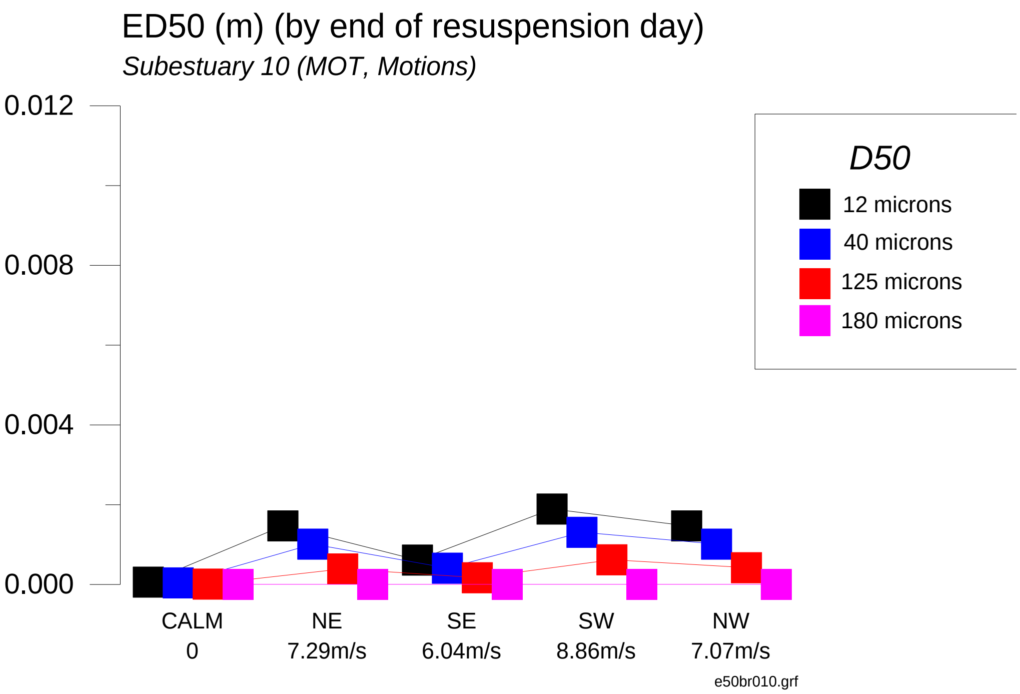
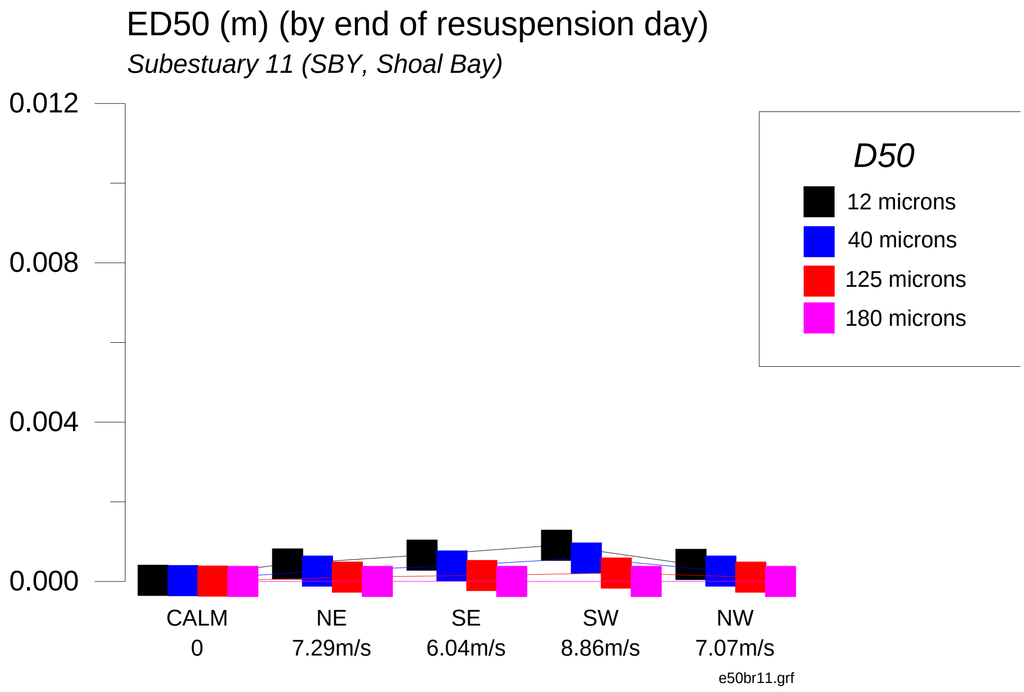


Figure 40


ED50 (m) (by end of resuspension day)
Subestuary 11 (SBY, Shoal Bay)
0.012
0.008
0.004
0.000
D50
12 microns
40 microns
125 microns
180 microns
CALM
0
NE
7.29m/s
SE
6.04m/s
SW
8.86m/s
NW
7.07m/s
e50br11.grf

# 11 Appendix 2: ED50, Raining

**Figure 41**

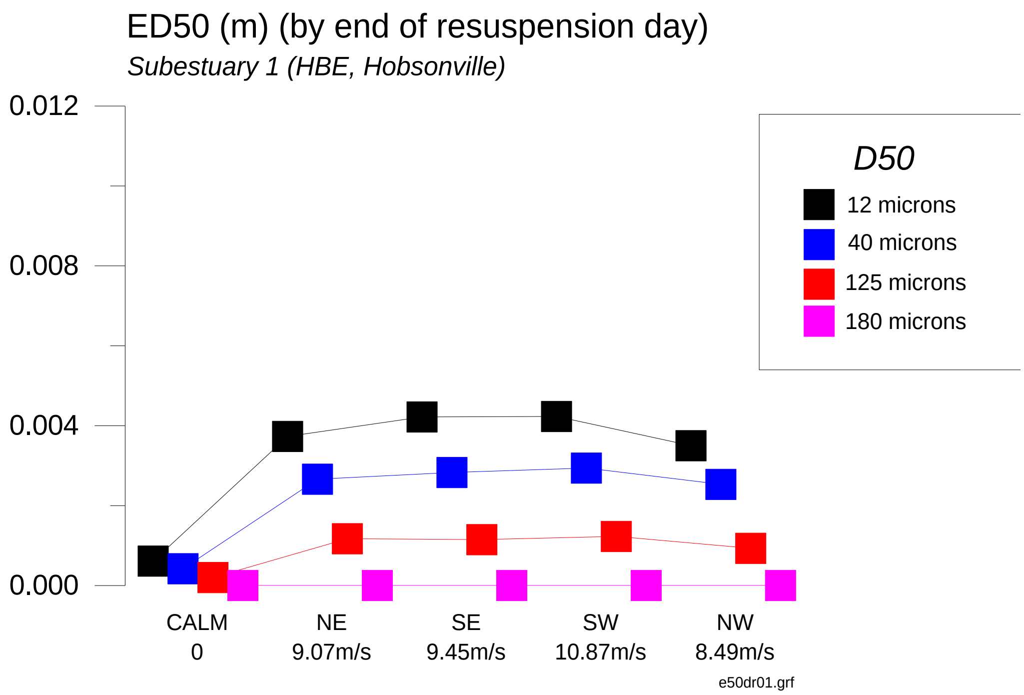


Figure 42

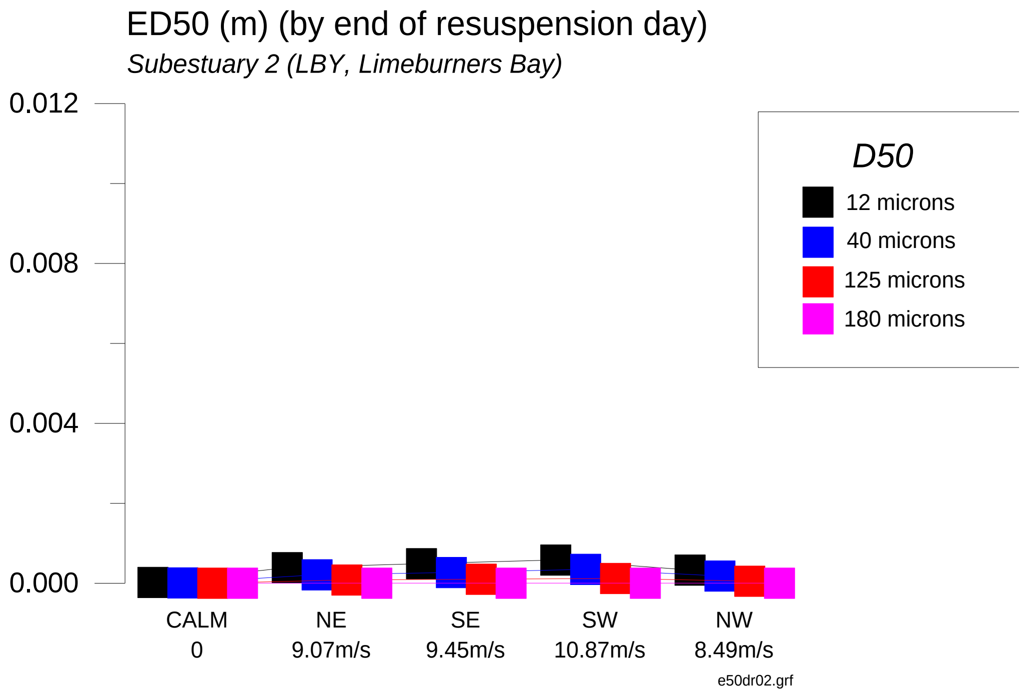



Figure 43

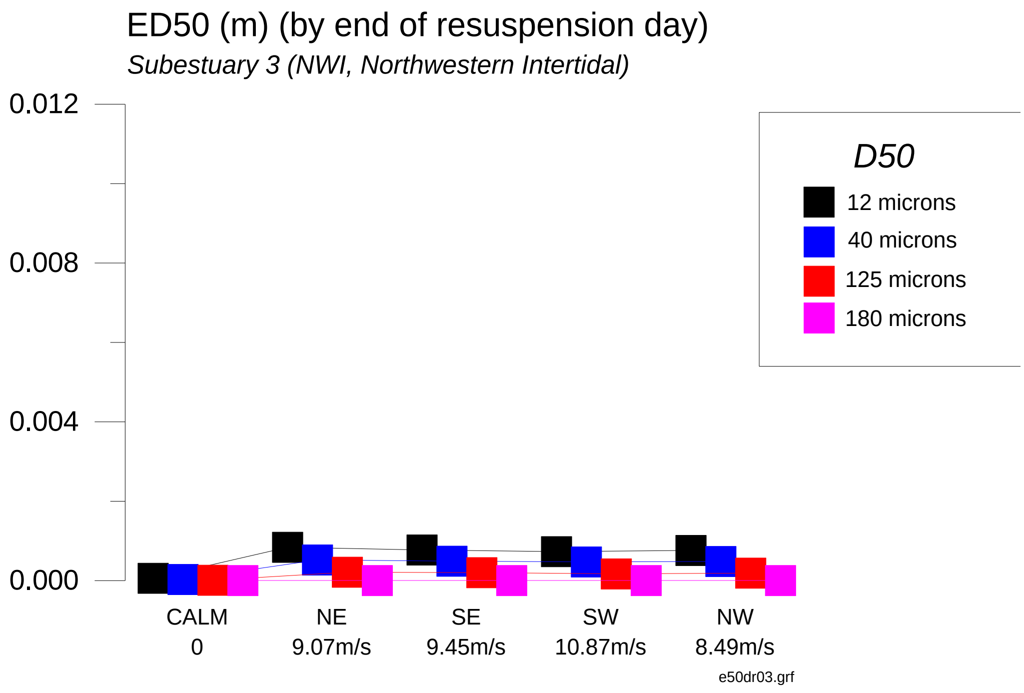


Figure 44

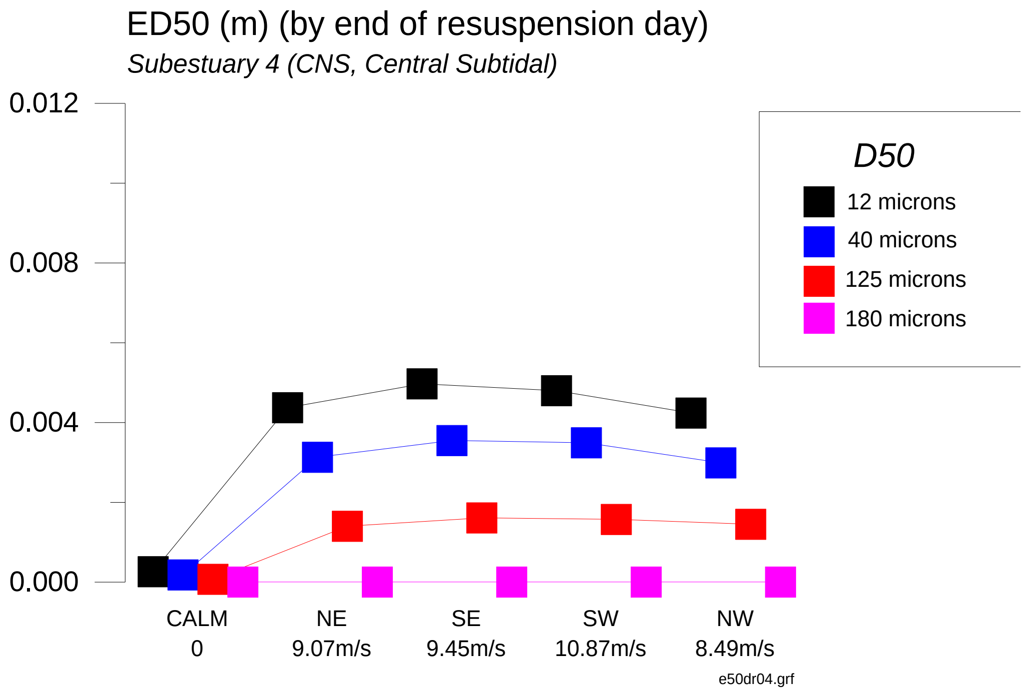



Figure 45

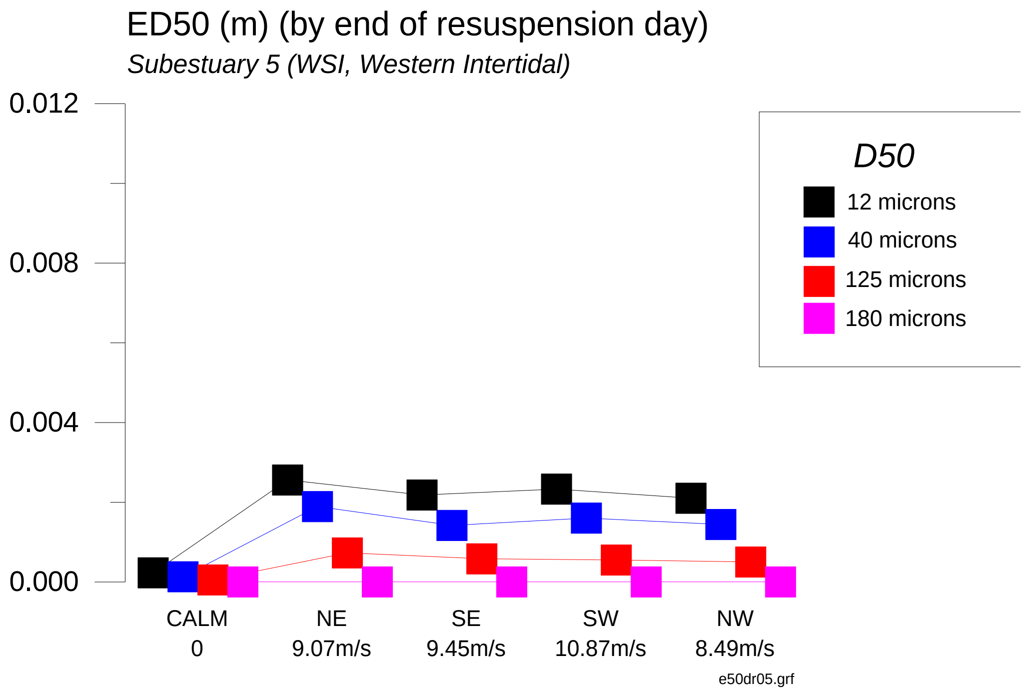


Figure 46

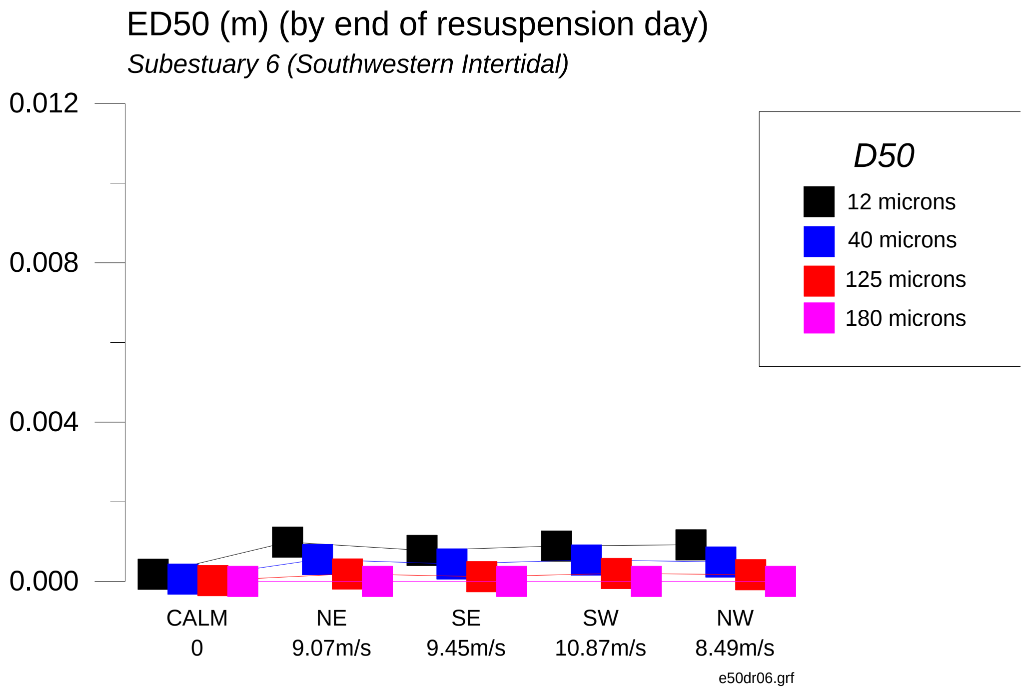



Figure 47

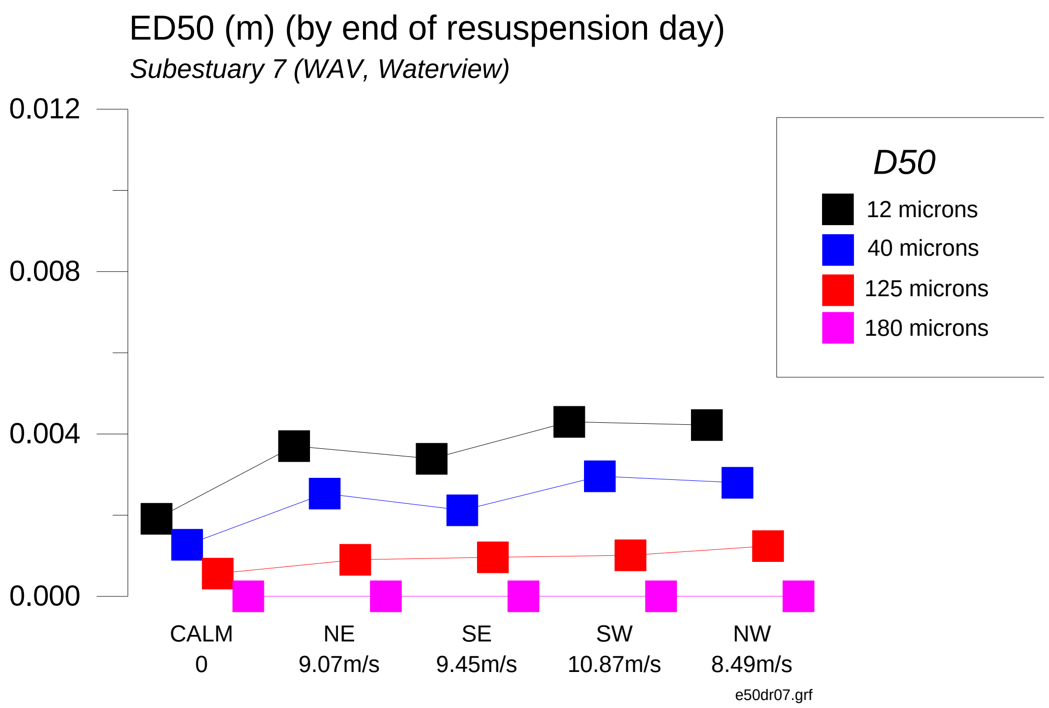


Figure 48

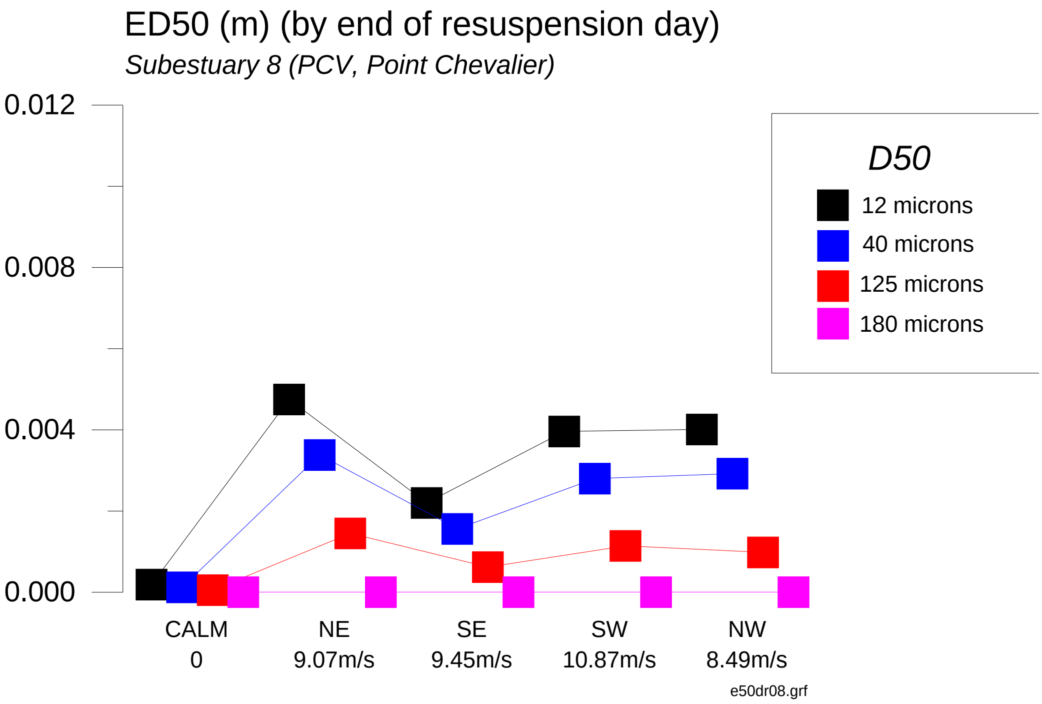



Figure 49

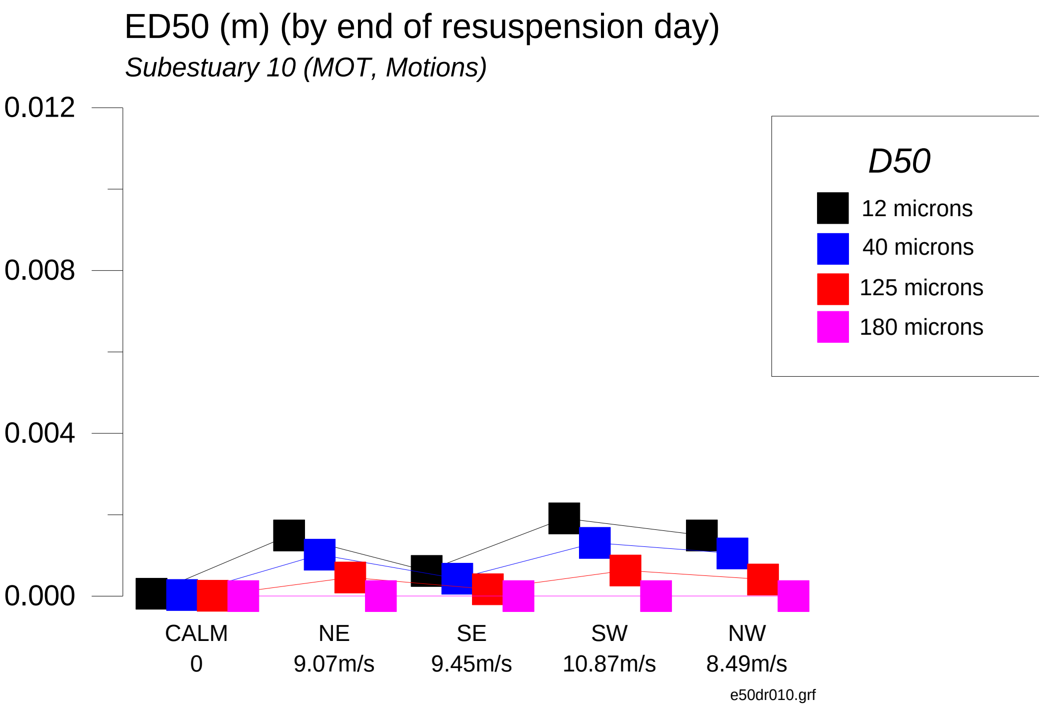
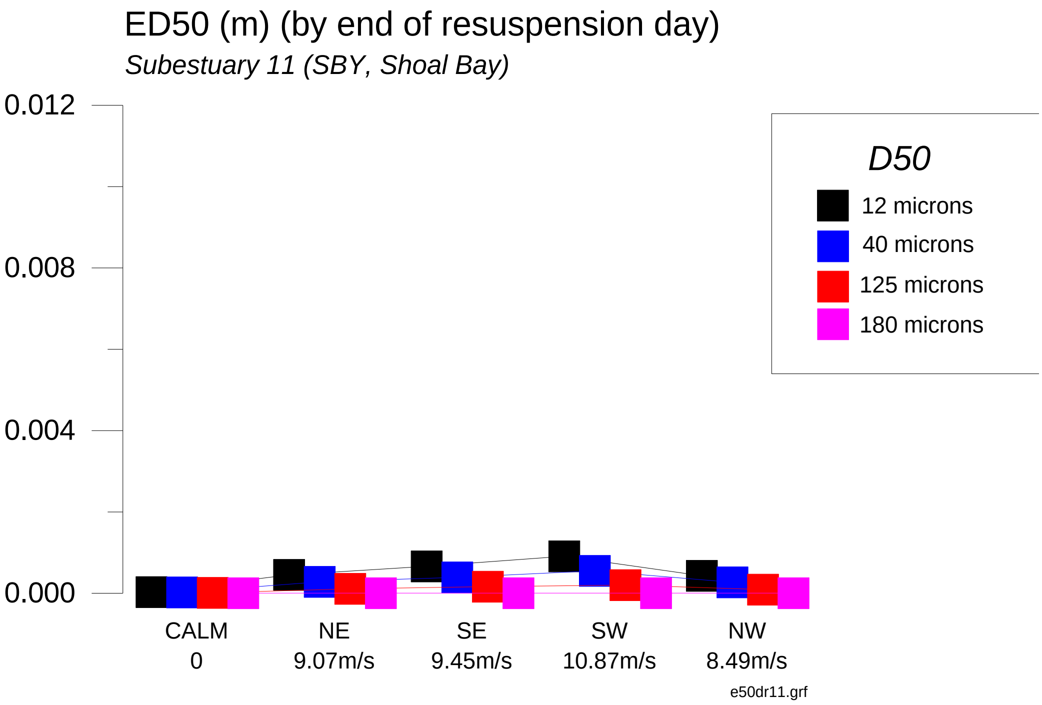


**Figure 50**



ED50 (m) (by end of resuspension day)
Subestuary 11 (SBY, Shoal Bay)
0.012
0.008
0.004
0.000
D50
12 microns
40 microns
125 microns
180 microns
CALM
0
NE
9.07m/s
SE
9.45m/s
SW
10.87m/s
NW
8.49m/s
e50dr11.grf

# 12 Appendix 3: R5 and R5SUSP (End of Resuspension Day), Not Raining

Figure 51

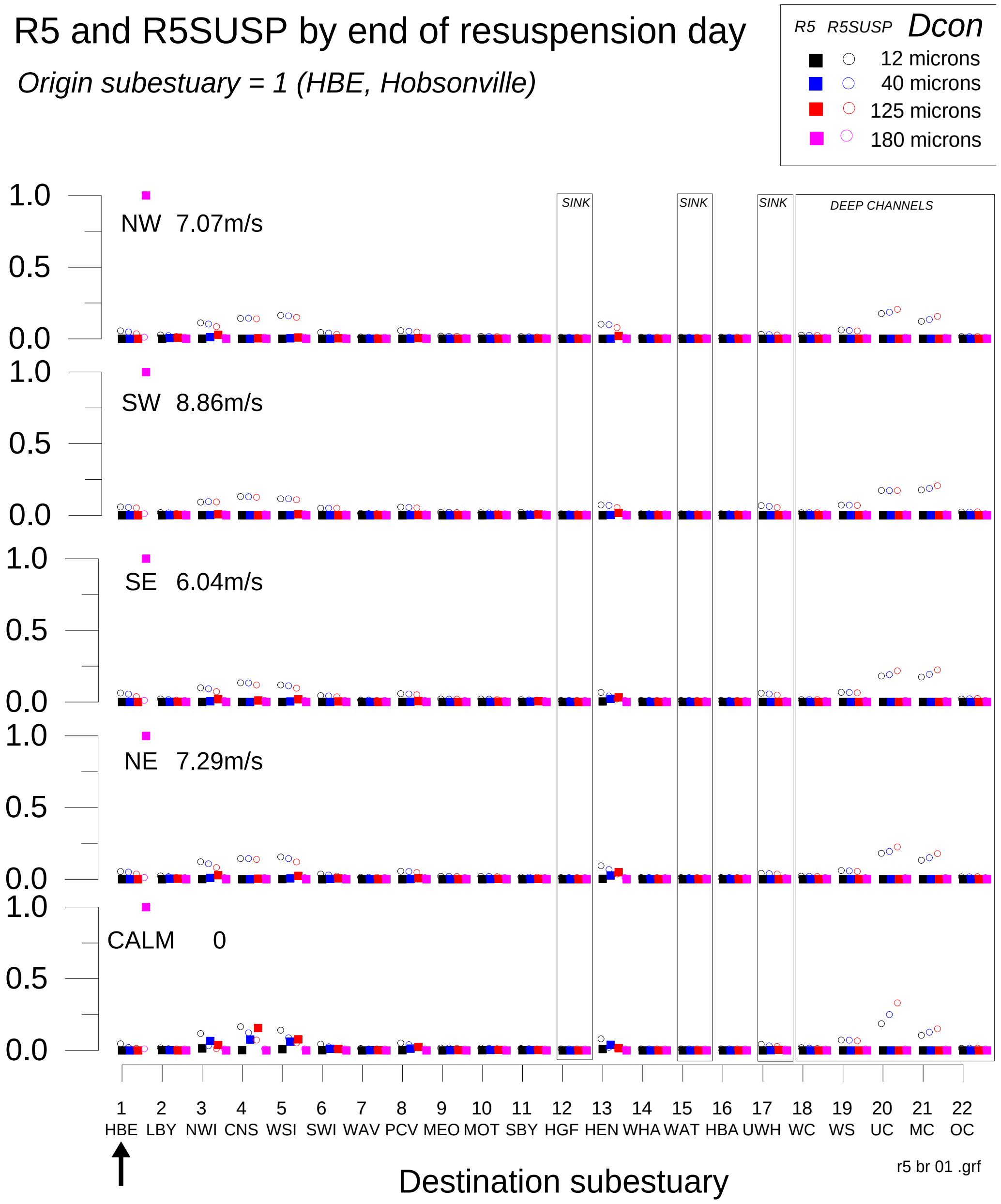
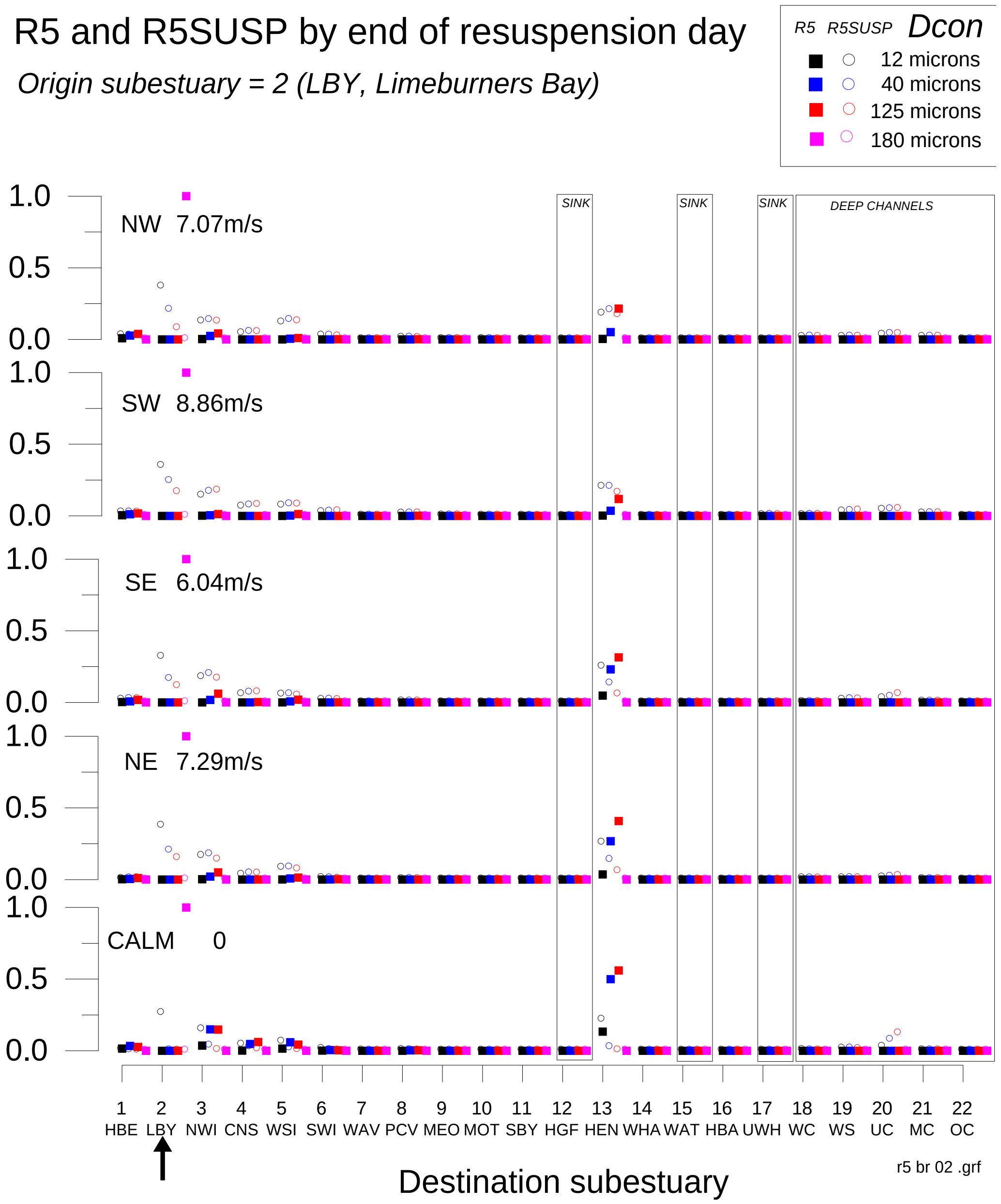
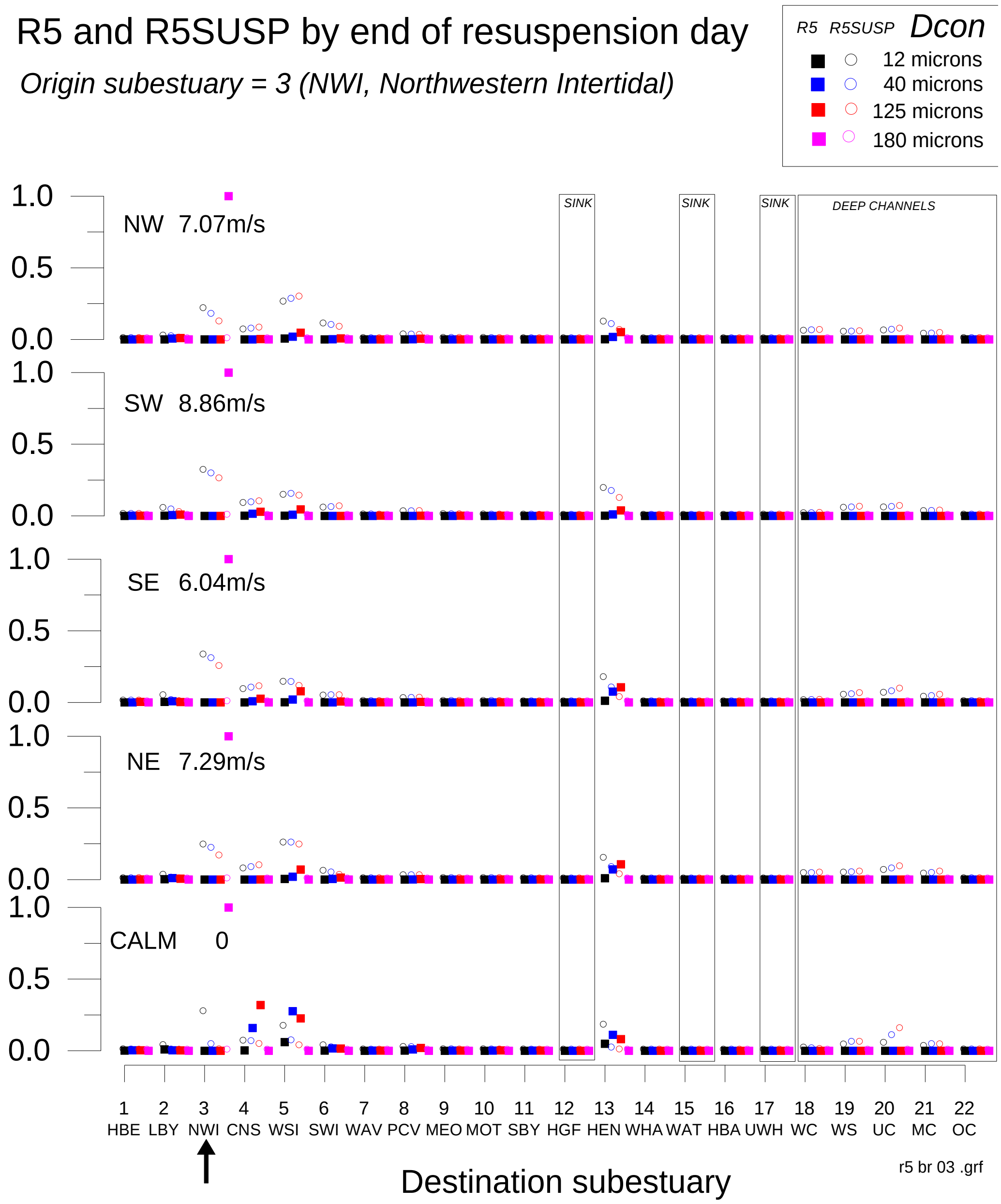


Figure 52



R5 and R5SUSP by end of resuspension day
Origin subestuary = 2 (LBY, Limeburners Bay)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 7.07m/s
SW 8.86m/s
SE 6.04m/s
NE 7.29m/s
CALM 0
1.0
0.5
0.0
SINK
SINK
SINK
DEEP CHANNELS
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22
HBE LBY NWI CNS WSI SWI WAV PCV MEO MOT SBY HGF HEN WHA WAT HBA UWH WC WS UC MC OC
Destination subestuary
r5 br 02 .grf

Figure 53



R5 and R5SUSP by end of resuspension day
Origin subestuary = 3 (NWI, Northwestern Intertidal)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
1.0
0.5
0.0
NW 7.07m/s
SW 8.86m/s
SE 6.04m/s
NE 7.29m/s
CALM 0
SINK
SINK
SINK
DEEP CHANNELS
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22
HBE LBY NWI CNS WSI SWI WAV PCV MEO MOT SBY HGF HEN WHA WAT HBA UWH WC WS UC MC OC
Destination subestuary
r5 br 03 .grf

Figure 54

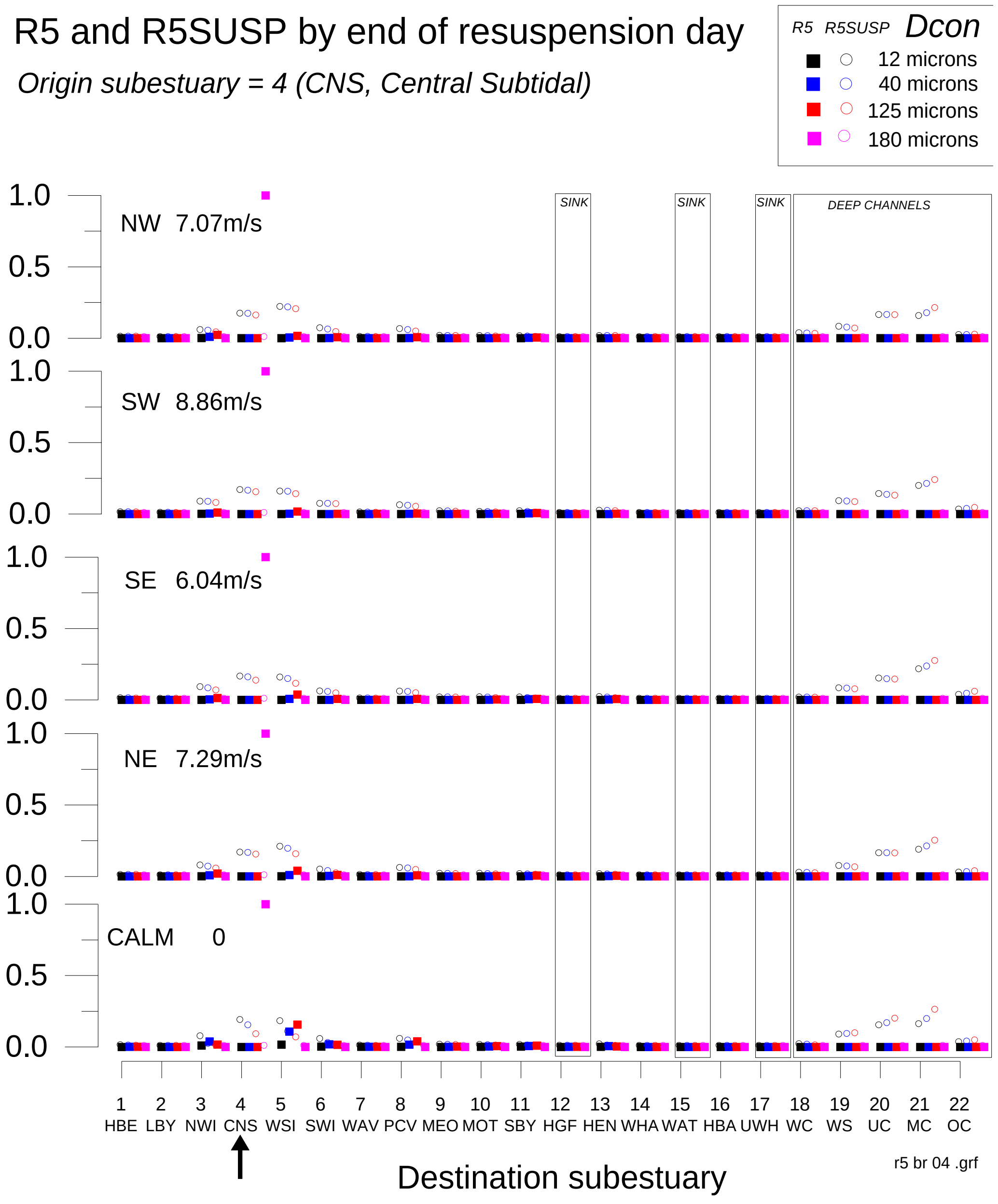
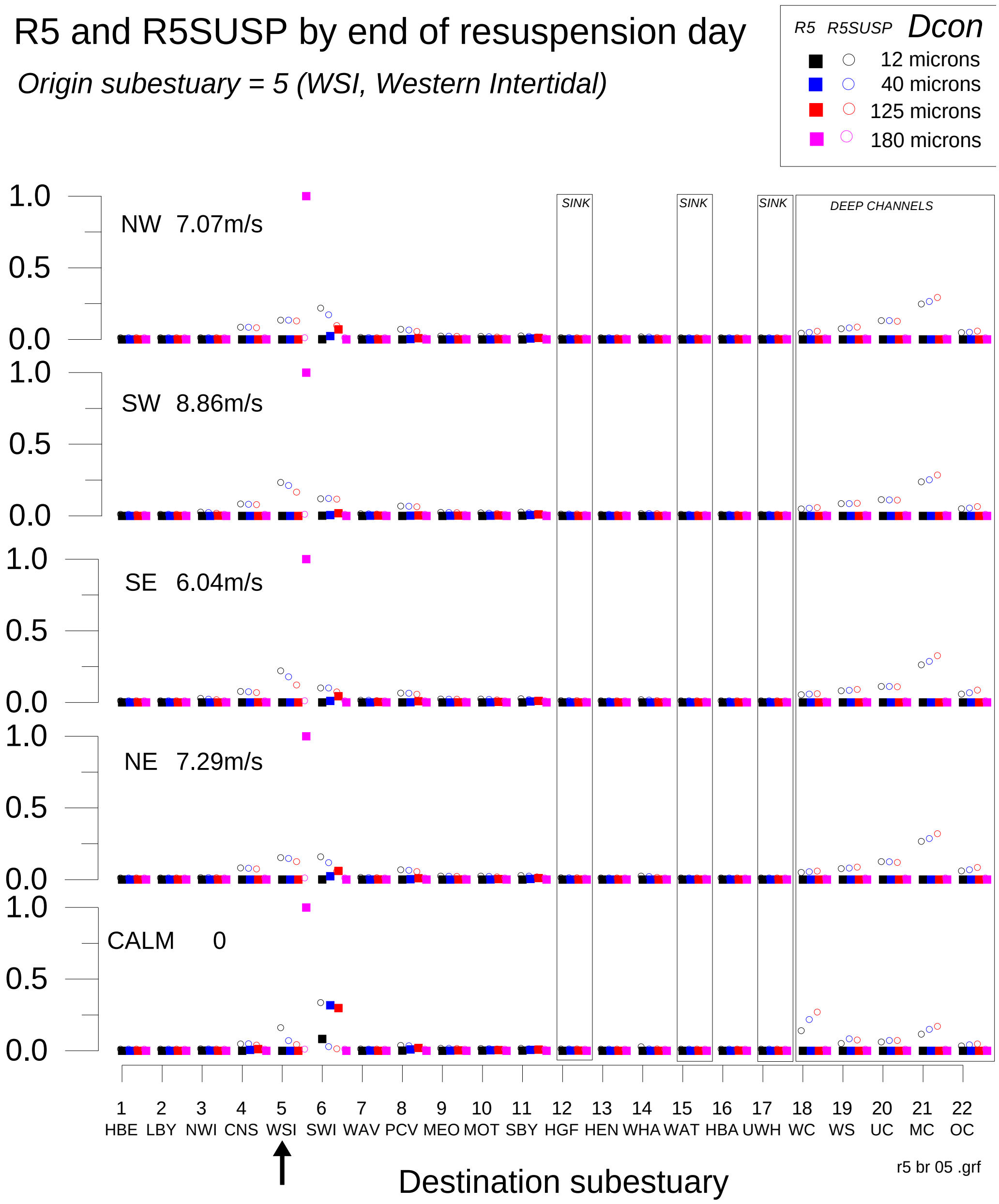

R5 and R5SUSP by end of resuspension day
Origin subestuary = 4 (CNS, Central Subtidal)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 7.07m/s
SW 8.86m/s
SE 6.04m/s
NE 7.29m/s
CALM 0
1.0
0.5
0.0
SINK
SINK
SINK
DEEP CHANNELS
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r5 br 04 .grf

Figure 55



R5 and R5SUSP by end of resuspension day
Origin subestuary = 5 (WSI, Western Intertidal)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 7.07m/s
SW 8.86m/s
SE 6.04m/s
NE 7.29m/s
CALM 0
1.0
0.5
0.0
SINK
SINK
SINK
DEEP CHANNELS
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r5 br 05 .grf

Figure 56

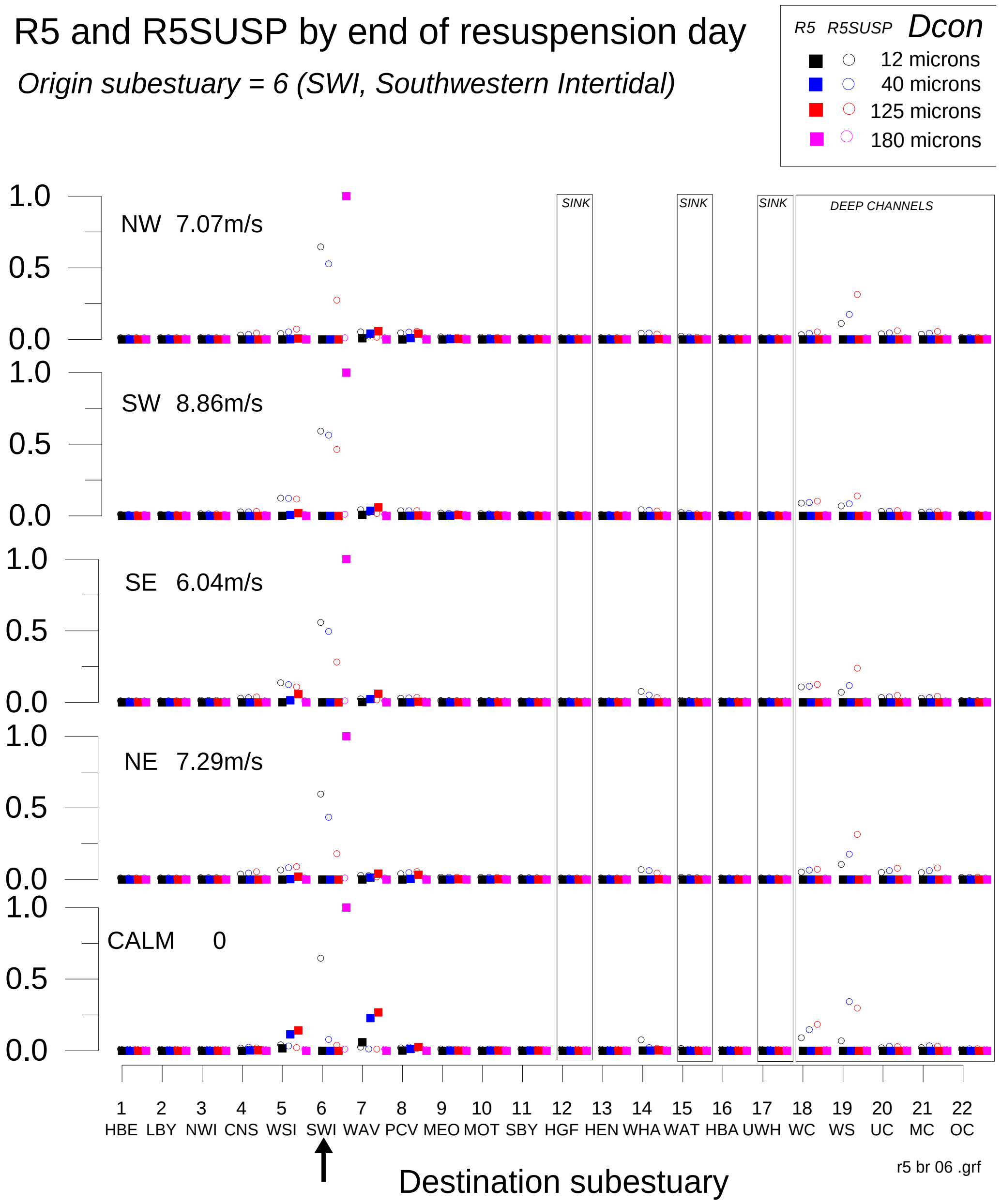

R5 and R5SUSP by end of resuspension day
Origin subestuary = 6 (SWI, Southwestern Intertidal)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 7.07m/s
SW 8.86m/s
SE 6.04m/s
NE 7.29m/s
CALM 0
1.0
0.5
0.0
SINK
SINK
SINK
DEEP CHANNELS
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r5 br 06 .grf

Figure 57

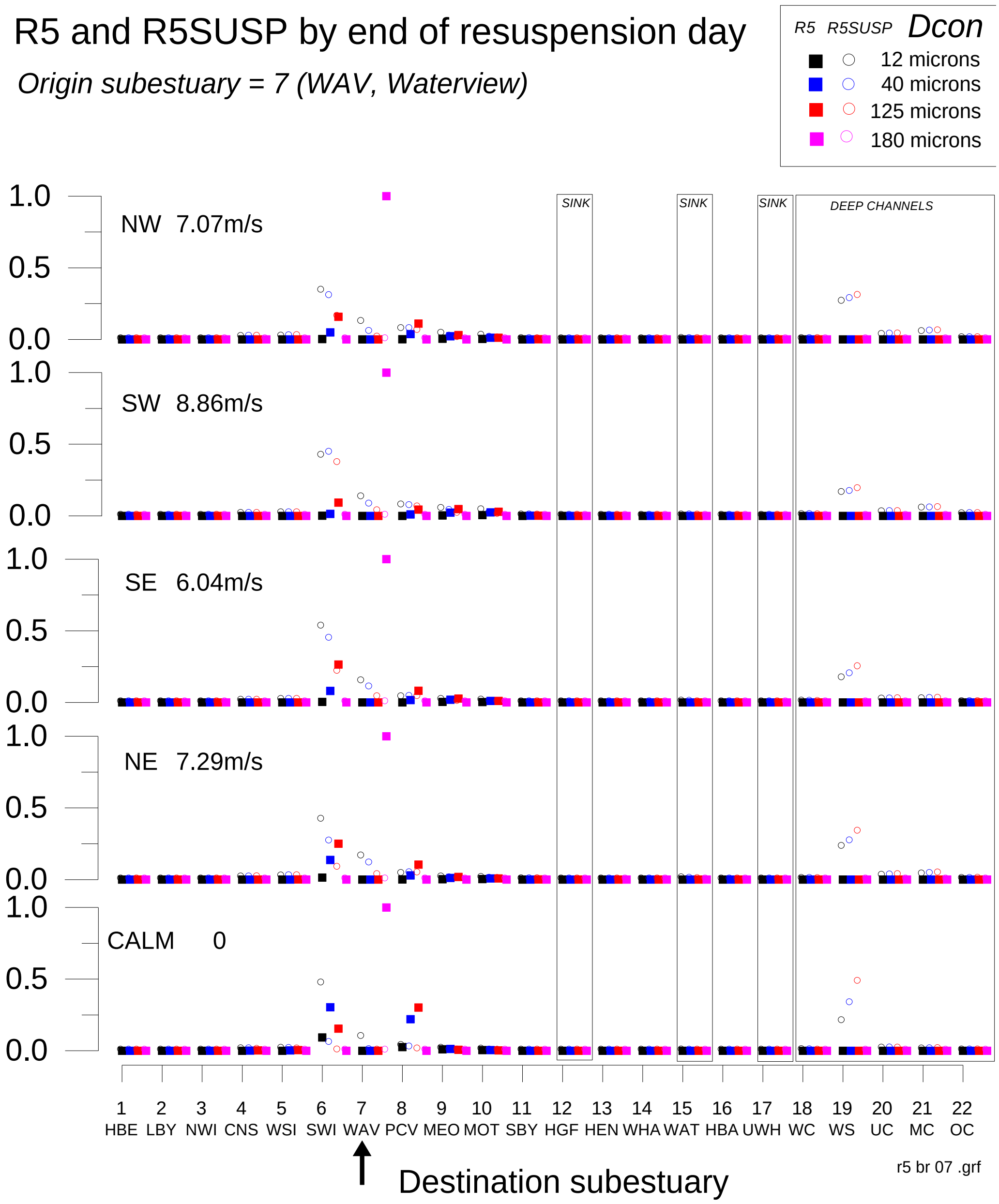
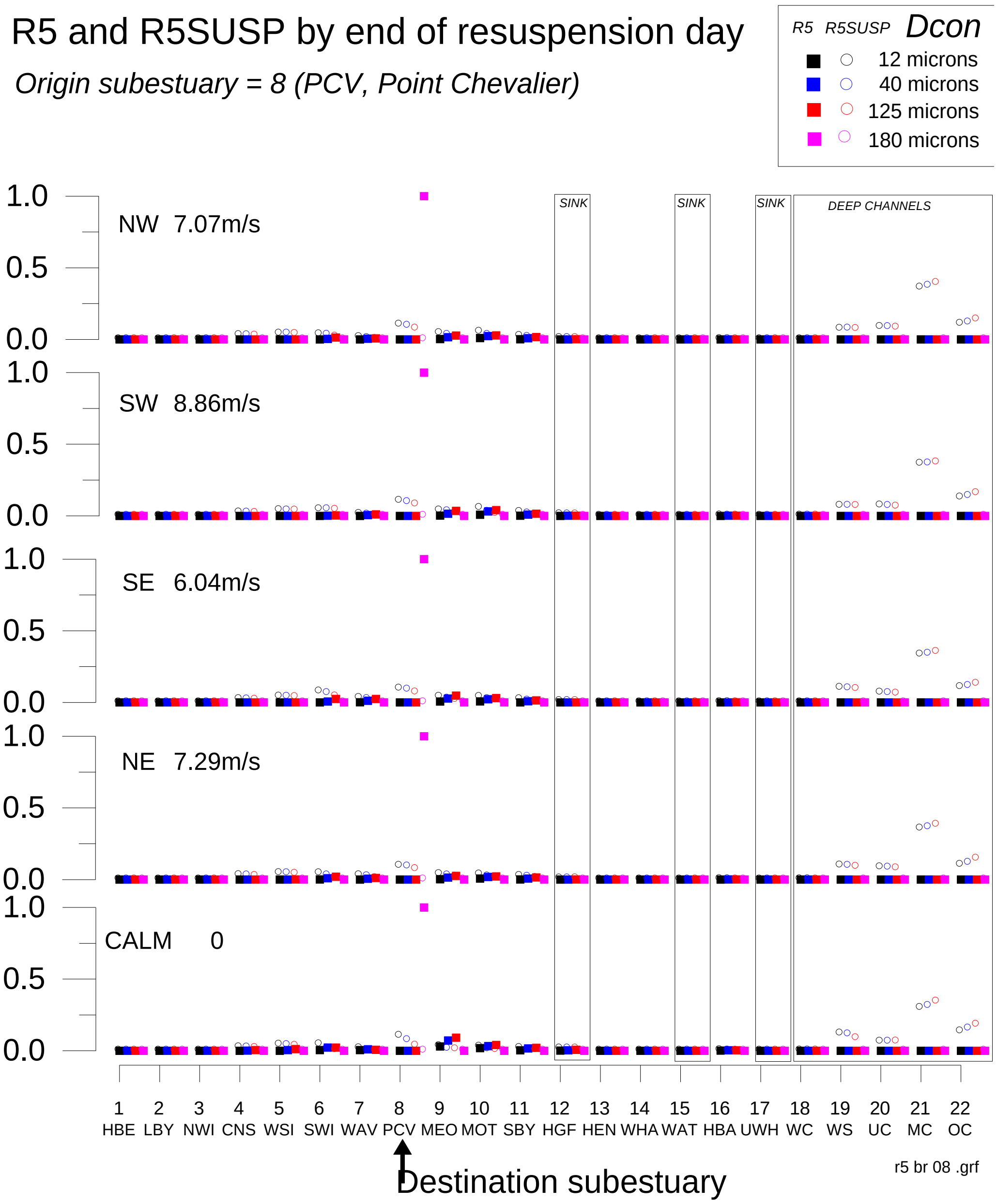

R5 and R5SUSP by end of resuspension day
Origin subestuary = 7 (WAV, Waterview)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 7.07m/s
SW 8.86m/s
SE 6.04m/s
NE 7.29m/s
CALM 0
1.0
0.5
0.0
SINK
SINK
SINK
DEEP CHANNELS
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r5 br 07 .grf

Figure 58



R5 and R5SUSP by end of resuspension day
Origin subestuary = 8 (PCV, Point Chevalier)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 7.07m/s
SW 8.86m/s
SE 6.04m/s
NE 7.29m/s
CALM 0
1.0
0.5
0.0
SINK
DEEP CHANNELS
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r5 br 08 .grf

Figure 59

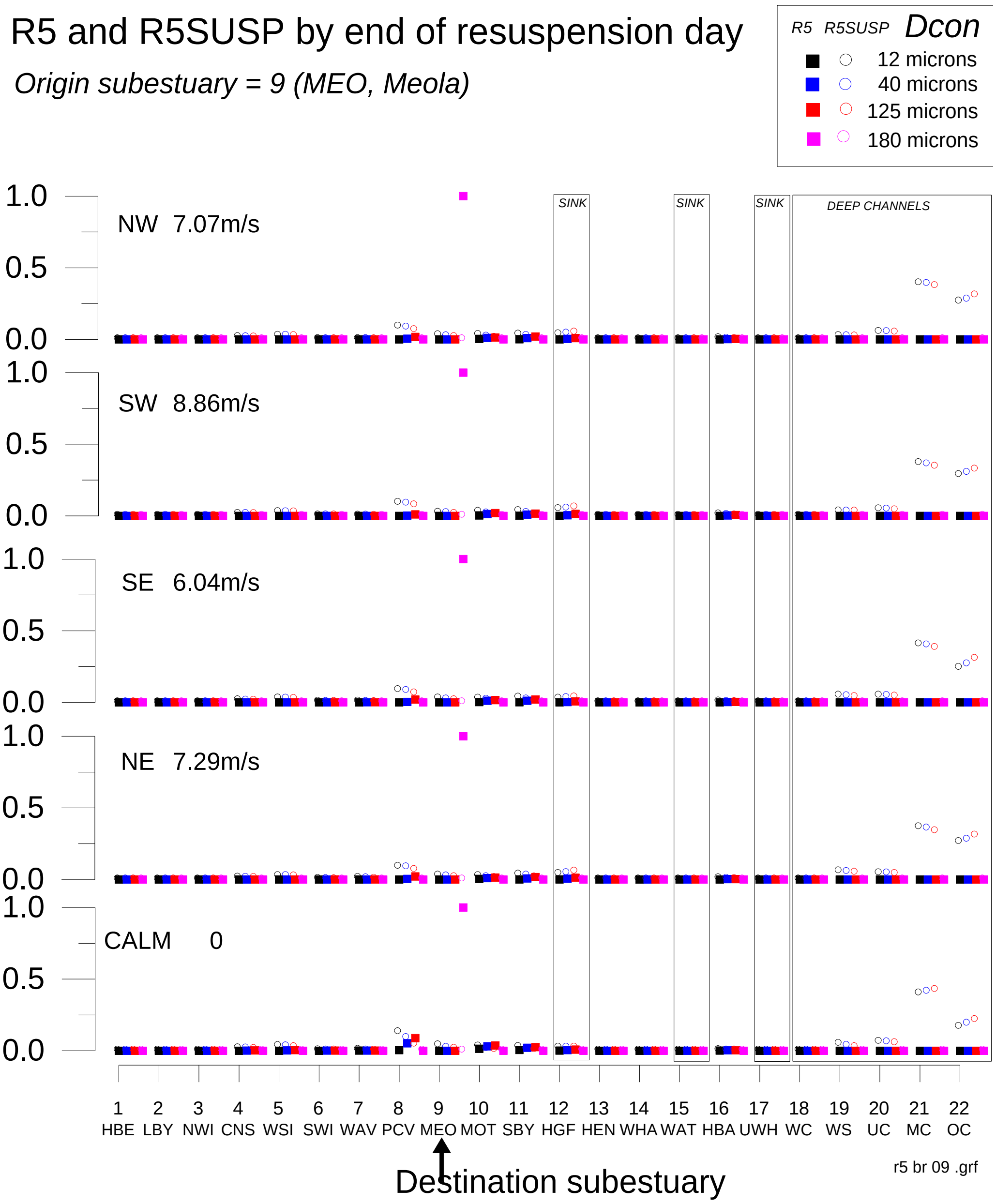
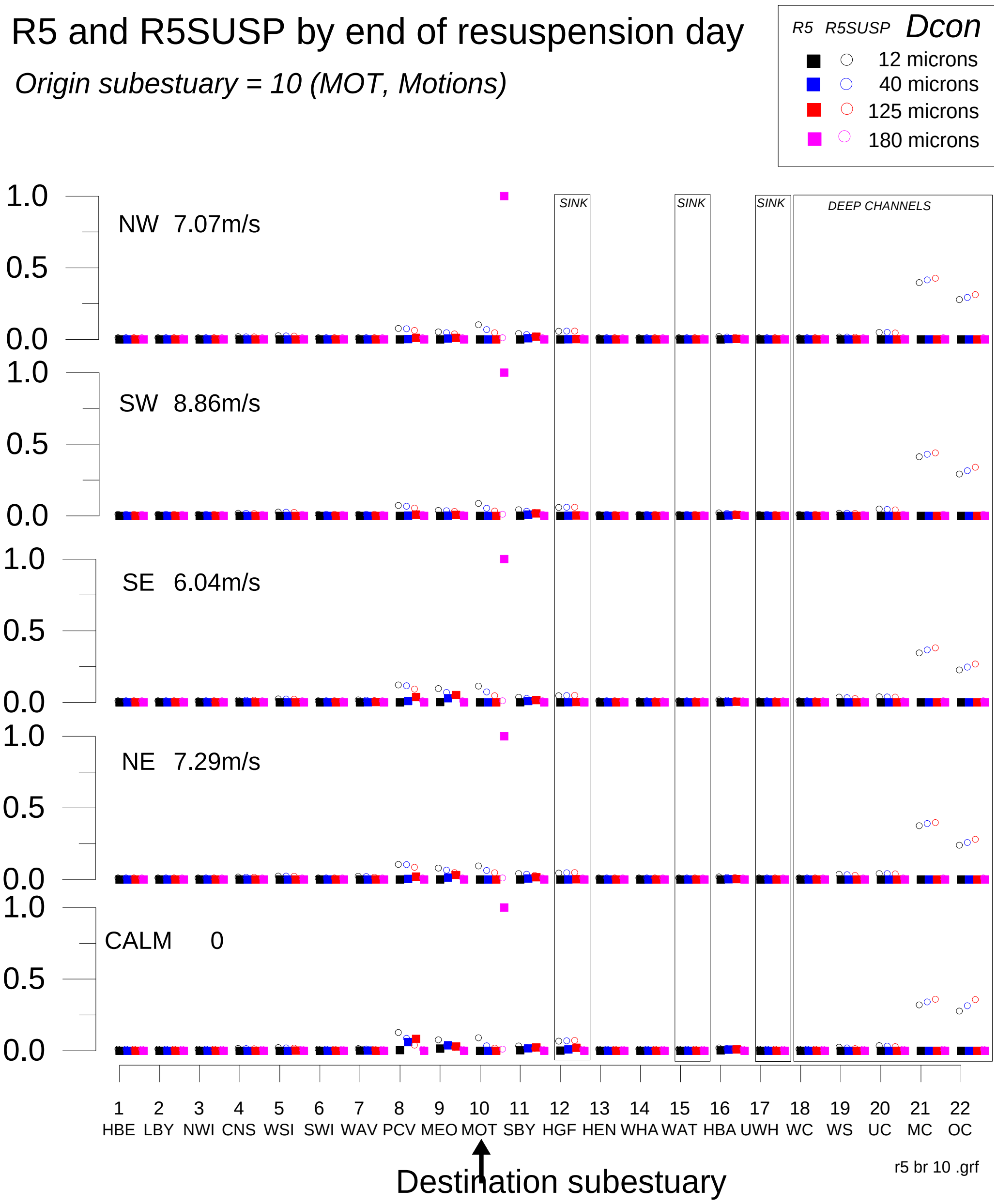
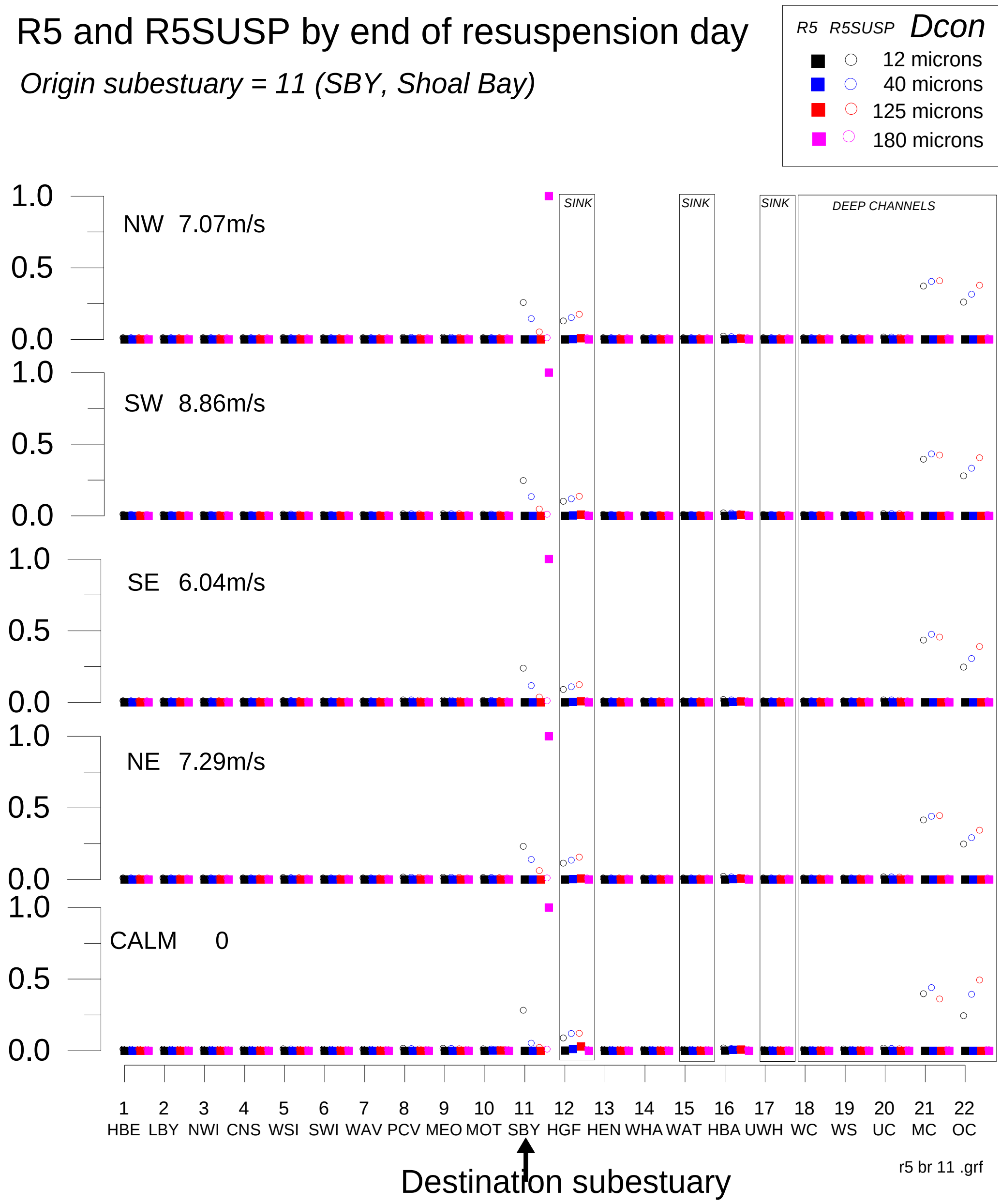

R5 and R5SUSP by end of resuspension day
Origin subestuary = 9 (MEO, Meola)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 7.07m/s
SW 8.86m/s
SE 6.04m/s
NE 7.29m/s
CALM 0
1.0
0.5
0.0
SINK
SINK
SINK
DEEP CHANNELS
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r5 br 09 .grf

Figure 60



R5 and R5SUSP by end of resuspension day
Origin subestuary = 10 (MOT, Motions)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
1.0
0.5
0.0
NW 7.07m/s
SW 8.86m/s
SE 6.04m/s
NE 7.29m/s
CALM 0
SINK
SINK
SINK
DEEP CHANNELS
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22
HBE LBY NWI CNS WSI SWI WAV PCV MEO MOT SBY HGF HEN WHA WAT HBA UWH WC WS UC MC OC
Destination subestuary
r5 br 10 .grf

Figure 61



R5 and R5SUSP by end of resuspension day
Origin subestuary = 11 (SBY, Shoal Bay)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 7.07m/s
SW 8.86m/s
SE 6.04m/s
NE 7.29m/s
CALM 0
1.0
0.5
0.0
SINK
SINK
SINK
DEEP CHANNELS
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22
HBE LBY NWI CNS WSI SWI WAV PCV MEO MOT SBY HGF HEN WHA WAT HBA UWH WC WS UC MC OC
Destination subestuary
r5 br 11 .grf

# 13 Appendix 4: R5 and R5SUSP (End of Resuspension Day), Raining

**Figure 62**

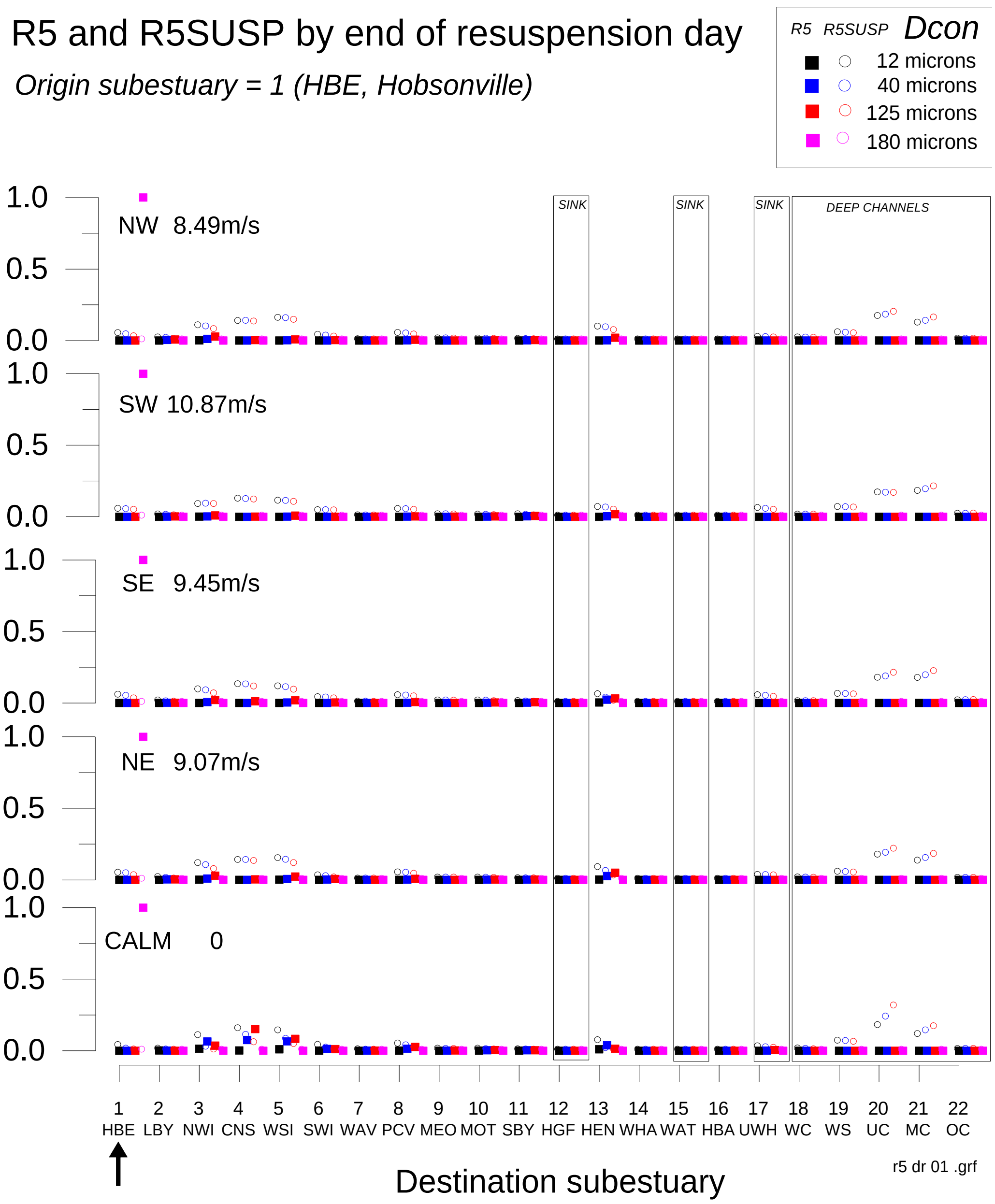


Figure 63

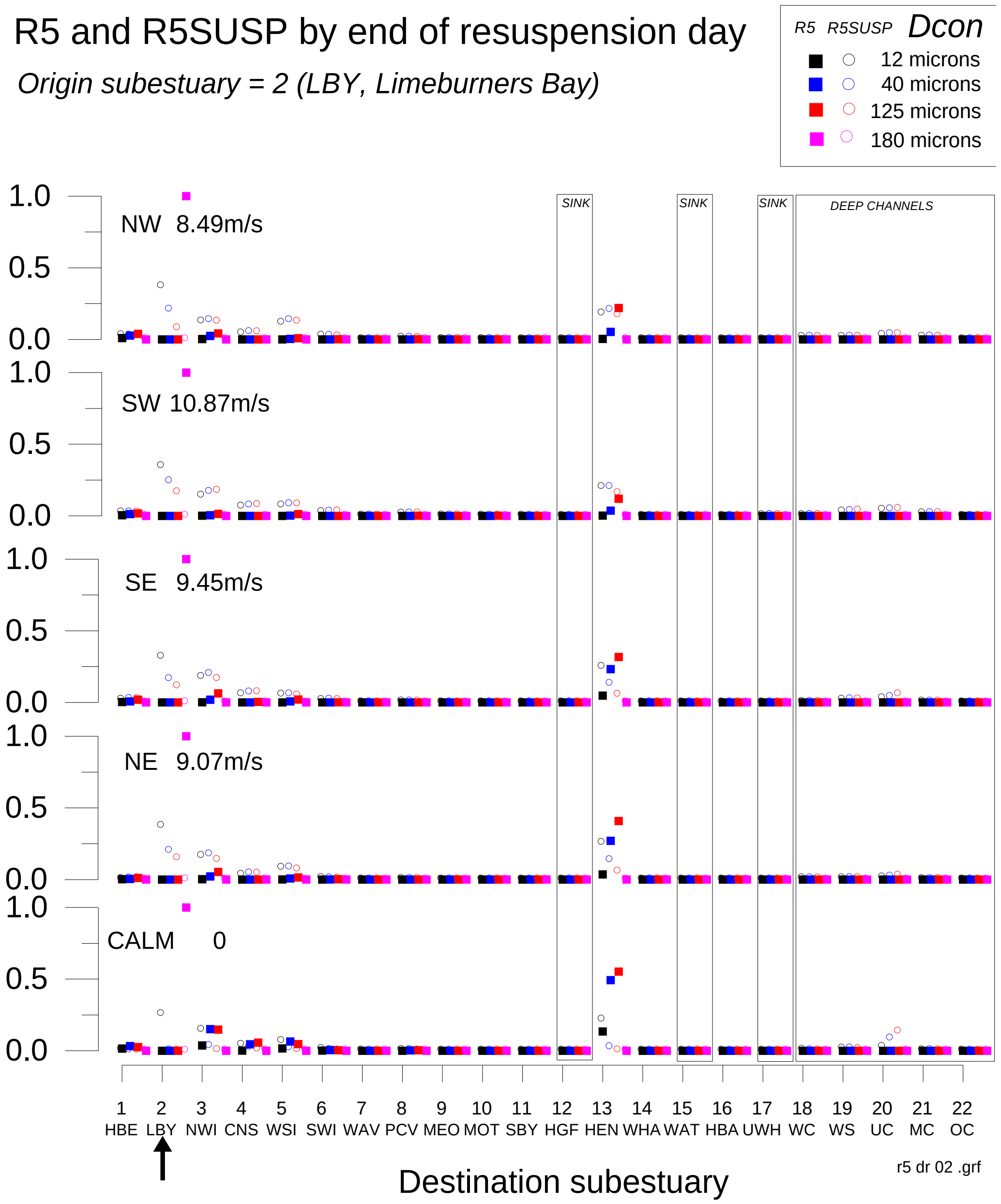
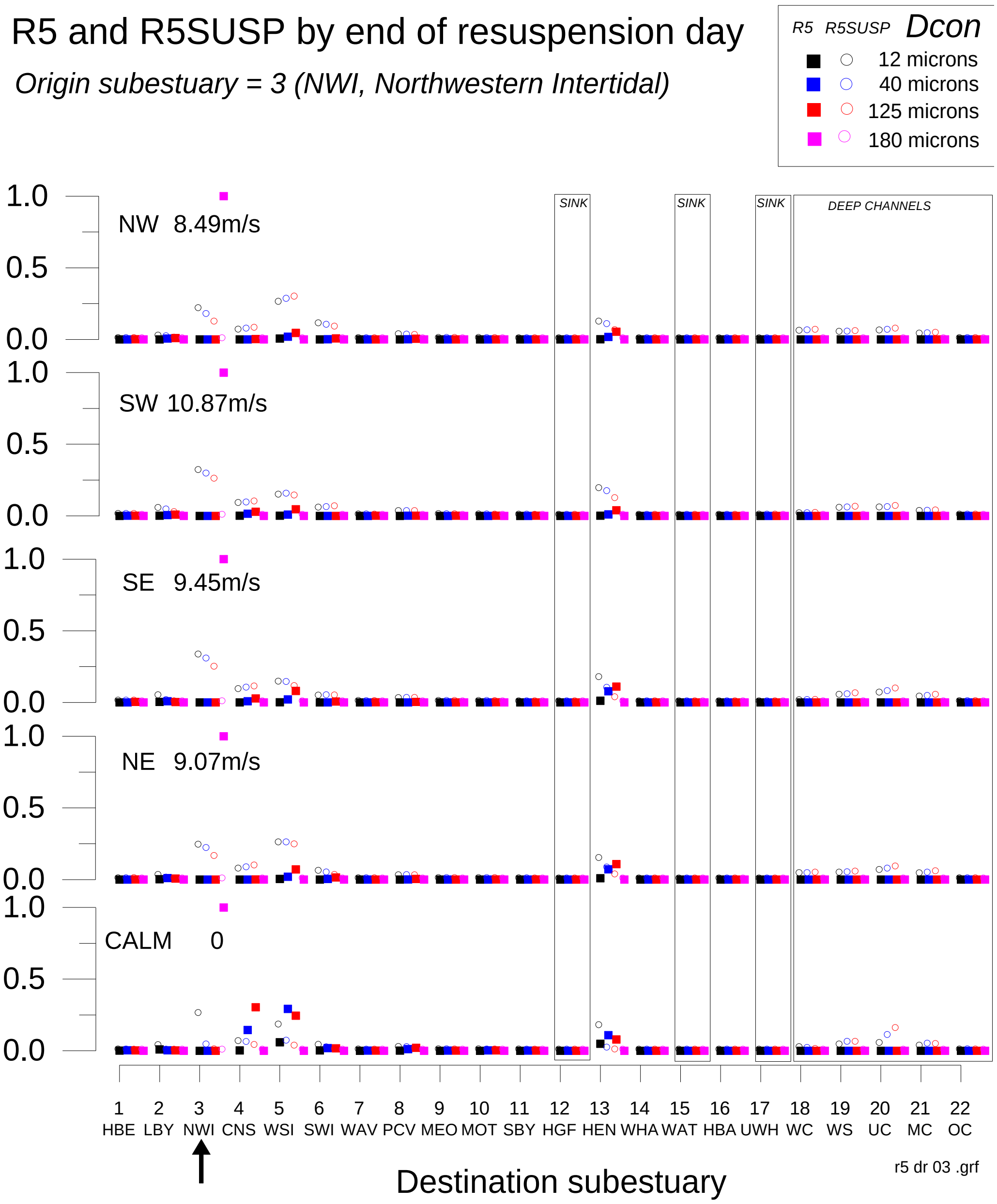

R5 and R5SUSP by end of resuspension day
Origin subestuary = 2 (LBY, Limeburners Bay)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
1.0
0.5
0.0
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
SINK
SINK
SINK
DEEP CHANNELS
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r5 dr 02 .grf

Figure 64



R5 and R5SUSP by end of resuspension day
Origin subestuary = 3 (NWI, Northwestern Intertidal)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
1.0
0.5
0.0
SINK
SINK
SINK
DEEP CHANNELS
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r5 dr 03 .grf

Figure 65

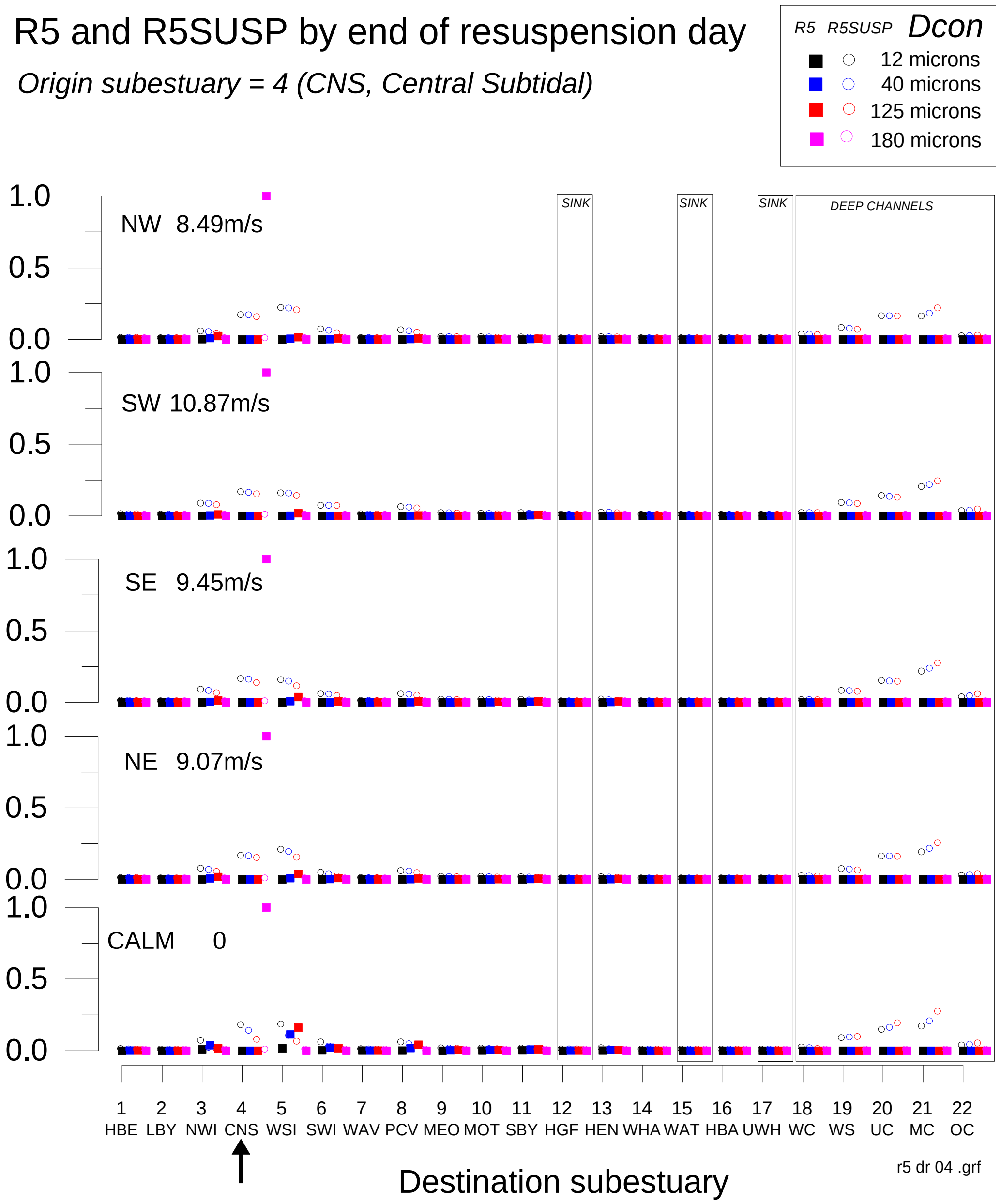

R5 and R5SUSP by end of resuspension day
Origin subestuary = 4 (CNS, Central Subtidal)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
1.0
0.5
0.0
SINK
SINK
SINK
DEEP CHANNELS
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r5 dr 04 .grf

Figure 66

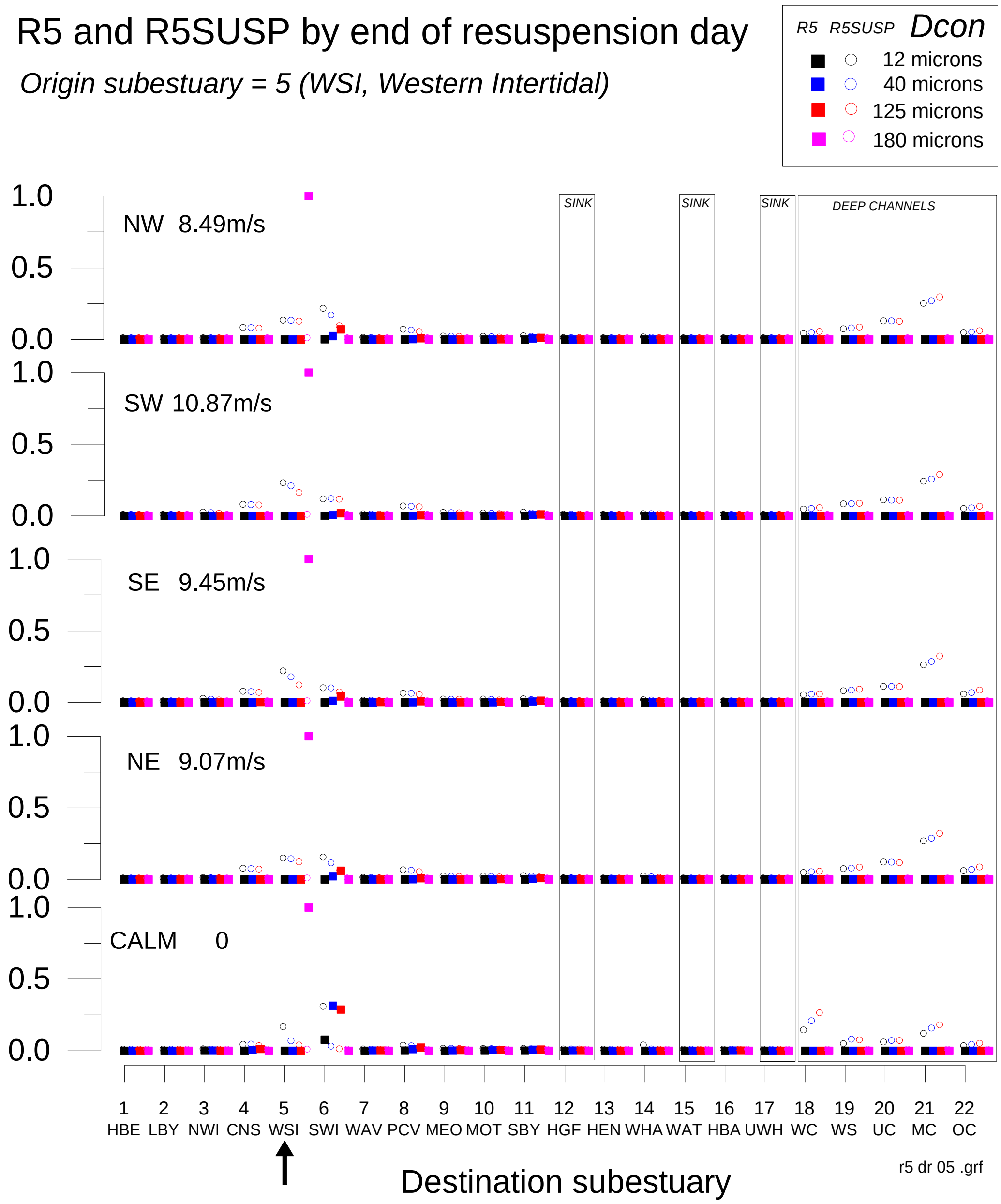
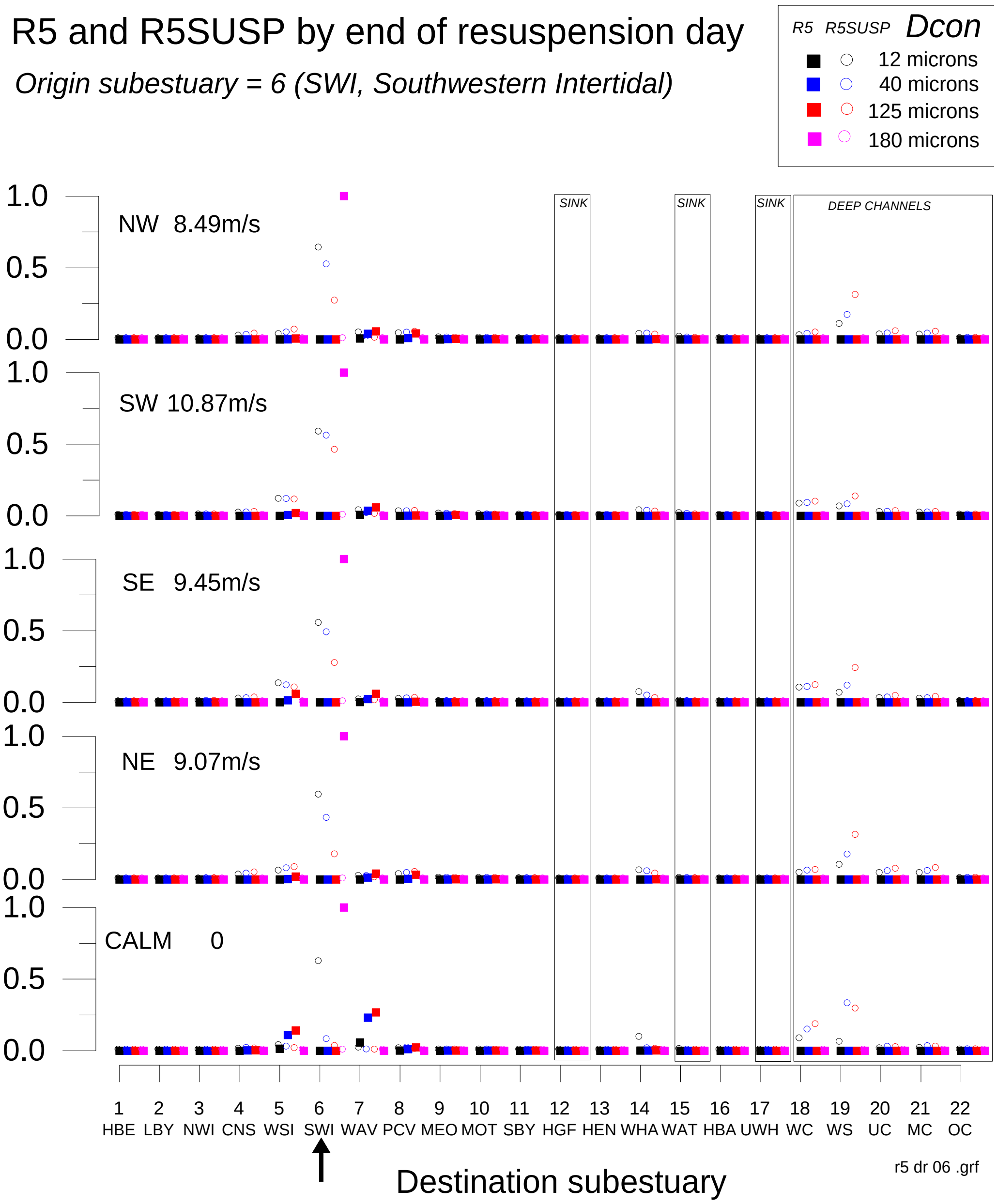
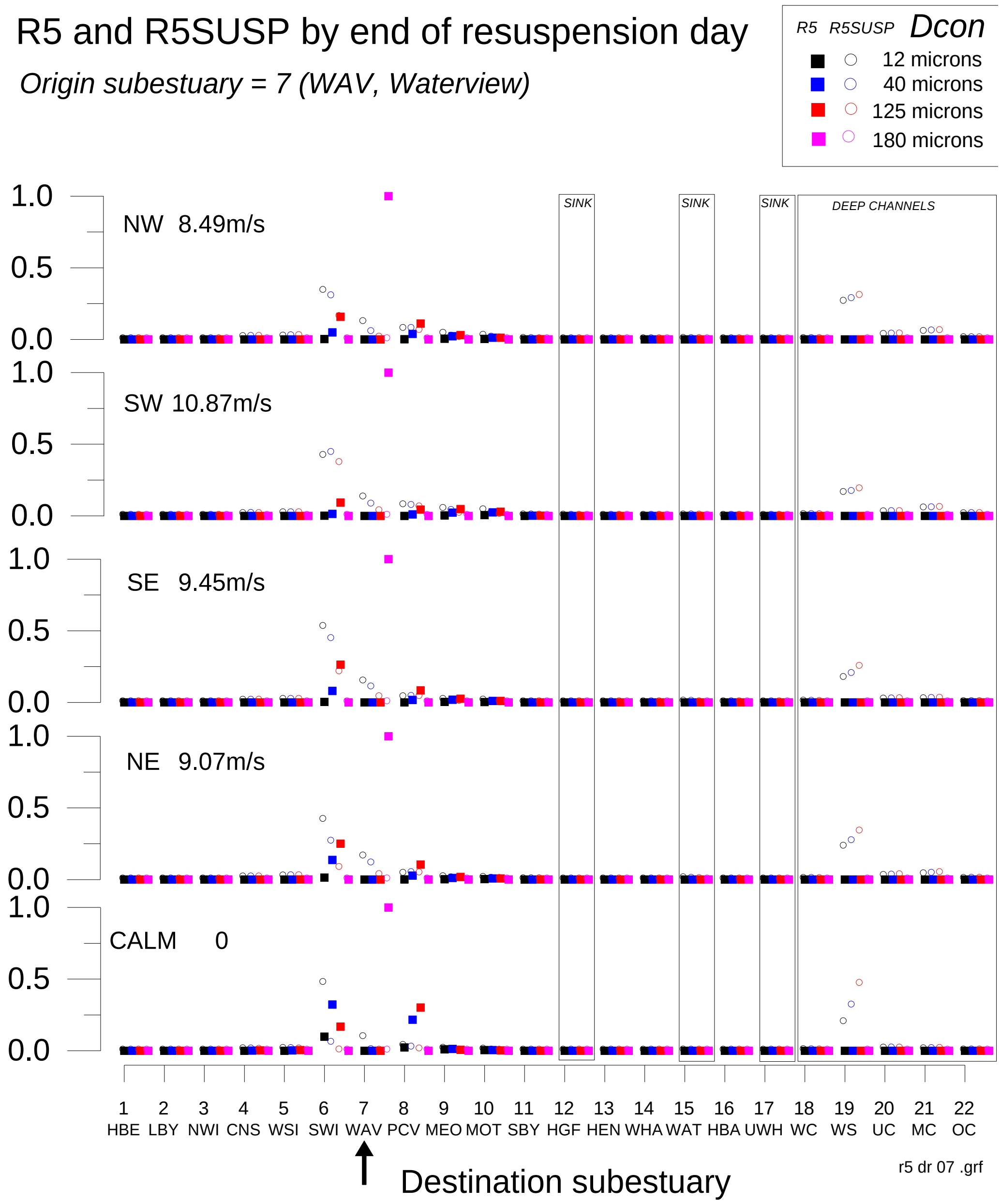

R5 and R5SUSP by end of resuspension day
Origin subestuary = 5 (WSI, Western Intertidal)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
1.0
0.5
0.0
SINK
SINK
SINK
DEEP CHANNELS
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22
HBE LBY NWI CNS WSI SWI WAV PCV MEO MOT SBY HGF HEN WHA WAT HBA UWH WC WS UC MC OC
Destination subestuary
r5 dr 05 .grf

**Figure 67**



R5 and R5SUSP by end of resuspension day
Origin subestuary = 6 (SWI, Southwestern Intertidal)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
1.0
0.5
0.0
SINK
SINK
SINK
DEEP CHANNELS
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r5 dr 06 .grf

Figure 68



R5 and R5SUSP by end of resuspension day
Origin subestuary = 7 (WAV, Waterview)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
1.0
0.5
0.0
SINK
SINK
SINK
DEEP CHANNELS
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22
HBE LBY NWI CNS WSI SWI WAV PCV MEO MOT SBY HGF HEN WHA WAT HBA UWH WC WS UC MC OC
Destination subestuary
r5 dr 07 .grf

Figure 69

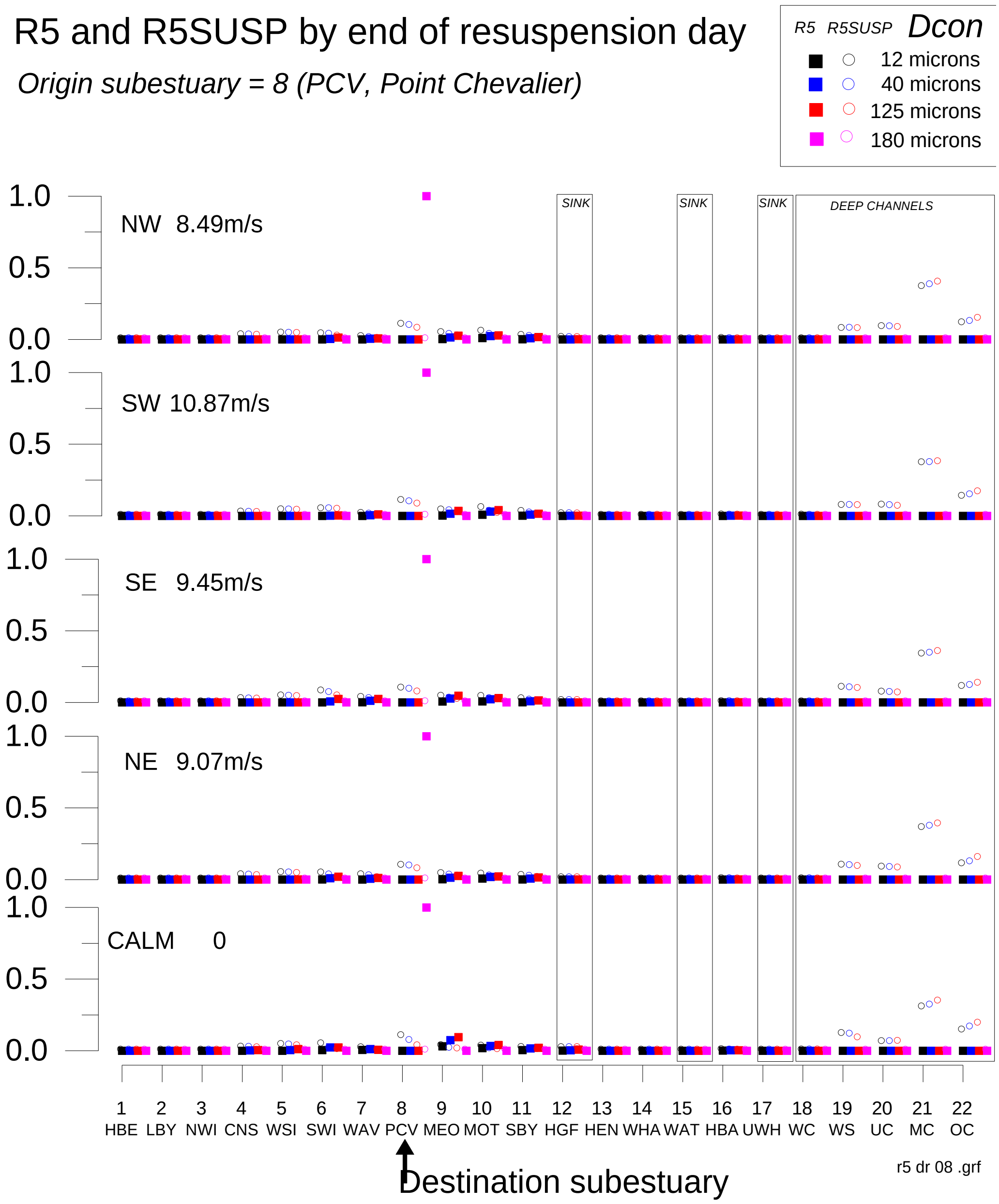

R5 and R5SUSP by end of resuspension day
Origin subestuary = 8 (PCV, Point Chevalier)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
1.0
0.5
0.0
SINK
SINK
SINK
DEEP CHANNELS
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r5 dr 08 .grf

Figure 70

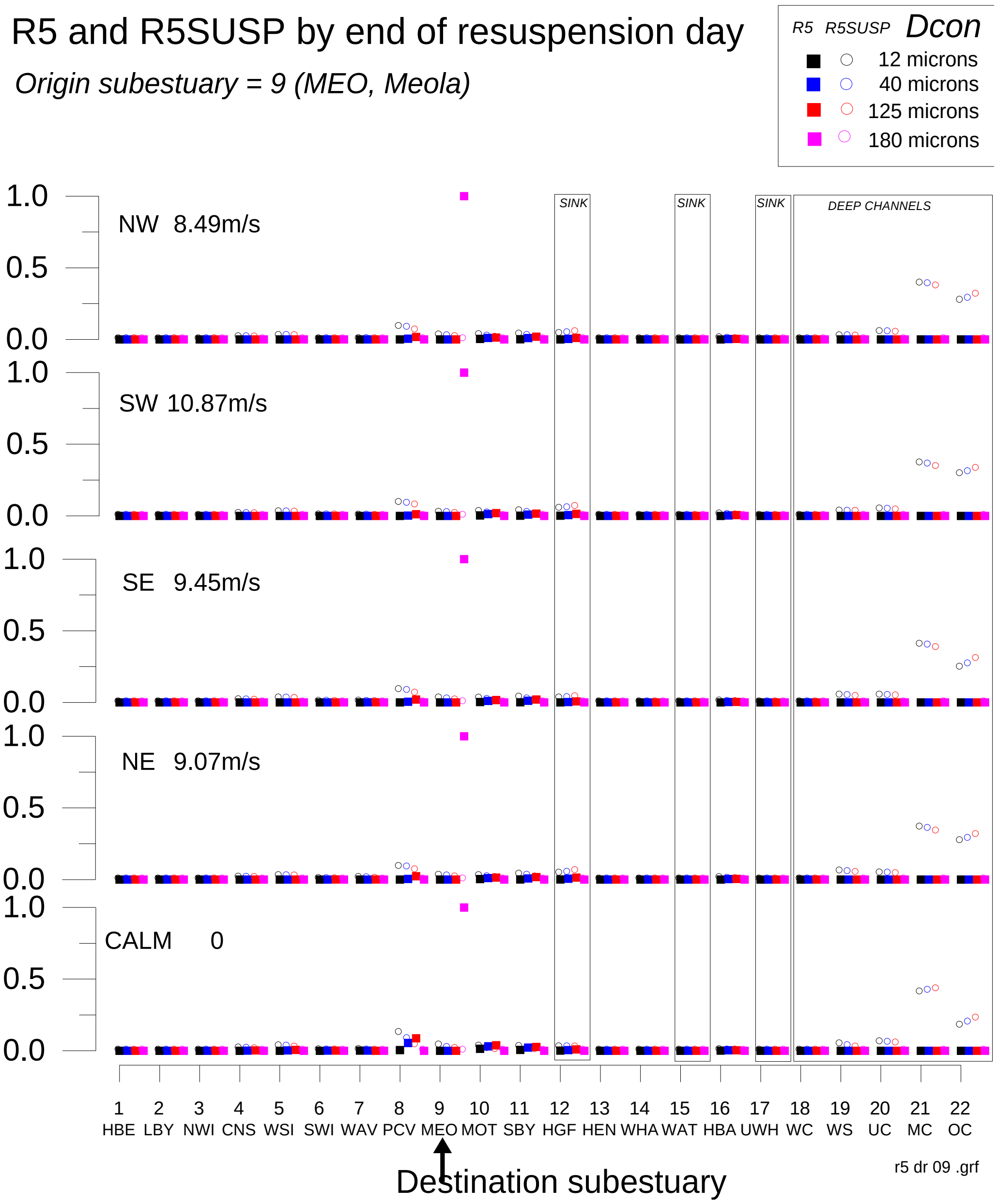

R5 and R5SUSP by end of resuspension day
Origin subestuary = 9 (MEO, Meola)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
1.0
0.5
0.0
SINK
SINK
SINK
DEEP CHANNELS
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r5 dr 09 .grf

Figure 71

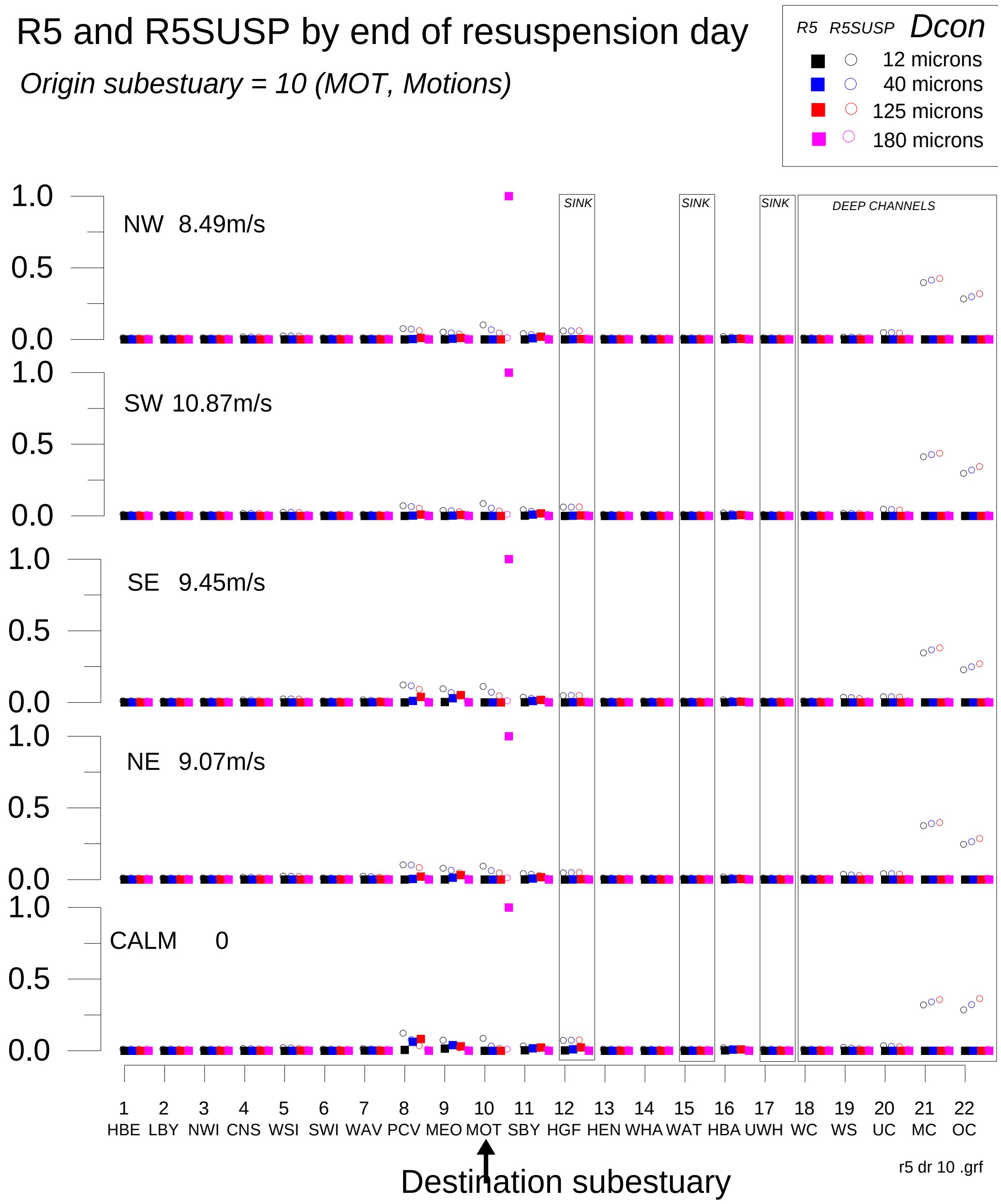
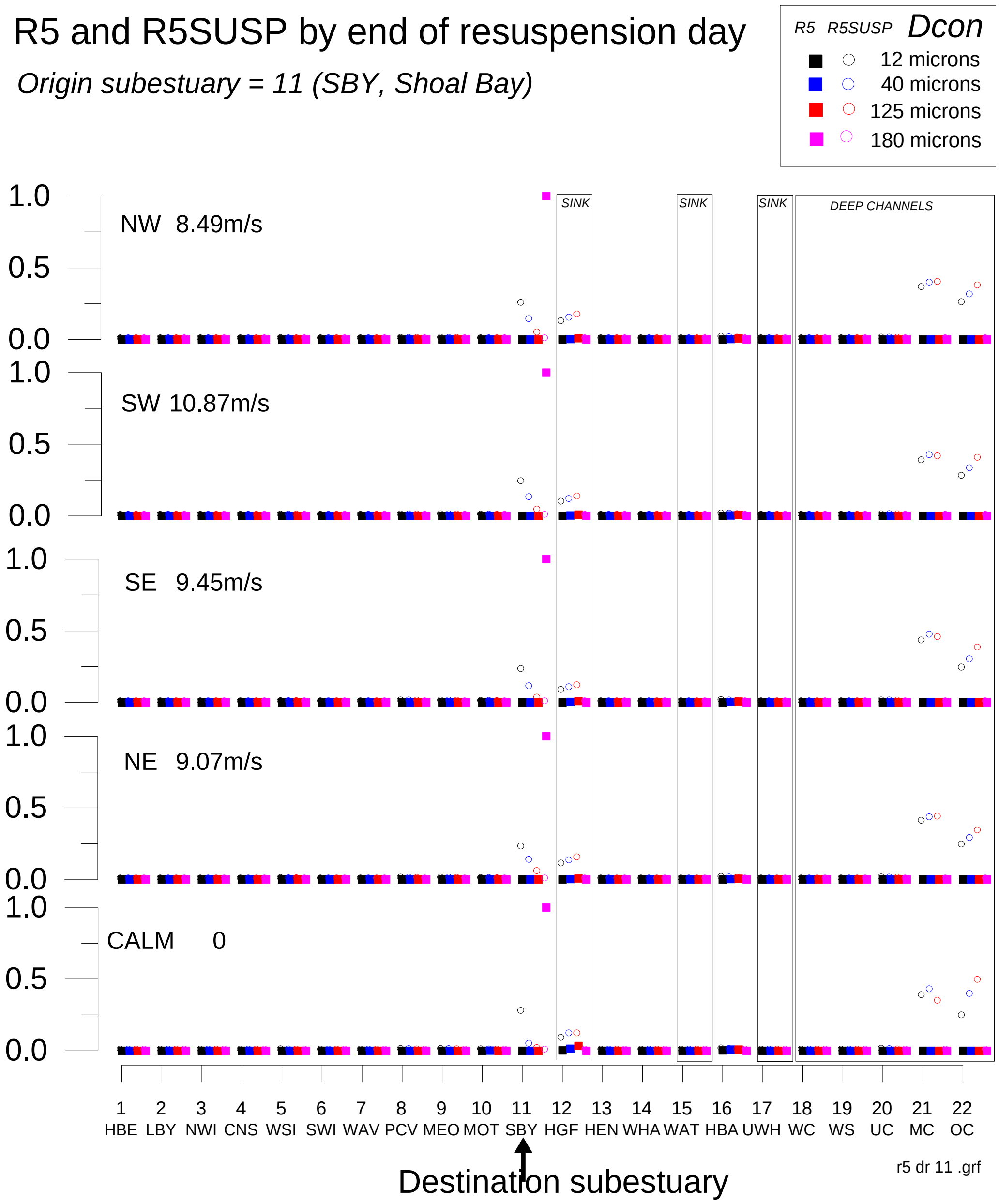

R5 and R5SUSP by end of resuspension day
Origin subestuary = 10 (MOT, Motions)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
1.0
0.5
0.0
SINK
SINK
SINK
DEEP CHANNELS
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r5 dr 10 .grf

Figure 72


R5 and R5SUSP by end of resuspension day
Origin subestuary = 11 (SBY, Shoal Bay)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
SINK
SINK
SINK
DEEP CHANNELS
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
1.0
0.5
0.0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22
HBE LBY NWI CNS WSI SWI WAV PCV MEO MOT SBY HGF HEN WHA WAT HBA UWH WC WS UC MC OC
Destination subestuary
r5 dr 11 .grf

# 14 Appendix 5: RTC

**Figure 73**

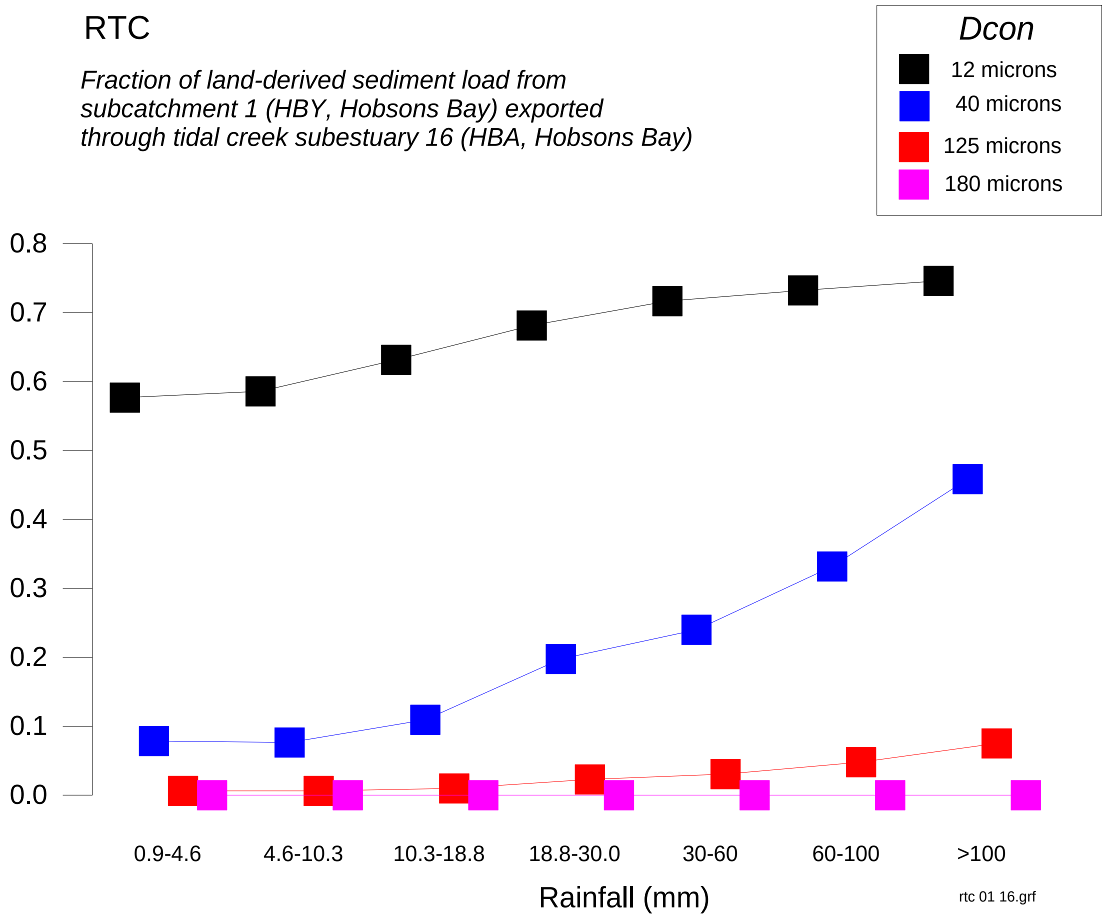


**Figure 74**

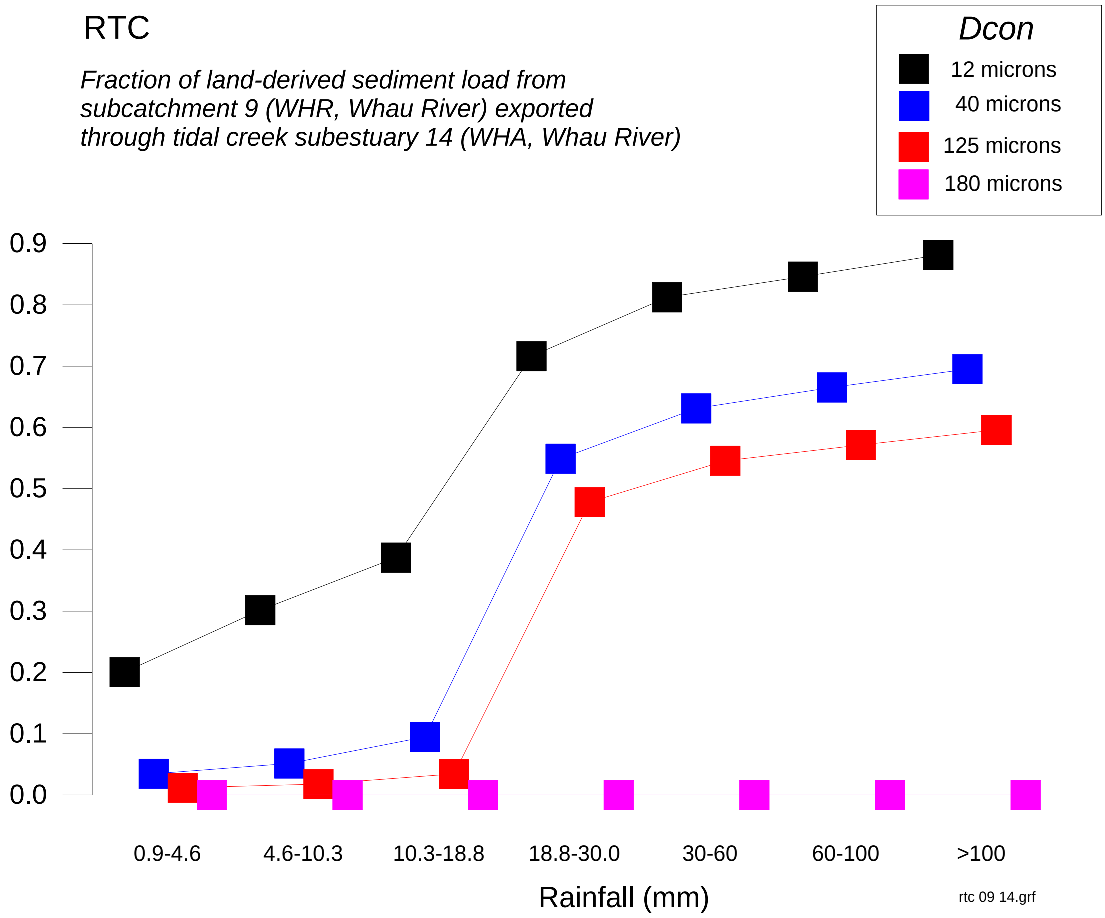
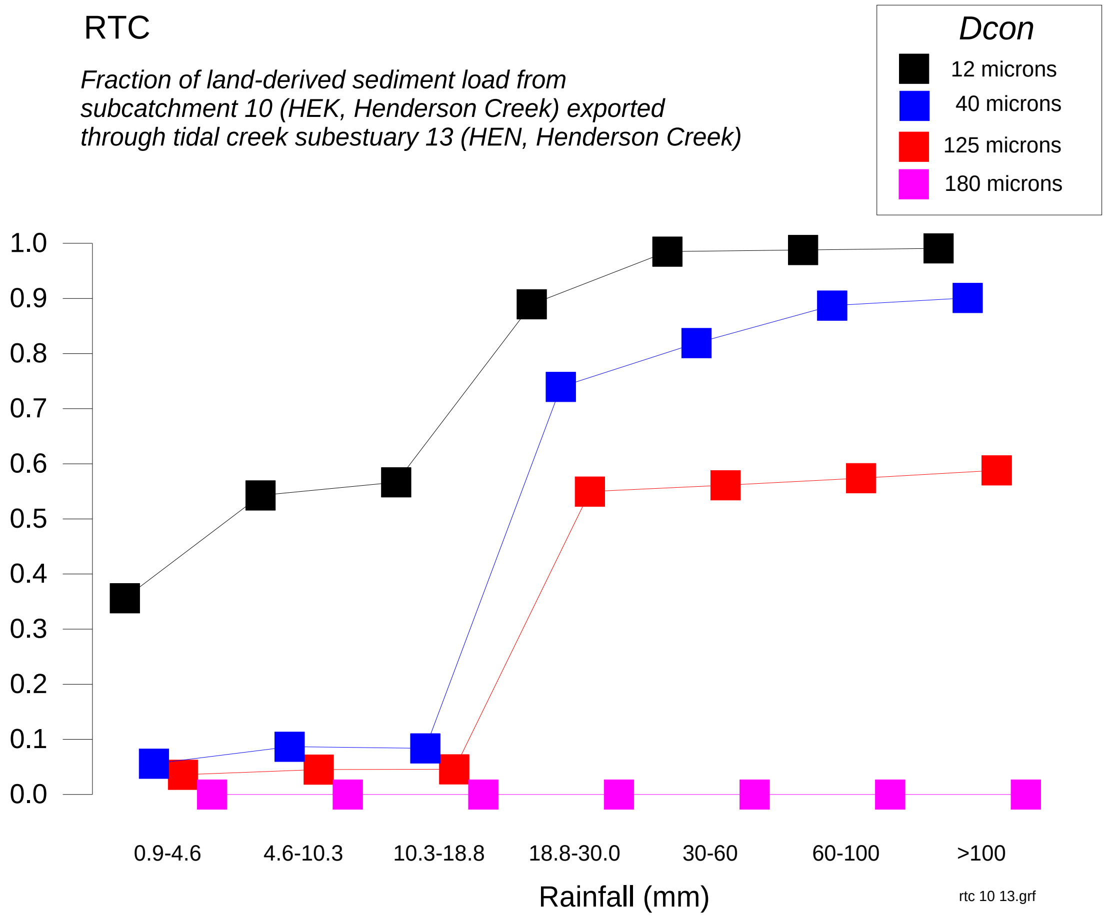

RTC
Fraction of land-derived sediment load from subcatchment 9 (WHR, Whau River) exported through tidal creek subestuary 14 (WHA, Whau River)
Dcon
12 microns
40 microns
125 microns
180 microns
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0.9-4.6
4.6-10.3
10.3-18.8
18.8-30.0
30-60
60-100
>100
Rainfall (mm)
rtc 09 14.grf

**Figure 75**



RTC
Fraction of land-derived sediment load from subcatchment 10 (HEK, Henderson Creek) exported through tidal creek subestuary 13 (HEN, Henderson Creek)
Dcon
12 microns
40 microns
125 microns
180 microns
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0.9-4.6
4.6-10.3
10.3-18.8
18.8-30.0
30-60
60-100
>100
Rainfall (mm)
rtc 10 13.grf

# 15 Appendix 6: R (End of Injection Day)

**Figure 76**

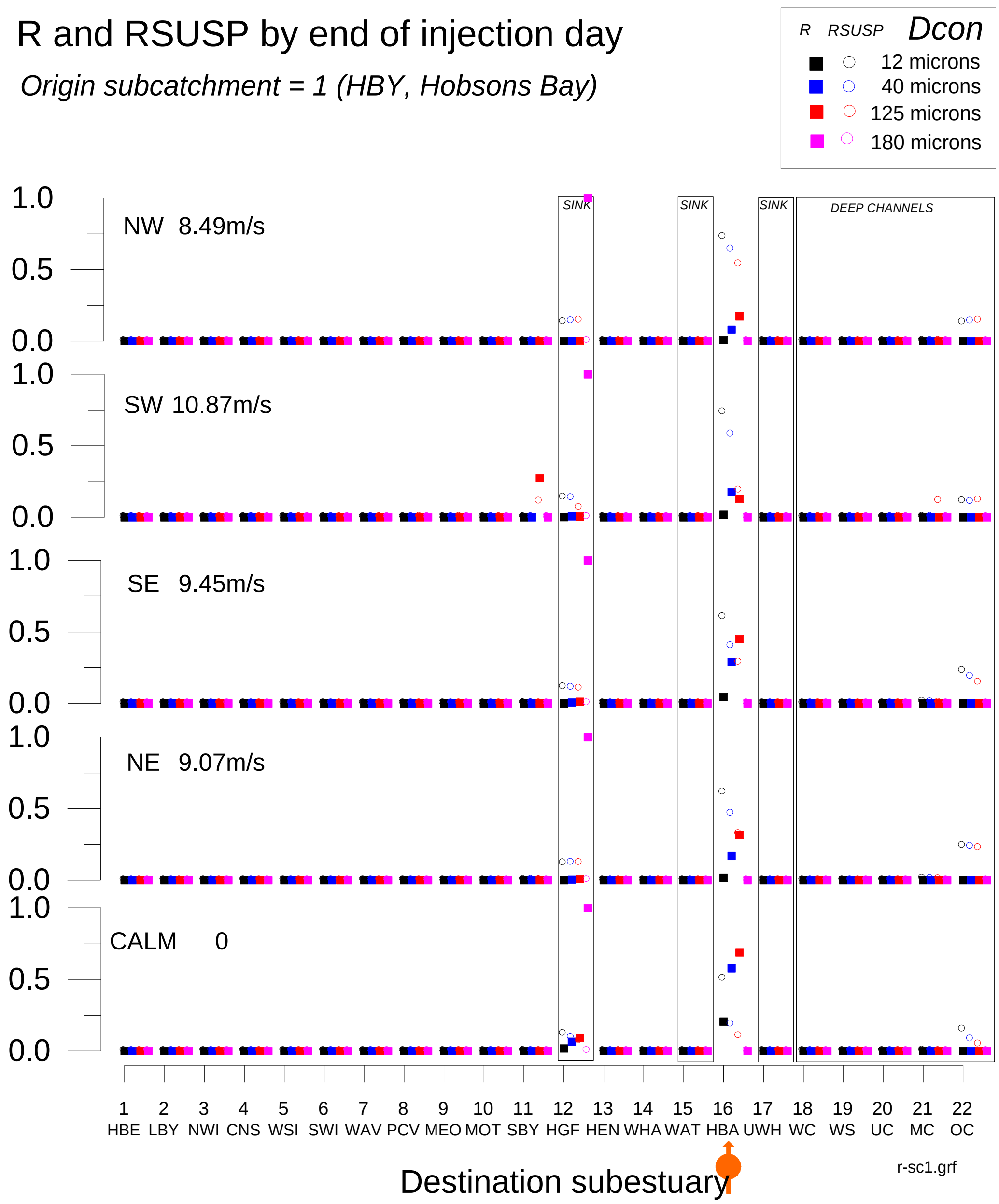


Figure 77

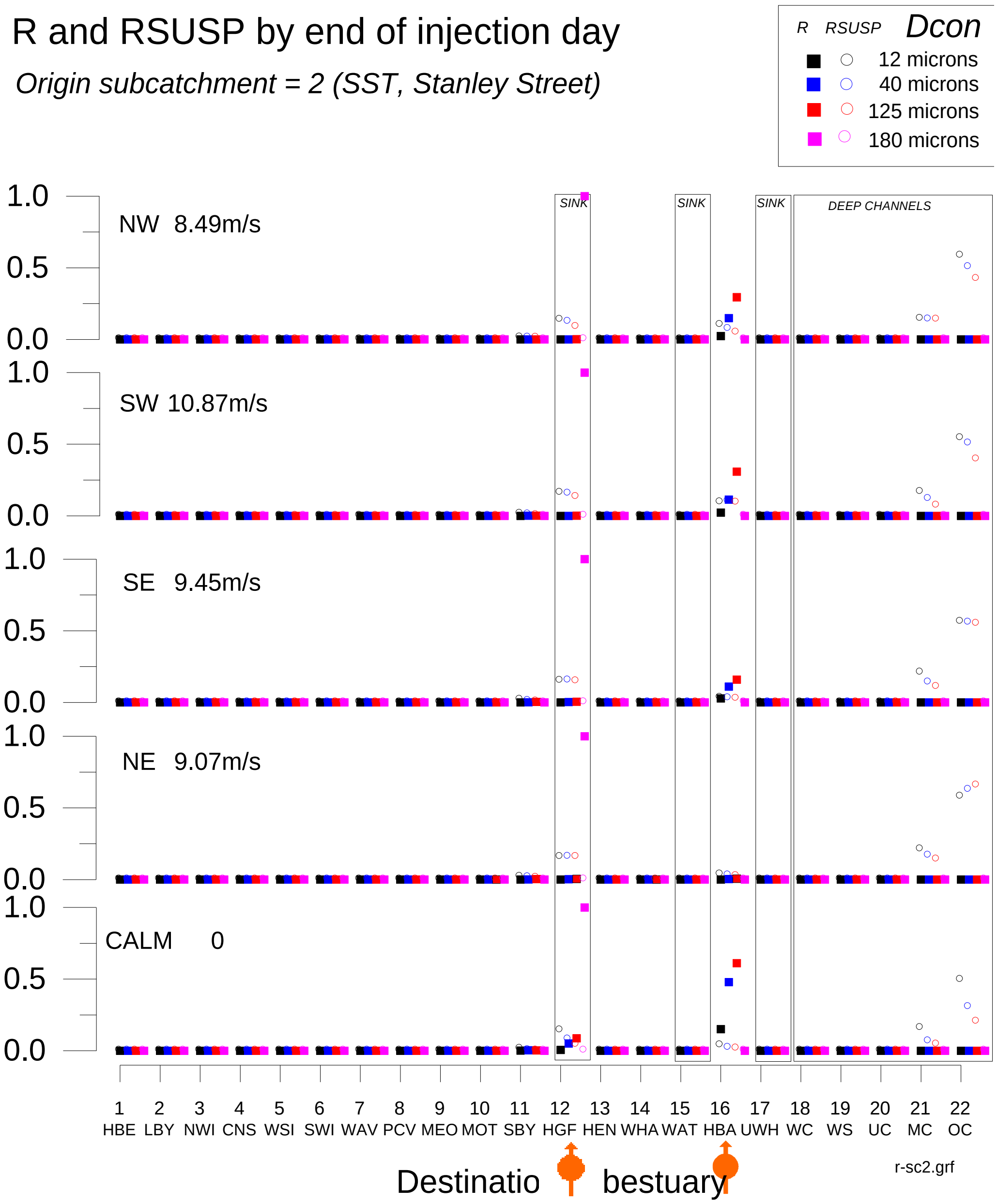

R and RSUSP by end of injection day
Origin subcatchment = 2 (SST, Stanley Street)
R RSUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
1.0
0.5
0.0
SINK
SINK
SINK
DEEP CHANNELS
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22
HBE LBY NWI CNS WSI SWI WAV PCV MEO MOT SBY HGF HEN WHA WAT HBA UWH WC WS UC MC OC
Destinatio bestuary
r-sc2.grf

Figure 78

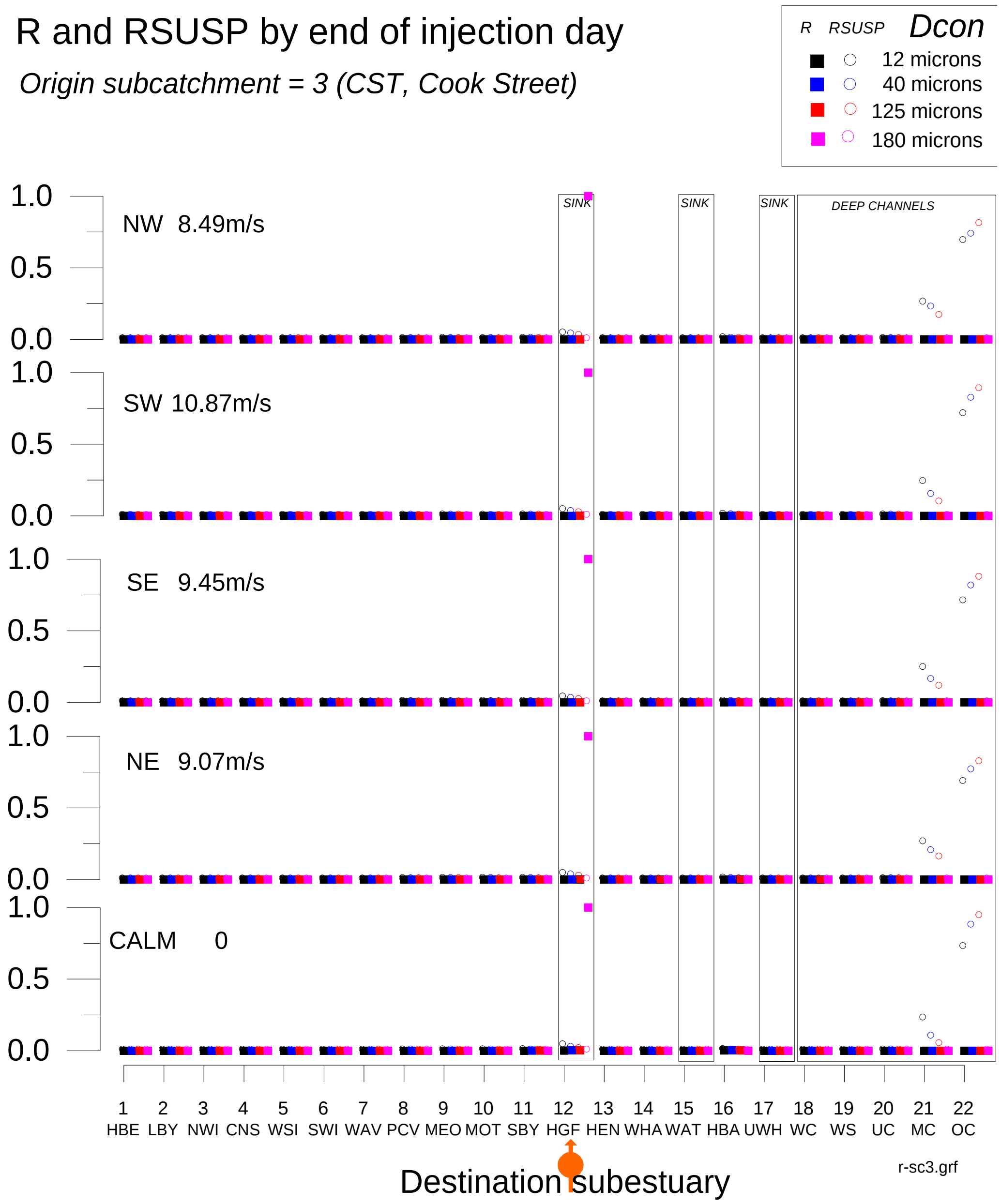

R and RSUSP by end of injection day
Origin subcatchment = 3 (CST, Cook Street)
R RSUSP Dcon
12 microns
40 microns
125 microns
180 microns
1.0
0.5
0.0
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
SINK
SINK
SINK
DEEP CHANNELS
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r-sc3.grf

**Figure 79**

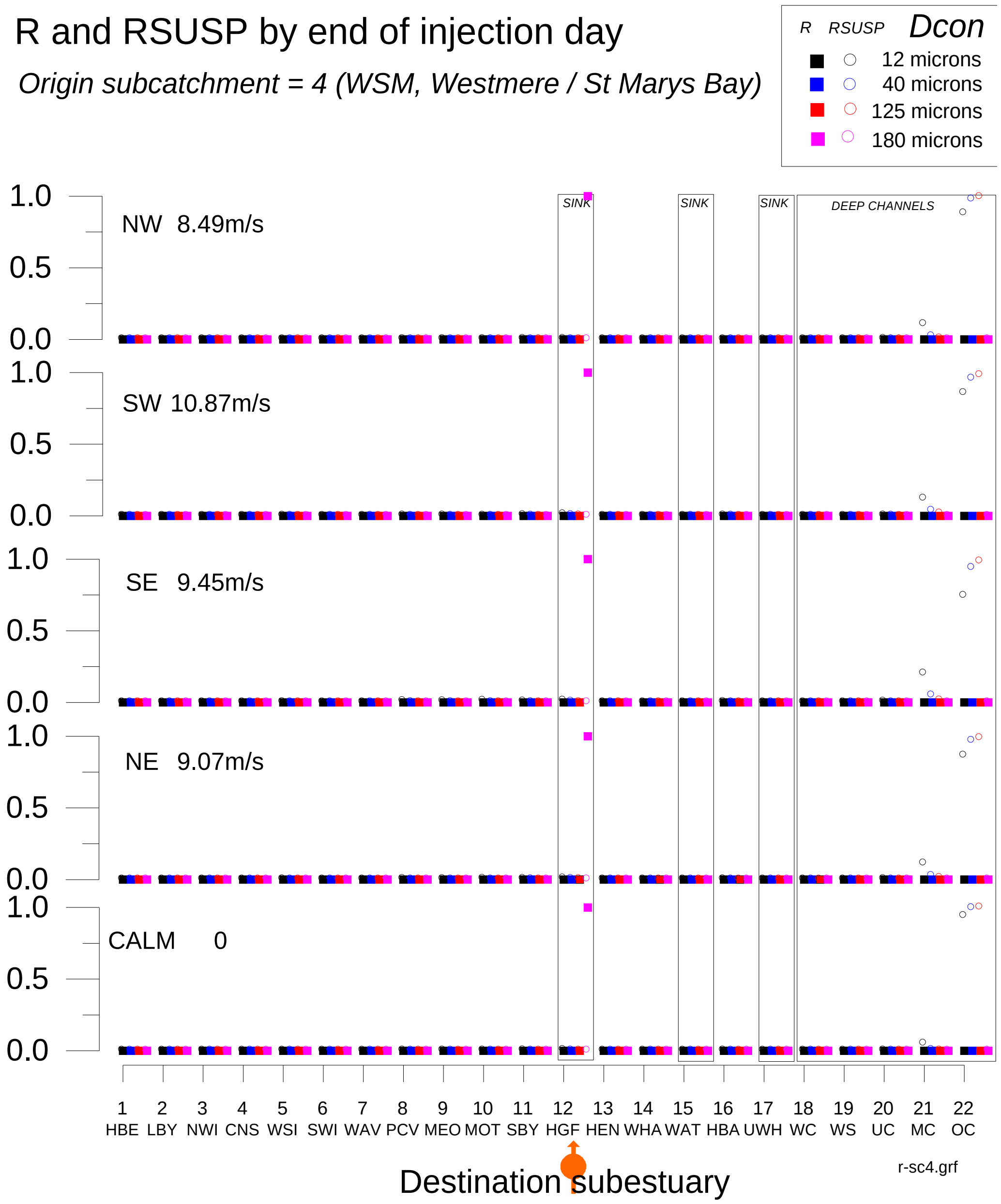

R and RSUSP by end of injection day
Origin subcatchment = 4 (WSM, Westmere / St Marys Bay)
R RSUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
1.0
0.5
0.0
SINK
SINK
SINK
DEEP CHANNELS
1 HBE 2 LBY 3 NWI 4 CNS 5 WSI 6 SWI 7 WAV 8 PCV 9 MEO 10 MOT 11 SBY 12 HGF 13 HEN 14 WHA 15 WAT 16 HBA 17 UWH 18 WC 19 WS 20 UC 21 MC 22 OC
Destination subestuary
r-sc4.grf

Figure 80

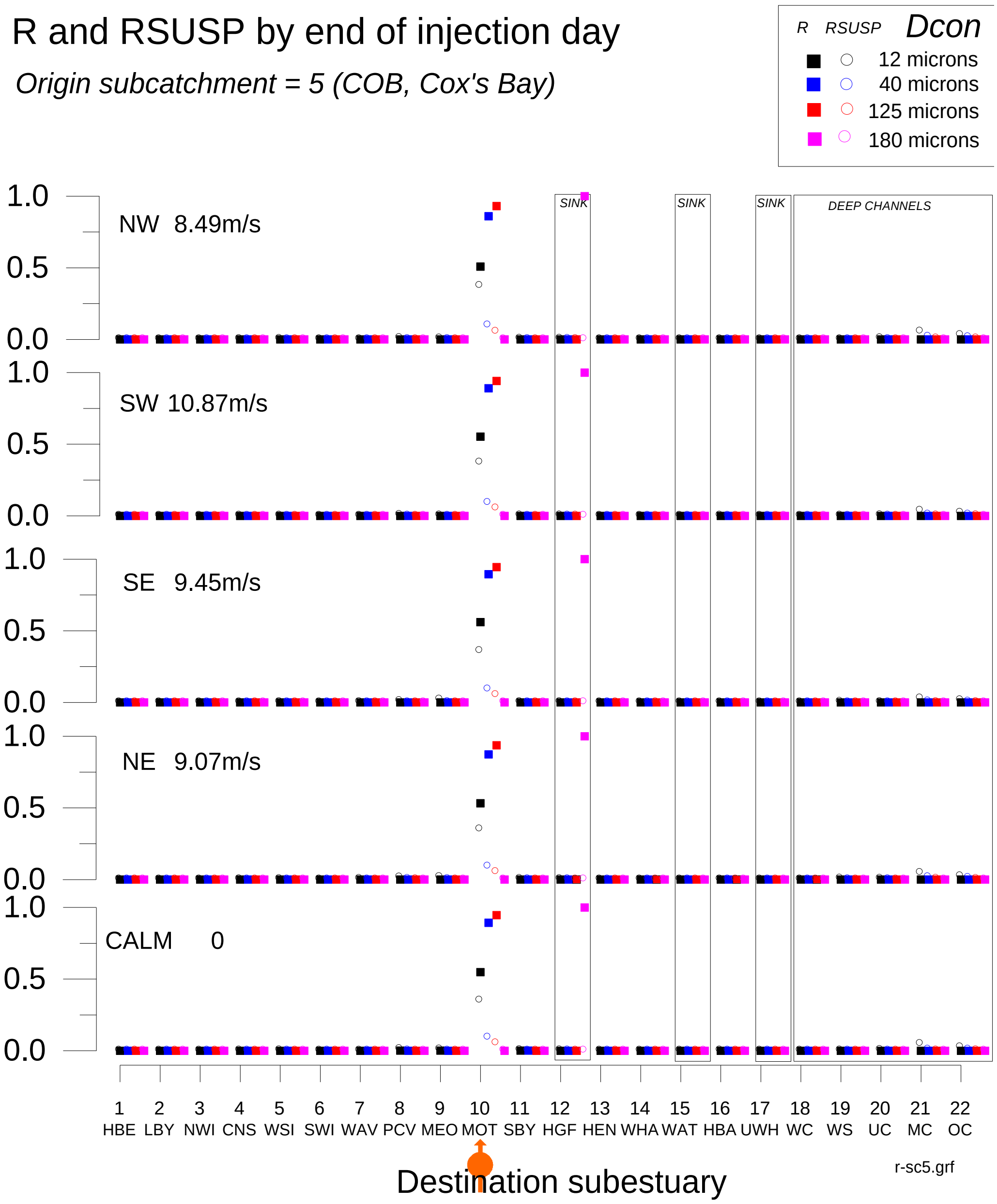

R and RSUSP by end of injection day
Origin subcatchment = 5 (COB, Cox's Bay)
R RSUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
1.0
0.5
0.0
SINK
SINK
SINK
DEEP CHANNELS
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r-sc5.grf

Figure 81

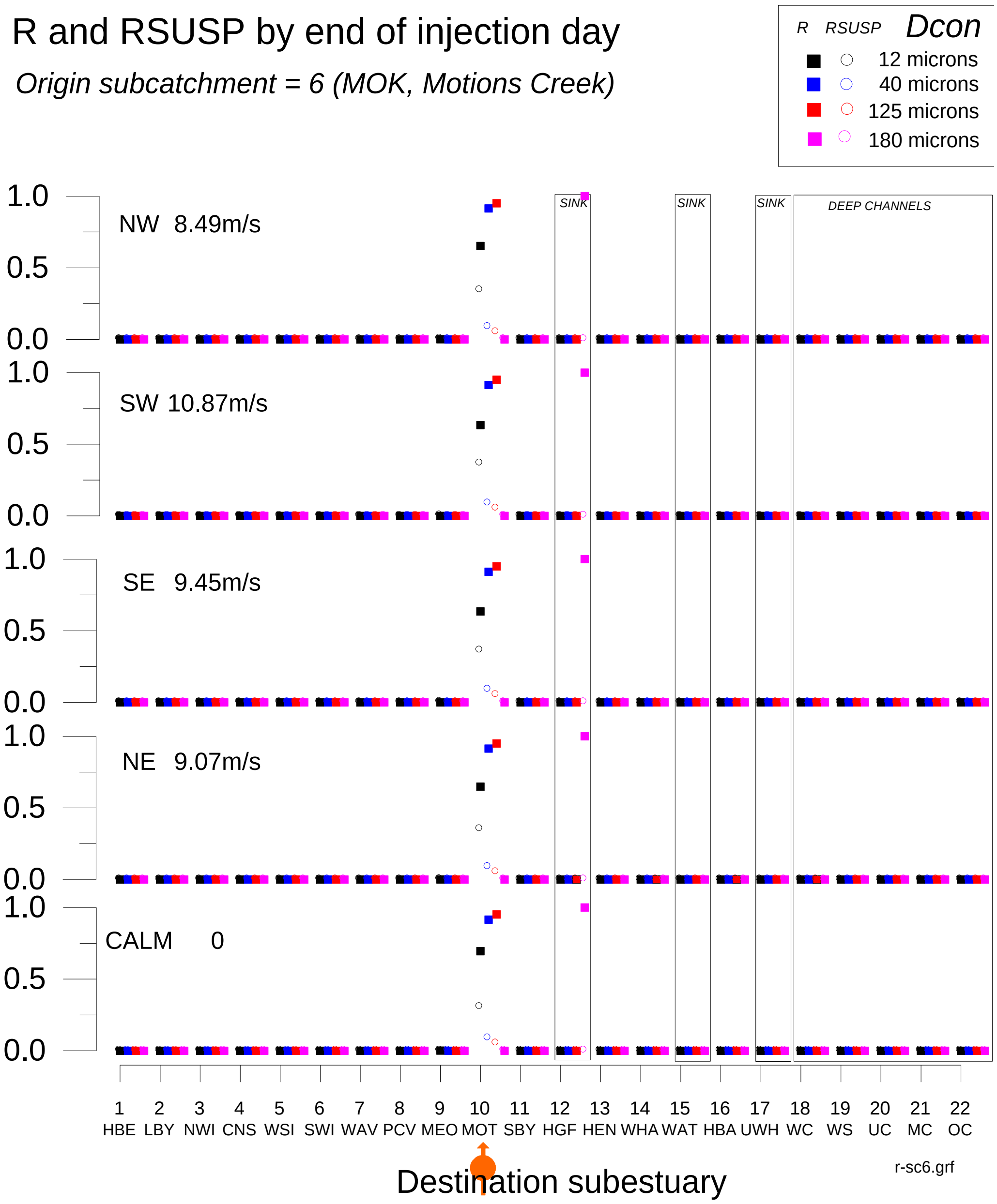

R and RSUSP by end of injection day
Origin subcatchment = 6 (MOK, Motions Creek)
R RSUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
1.0
0.5
0.0
SINK
SINK
SINK
DEEP CHANNELS
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r-sc6.grf

Figure 82

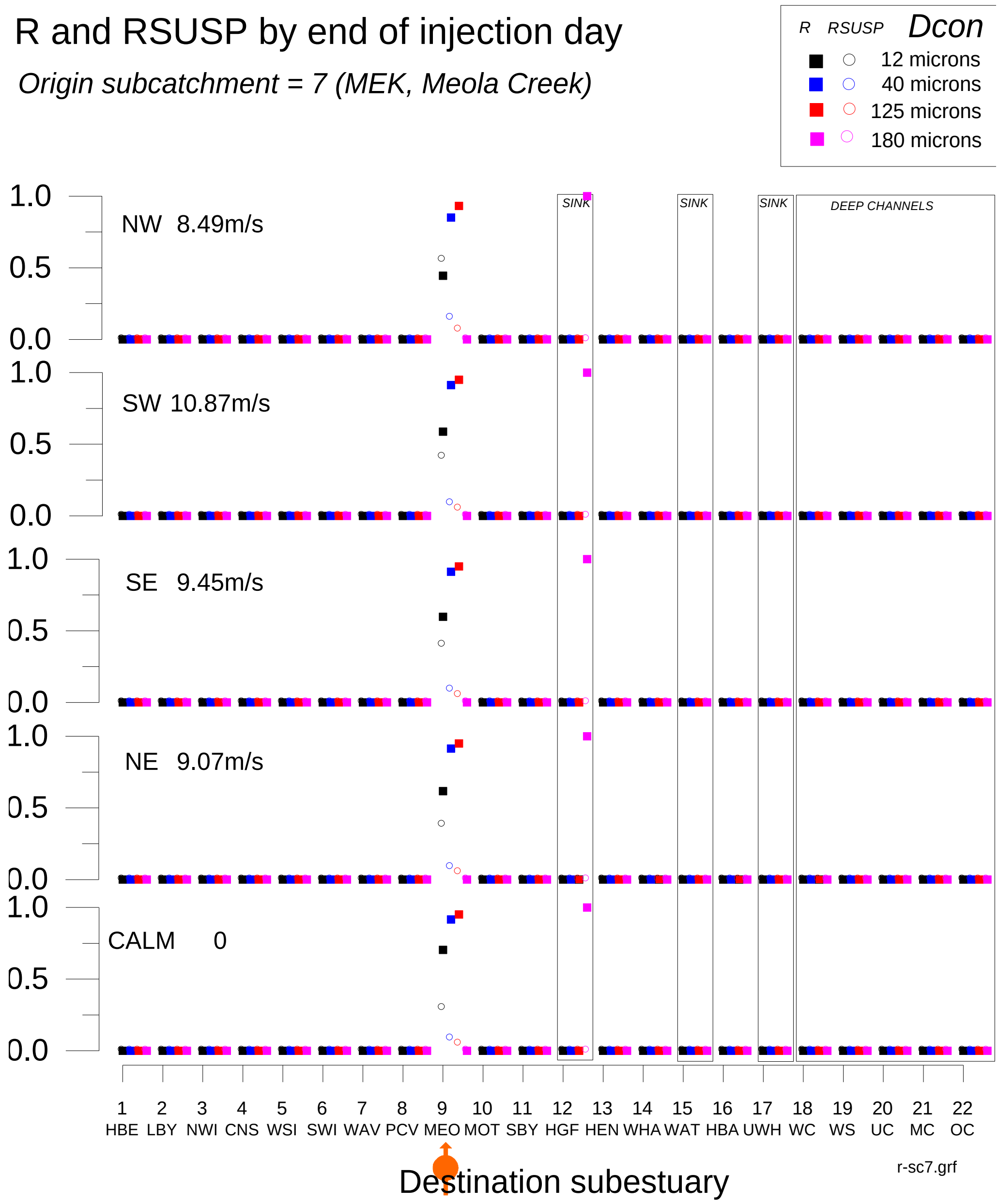

R and RSUSP by end of injection day
Origin subcatchment = 7 (MEK, Meola Creek)
R RSUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
1.0
0.5
0.0
SINK
SINK
SINK
DEEP CHANNELS
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r-sc7.grf

Figure 83

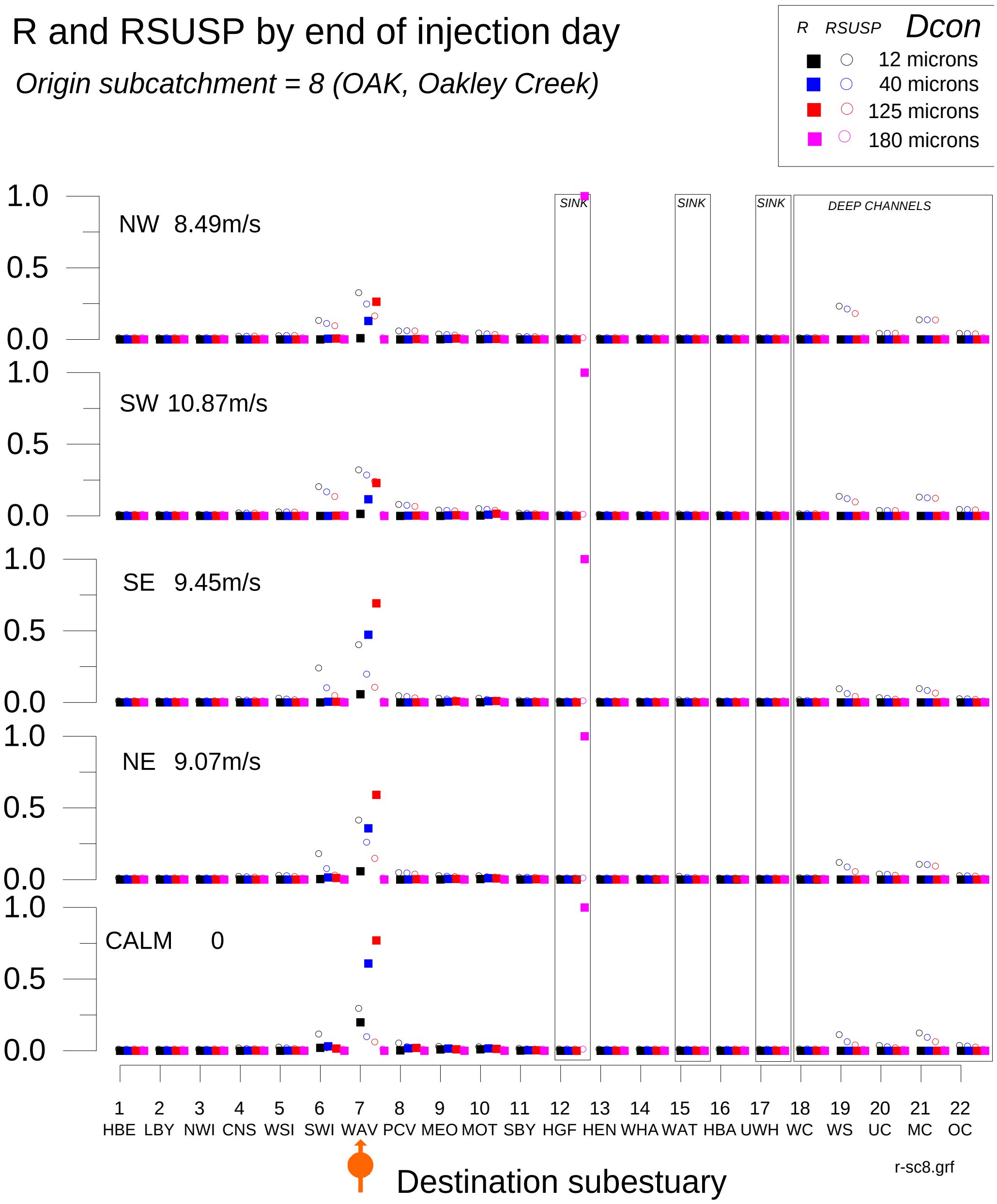

R and RSUSP by end of injection day
Origin subcatchment = 8 (OAK, Oakley Creek)
R RSUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
SINK
SINK
SINK
DEEP CHANNELS
1.0
0.5
0.0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22
HBE LBY NWI CNS WSI SWI WAV PCV MEO MOT SBY HGF HEN WHA WAT HBA UWH WC WS UC MC OC
Destination subestuary
r-sc8.grf

Figure 84

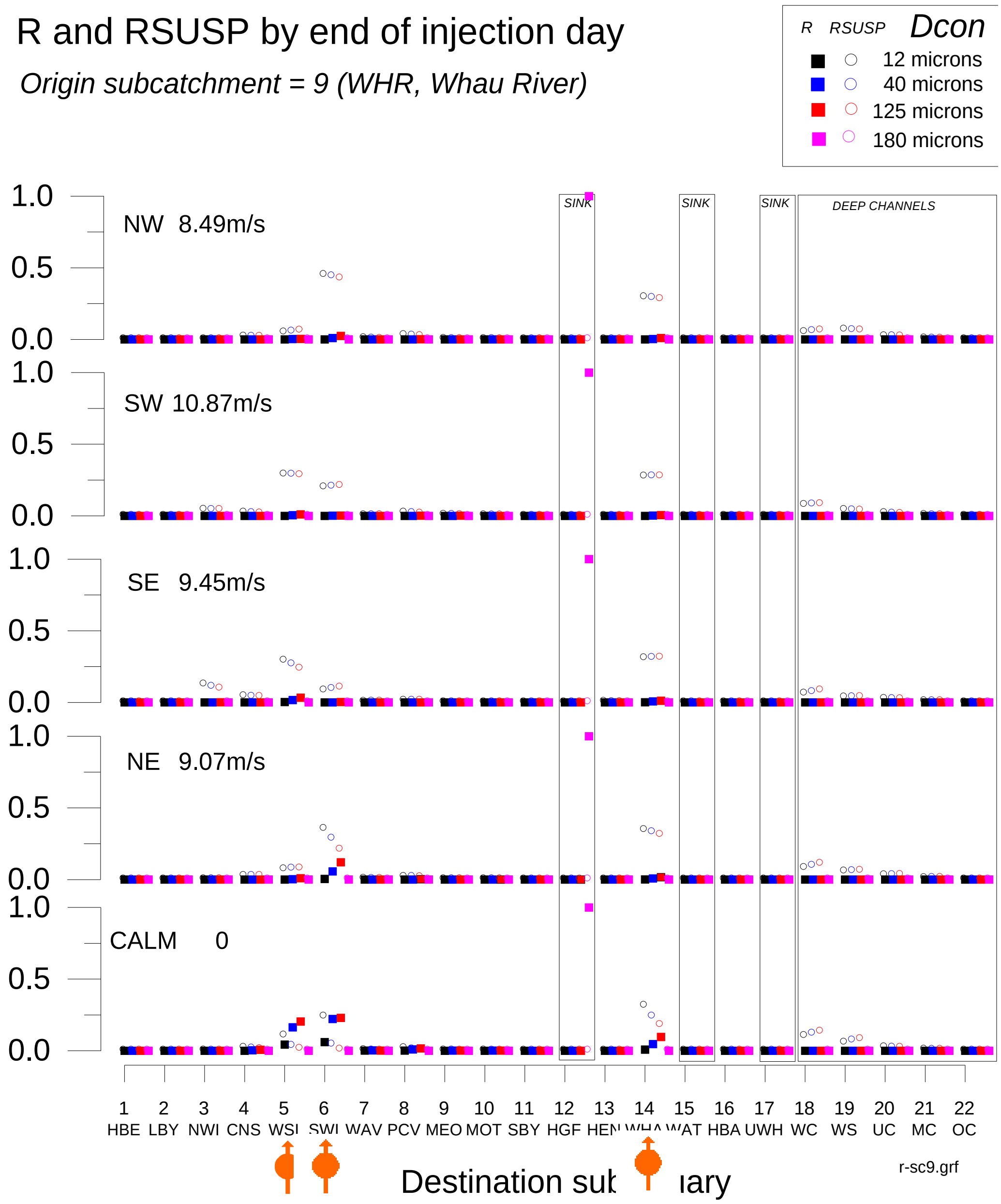

R and RSUSP by end of injection day
Origin subcatchment = 9 (WHR, Whau River)
R RSUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
SINK
SINK
SINK
DEEP CHANNELS
1.0
0.5
0.0
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subcatchment
r-sc9.grf

**Figure 85**

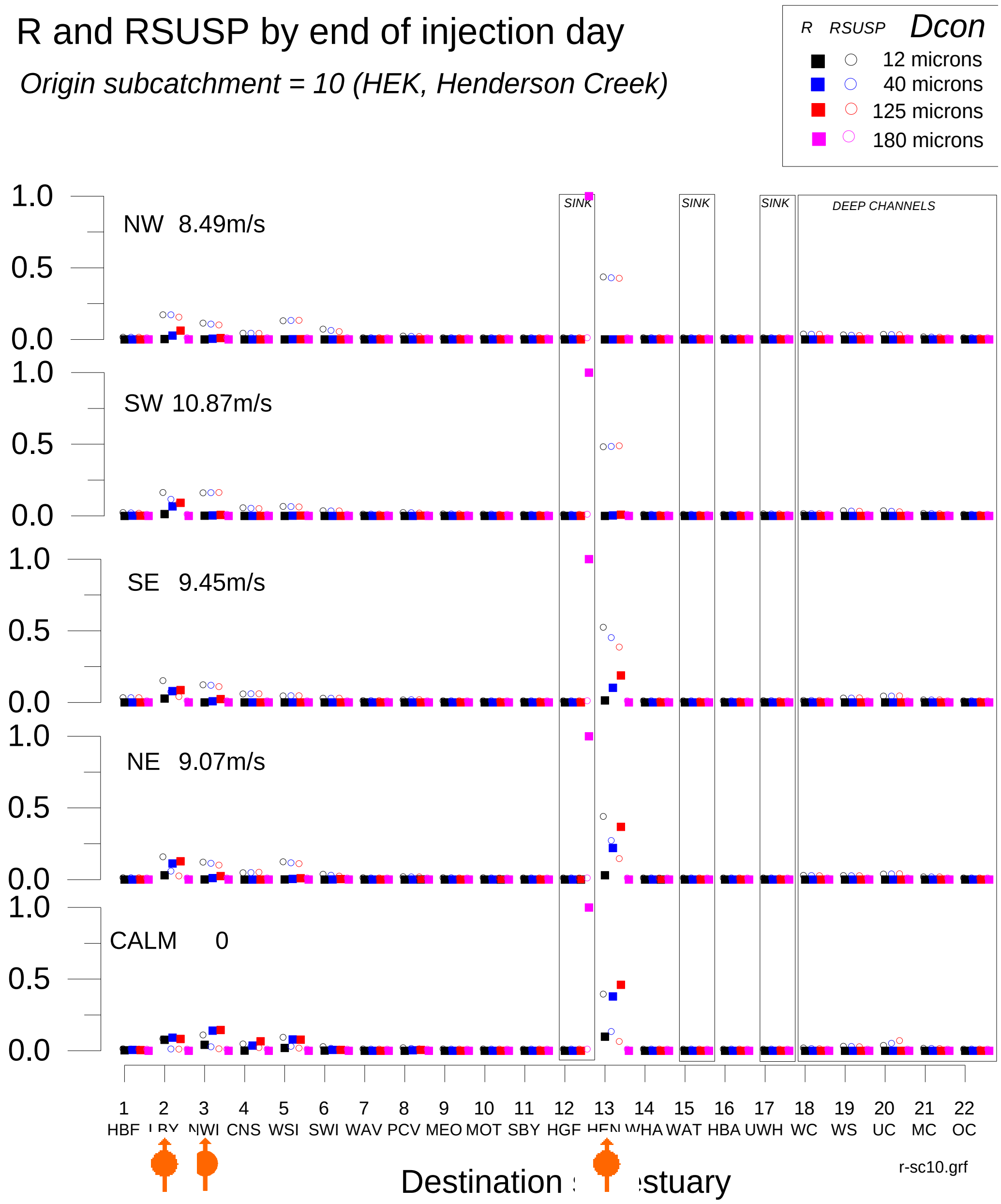

R and RSUSP by end of injection day
Origin subcatchment = 10 (HEK, Henderson Creek)
R RSUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
SINK
SINK
SINK
DEEP CHANNELS
1.0
0.5
0.0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22
HBF NWI CNS WSI SWI WAV PCV MEO MOT SBY HGF WAT HBA UWH WC WS UC MC OC
r-sc10.grf

Figure 86

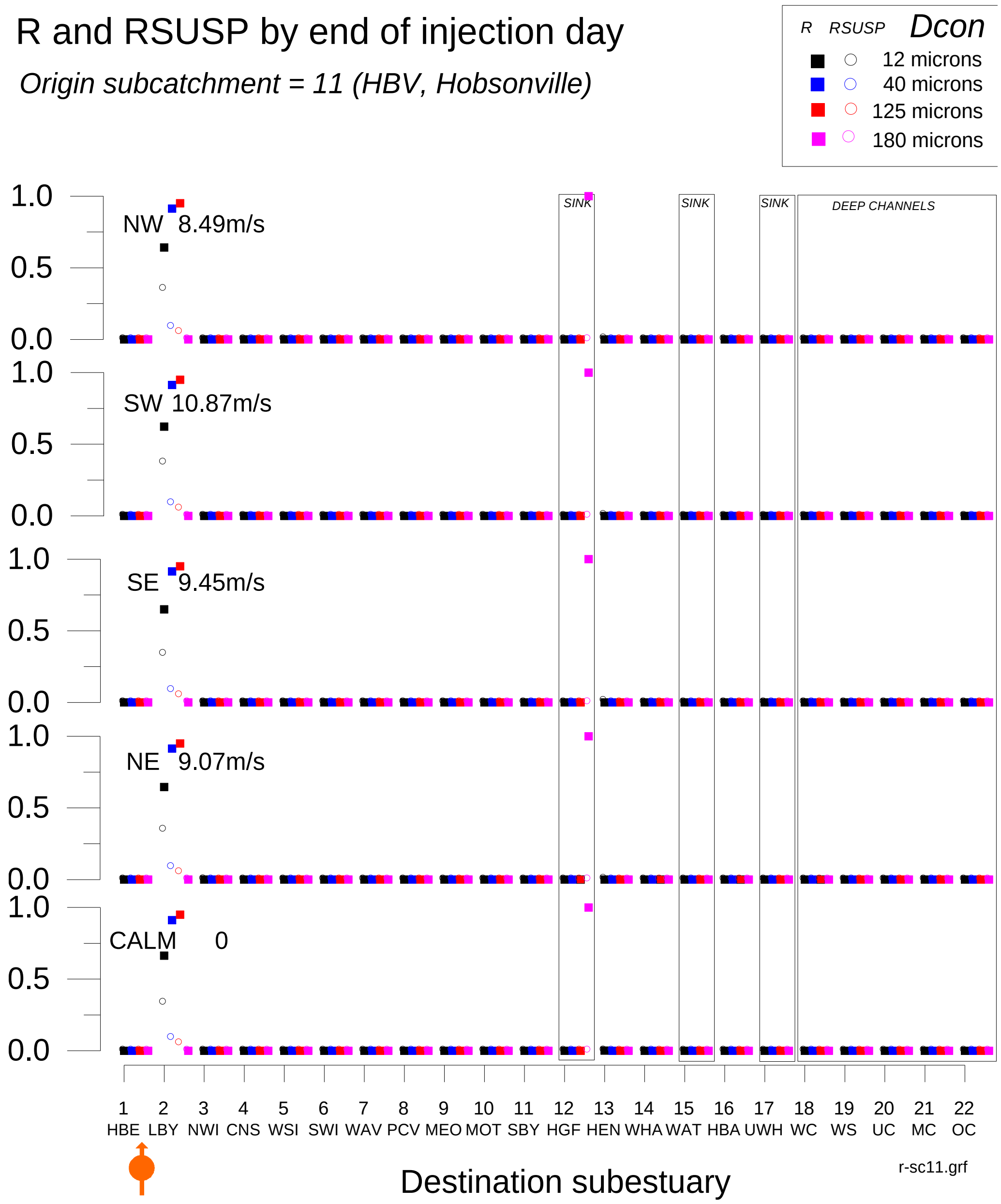

R and RSUSP by end of injection day
Origin subcatchment = 11 (HBV, Hobsonville)
R RSUSP Dcon
12 microns
40 microns
125 microns
180 microns
1.0
0.5
0.0
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
SINK
SINK
SINK
DEEP CHANNELS
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22
HBE LBY NWI CNS WSI SWI WAV PCV MEO MOT SBY HGF HEN WHA WAT HBA UWH WC WS UC MC OC
Destination subestuary
r-sc11.grf

Figure 87

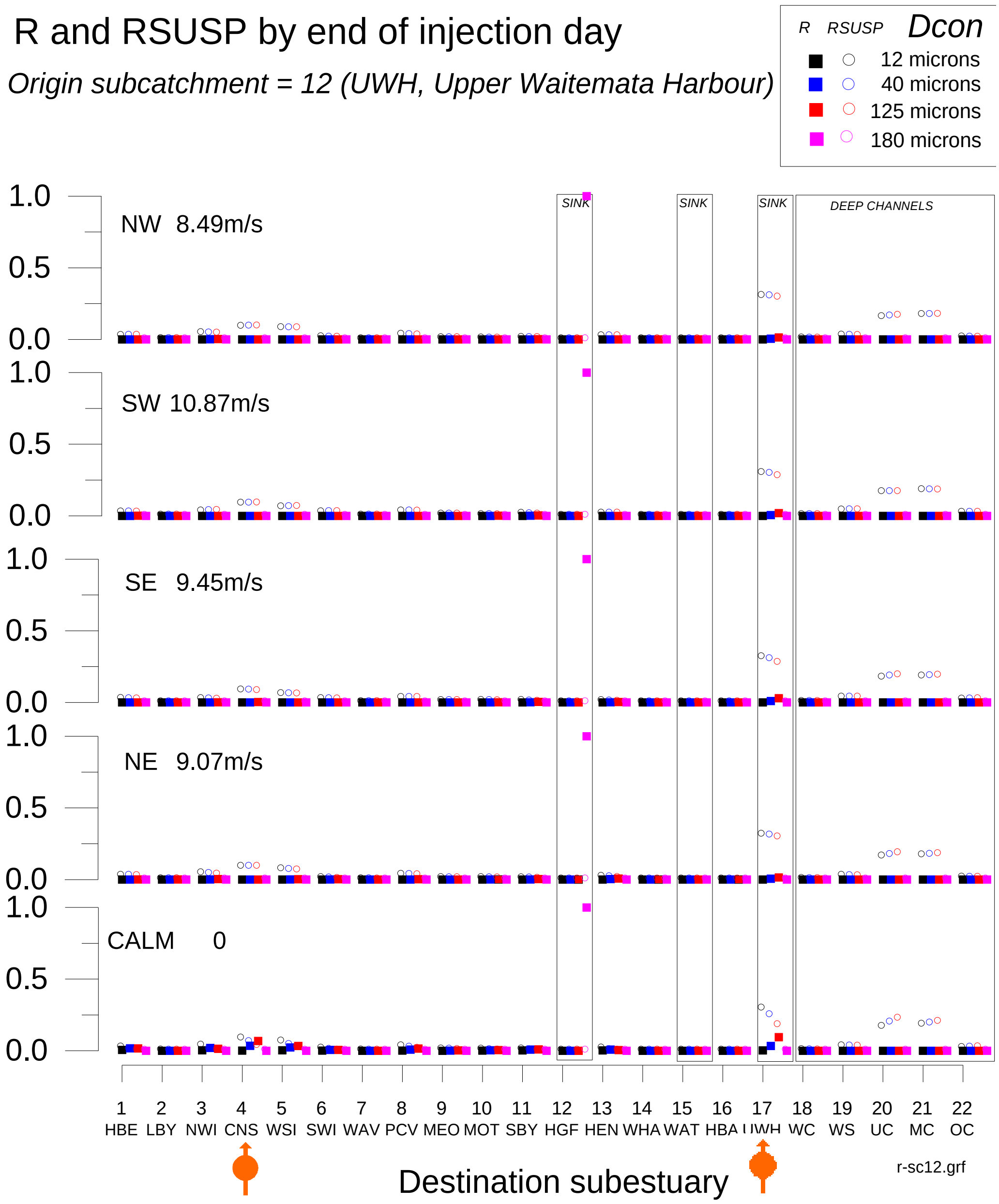
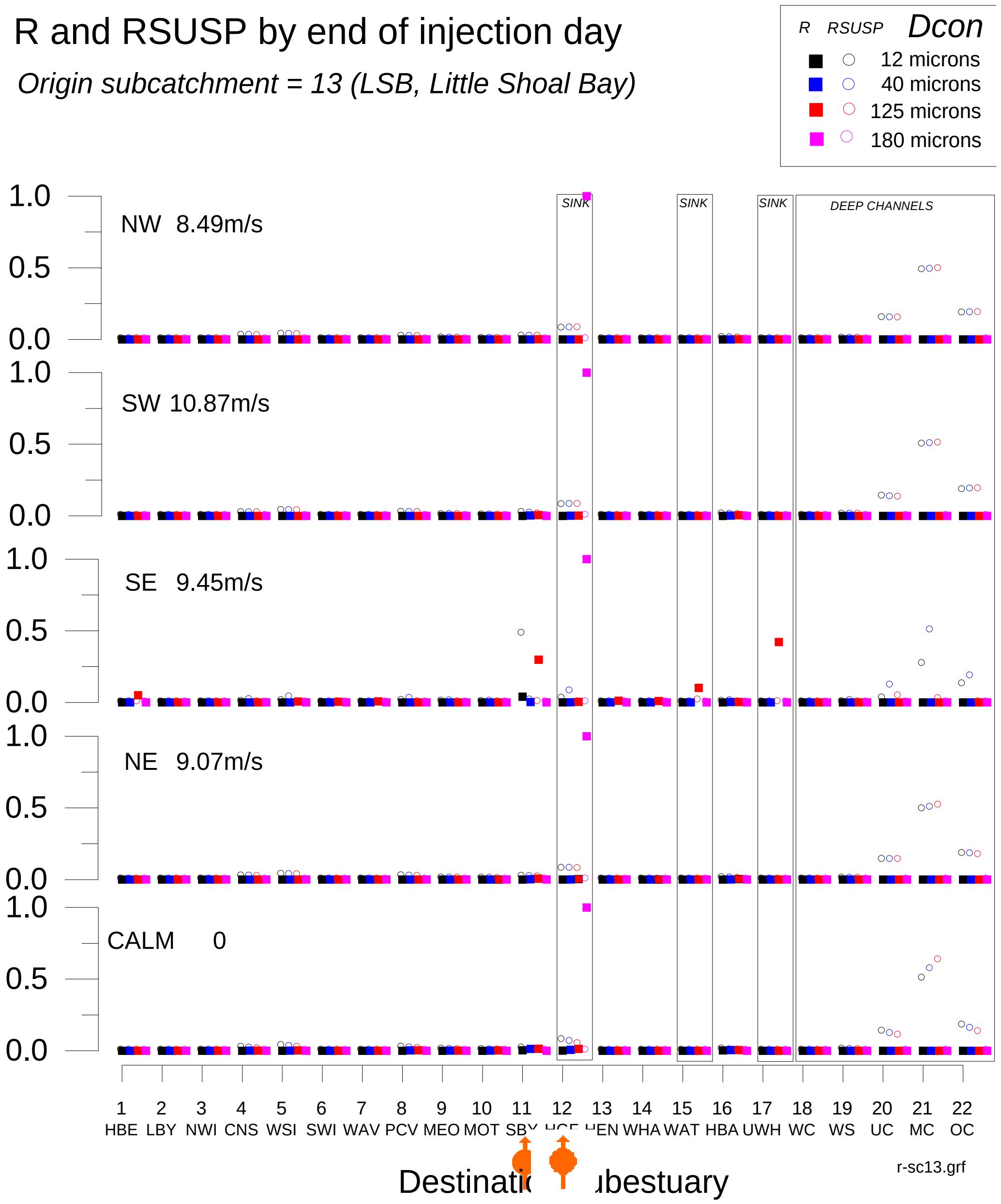
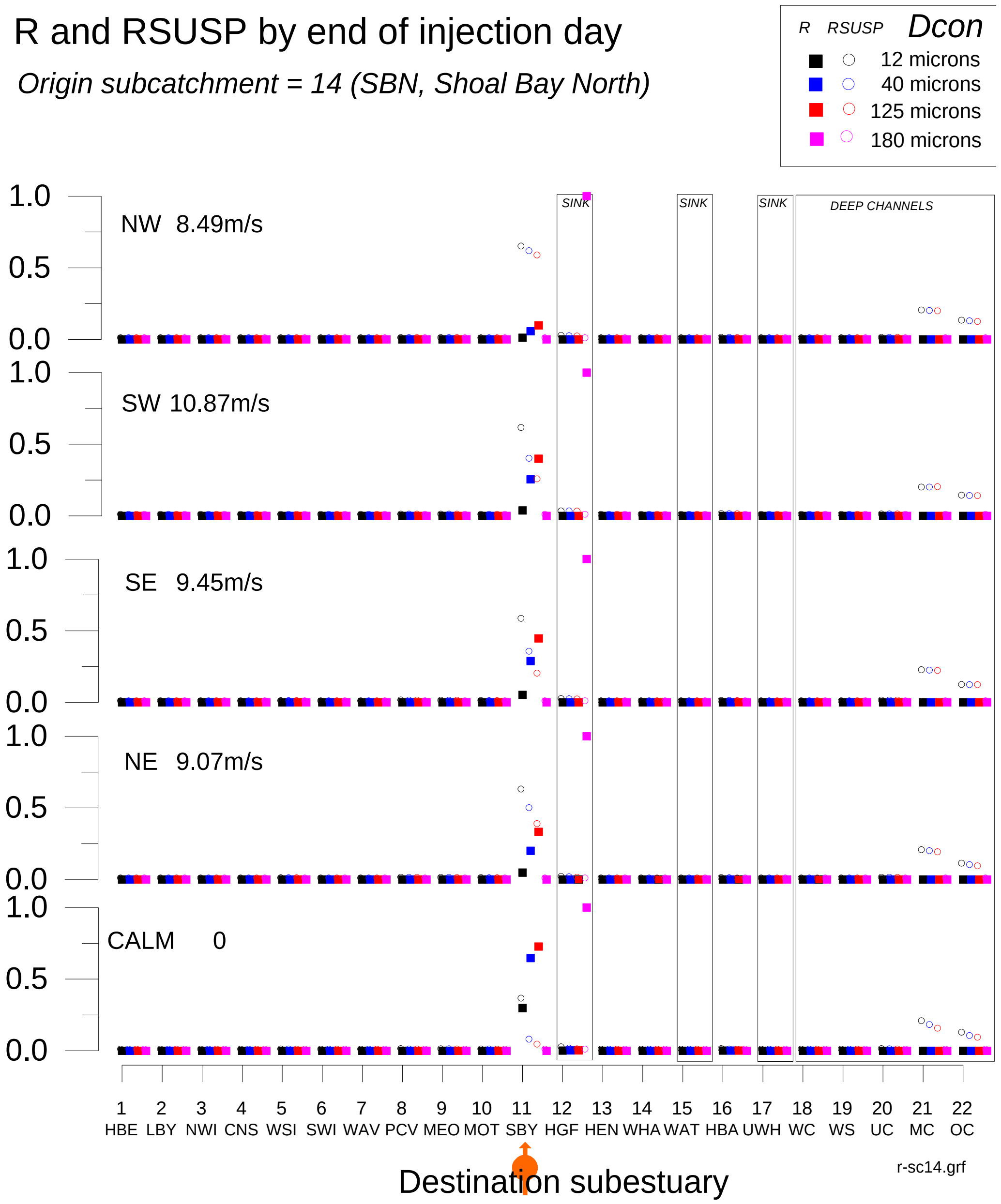

R and RSUSP by end of injection day
Origin subcatchment = 12 (UWH, Upper Waitemata Harbour)
R RSUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
1.0
0.5
0.0
SINK
SINK
SINK
DEEP CHANNELS
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r-sc12.grf

Figure 88



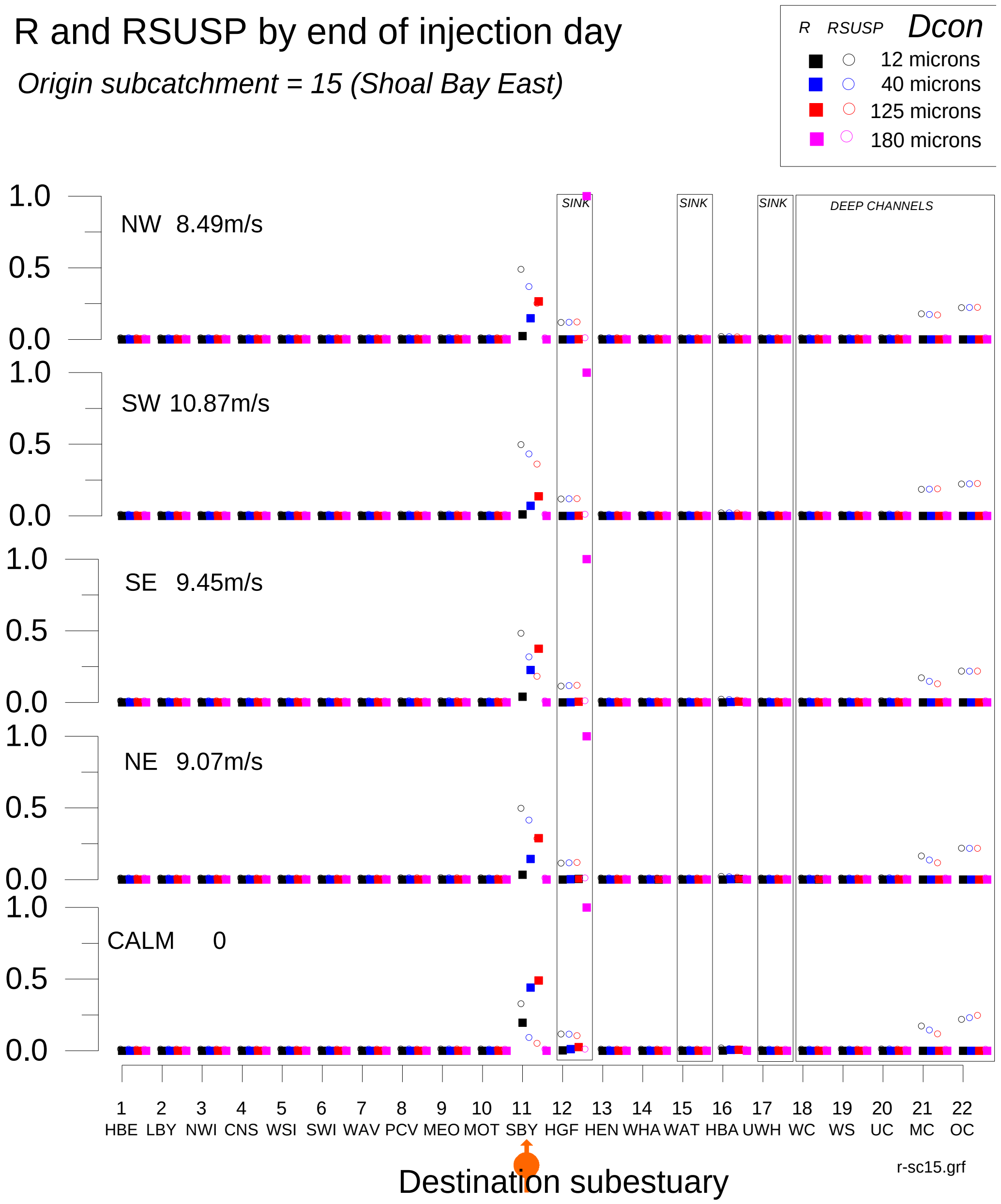
R and RSUSP by end of injection day
Origin subcatchment = 13 (LSB, Little Shoal Bay)
R RSUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
1.0
0.5
0.0
SINK
DEEP CHANNELS
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
r-sc13.grf

Figure 89



R and RSUSP by end of injection day
Origin subcatchment = 14 (SBN, Shoal Bay North)
R RSUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
1.0
0.5
0.0
SINK
SINK
SINK
DEEP CHANNELS
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r-sc14.grf

Figure 90



R and RSUSP by end of injection day
Origin subcatchment = 15 (Shoal Bay East)
R RSUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
SINK
SINK
SINK
DEEP CHANNELS
1.0
0.5
0.0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22
HBE LBY NWI CNS WSI SWI WAV PCV MEO MOT SBY HGF HEN WHA WAT HBA UWH WC WS UC MC OC
Destination subestuary
r-sc15.grf

# 16 Appendix 7: R5 and R5SUSP (Equilibrium), Not Raining

## 16.1 Tide sequence neap–mean–spring

**Figure 91**

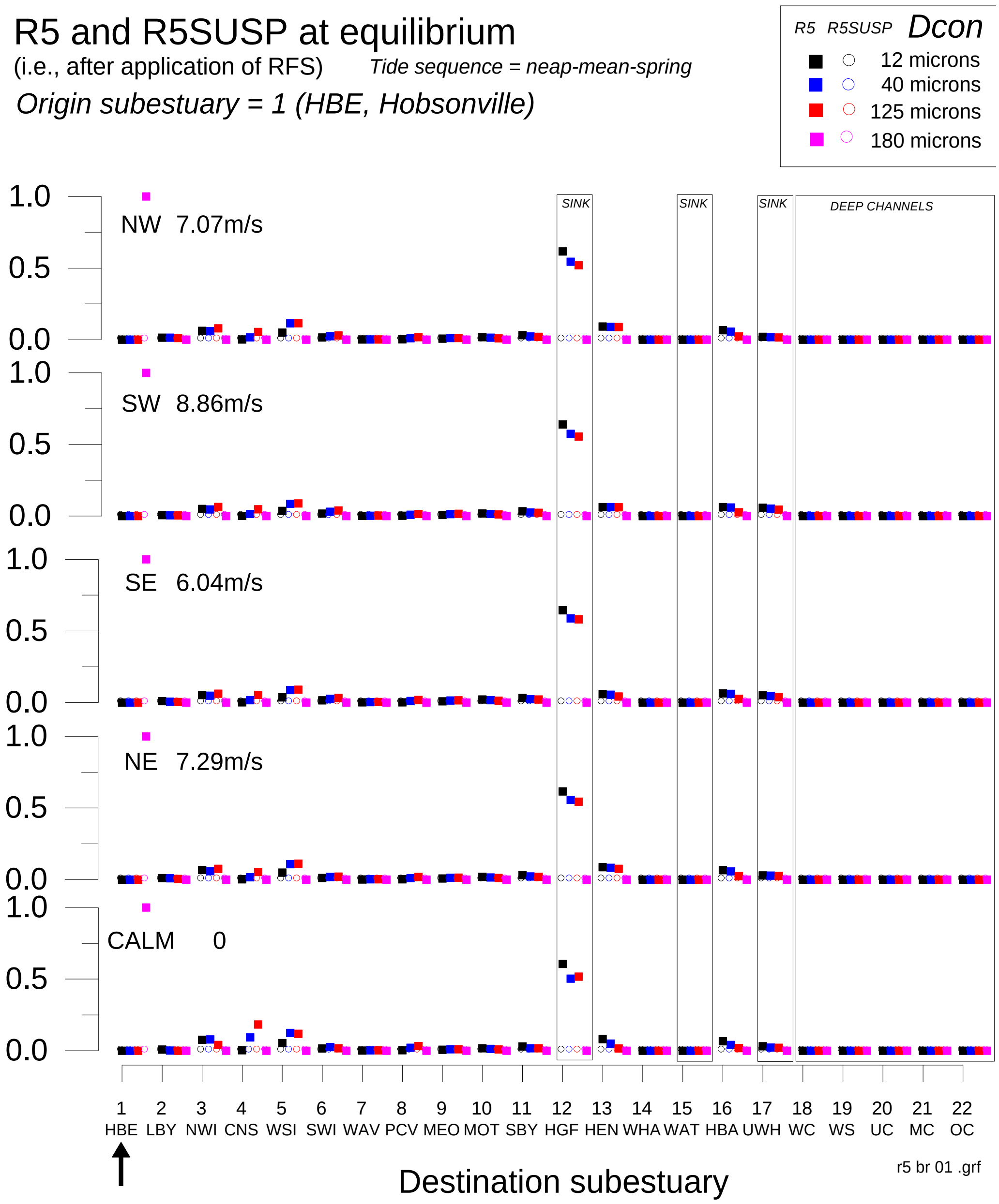


Figure 92

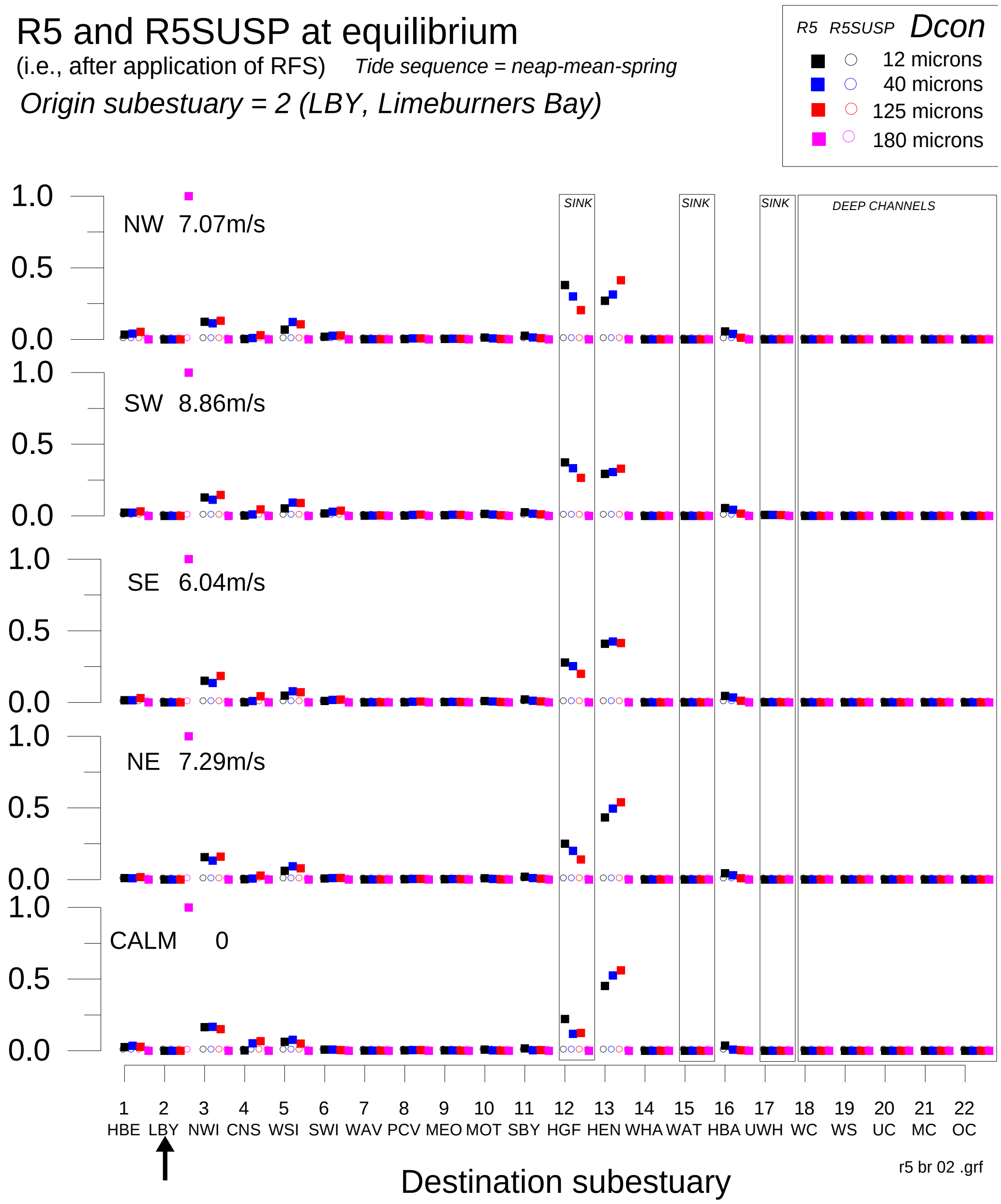

R5 and R5SUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = neap-mean-spring
Origin subestuary = 2 (LBY, Limeburners Bay)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 7.07m/s
SW 8.86m/s
SE 6.04m/s
NE 7.29m/s
CALM 0
SINK
SINK
SINK
DEEP CHANNELS
1.0
0.5
0.0
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r5 br 02 .grf

Figure 93

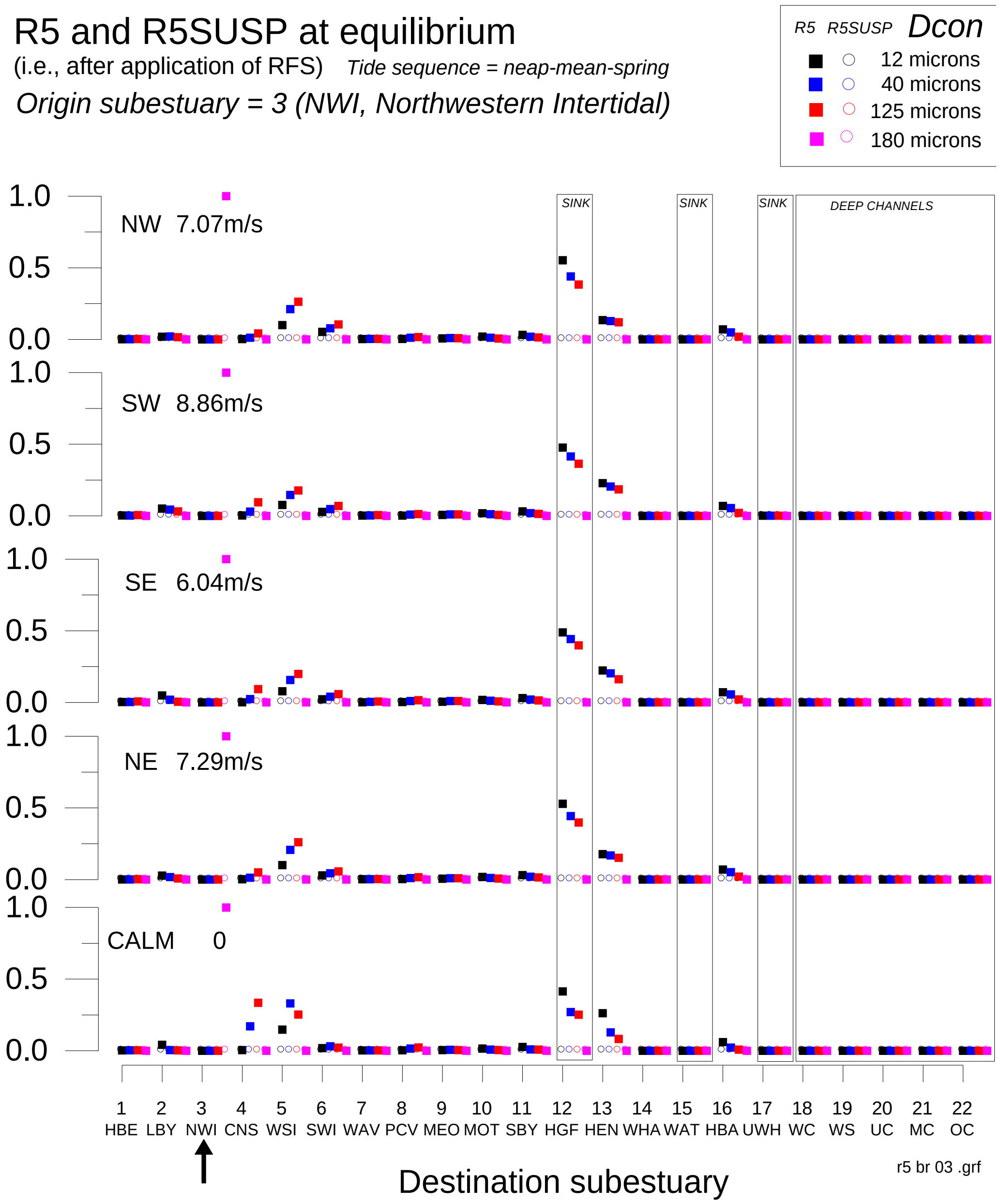

R5 and R5SUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = neap-mean-spring
Origin subestuary = 3 (NWI, Northwestern Intertidal)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 7.07m/s
SW 8.86m/s
SE 6.04m/s
NE 7.29m/s
CALM 0
1.0
0.5
0.0
SINK
SINK
SINK
DEEP CHANNELS
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r5 br 03 .grf

Figure 94

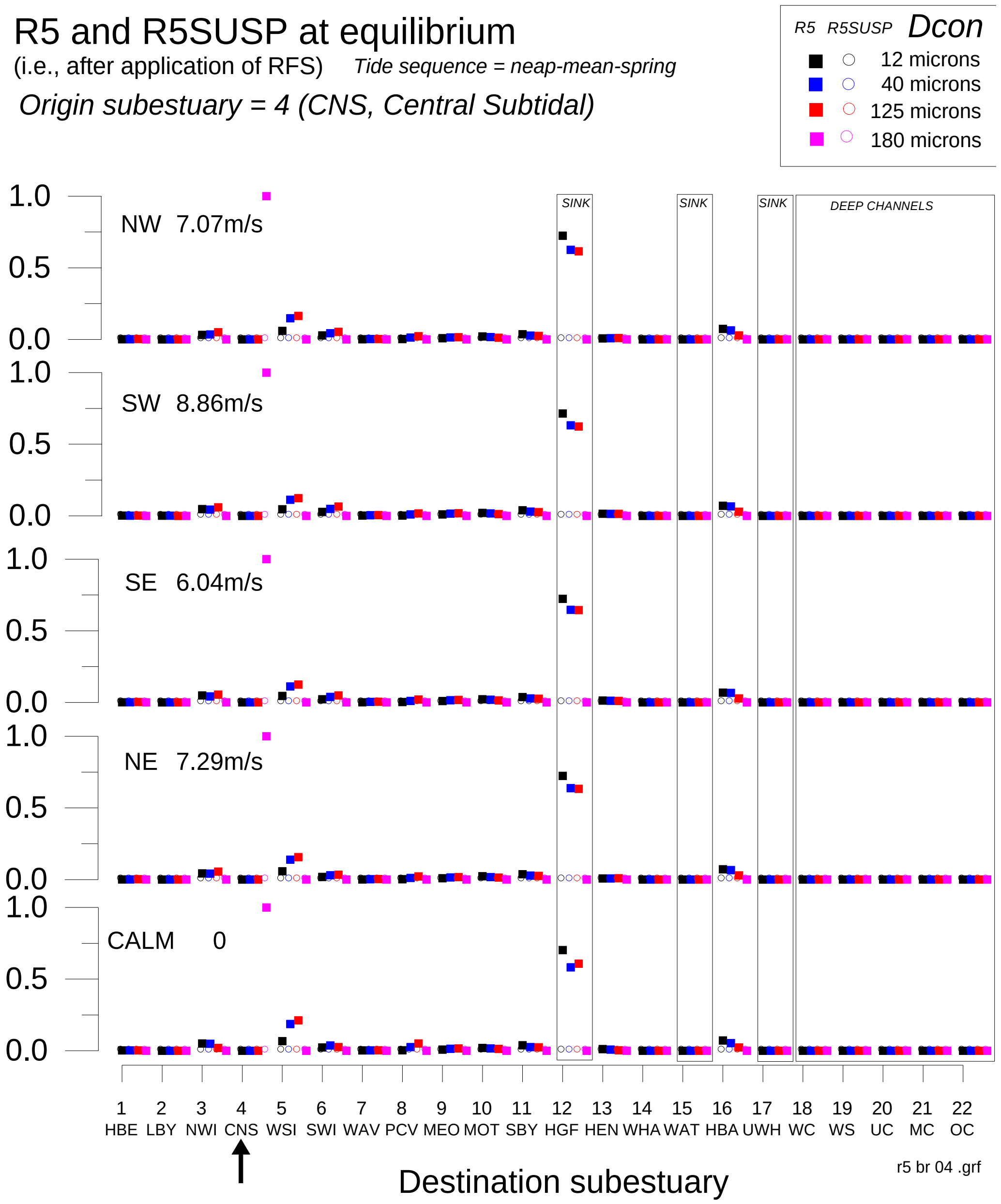
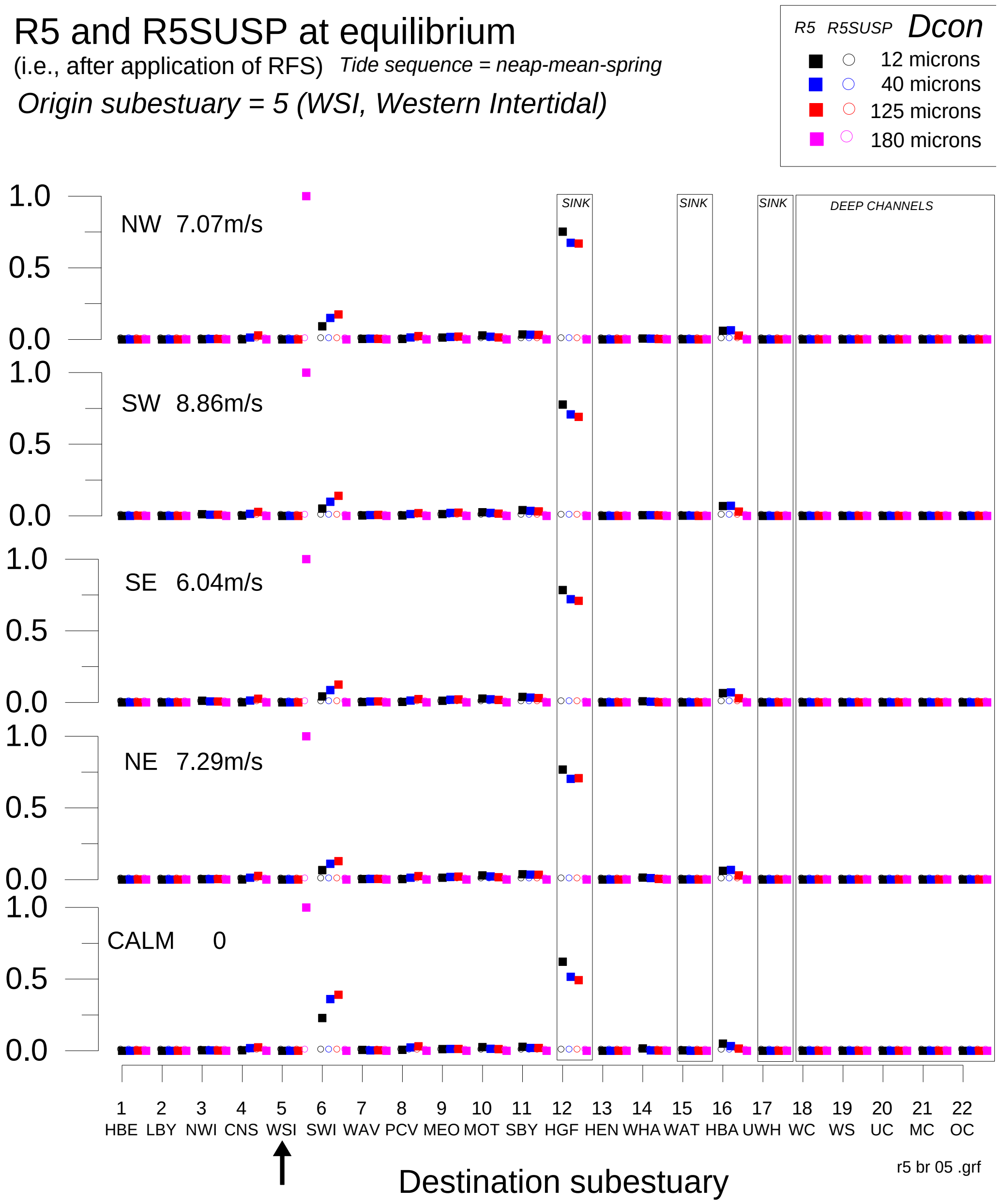
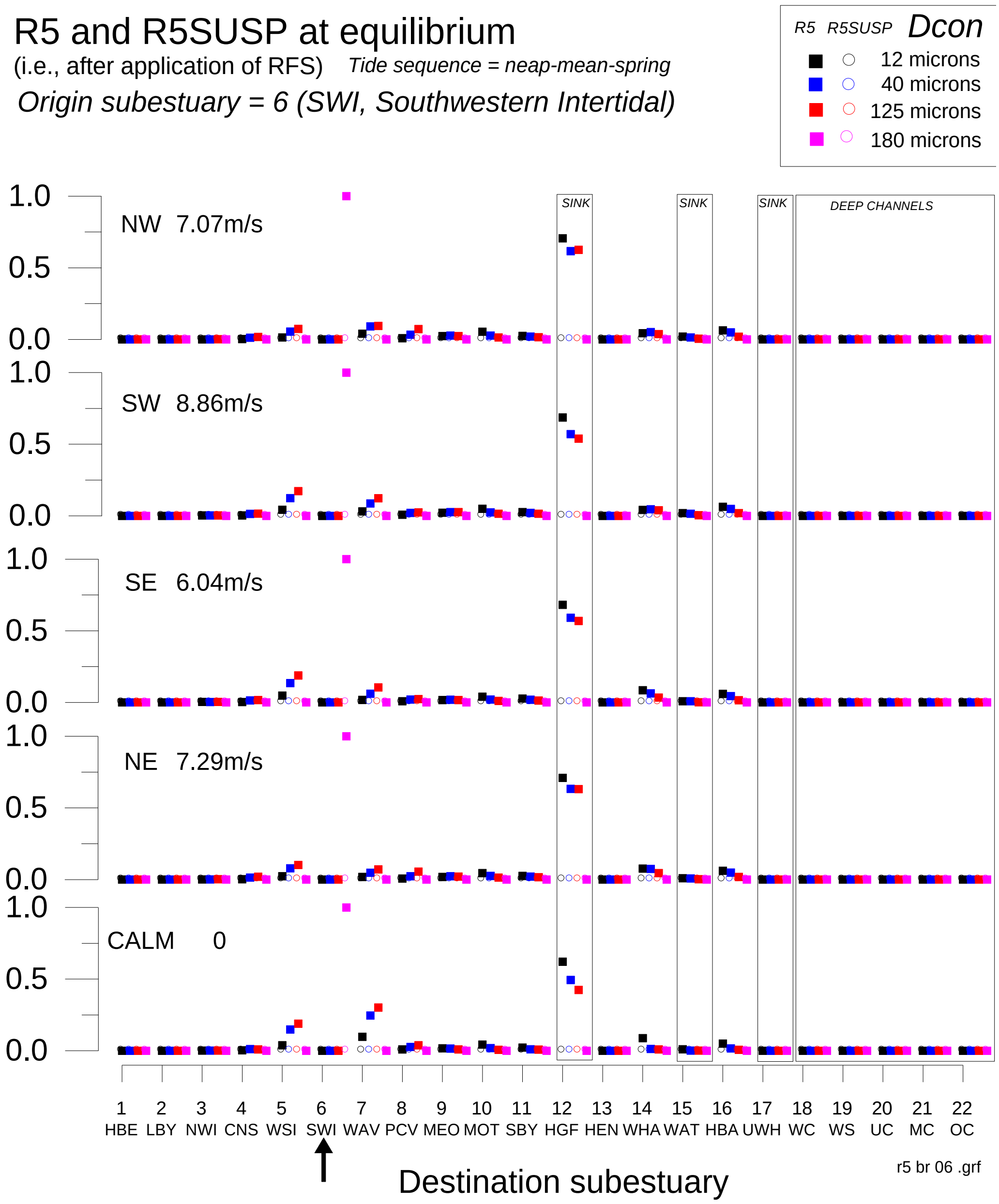

R5 and R5SUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = neap-mean-spring
Origin subestuary = 4 (CNS, Central Subtidal)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 7.07m/s
SW 8.86m/s
SE 6.04m/s
NE 7.29m/s
CALM 0
SINK
SINK
SINK
DEEP CHANNELS
1.0
0.5
0.0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22
HBE LBY NWI CNS WSI SWI WAV PCV MEO MOT SBY HGF HEN WHA WAT HBA UWH WC WS UC MC OC
Destination subestuary
r5 br 04 .grf

Figure 95



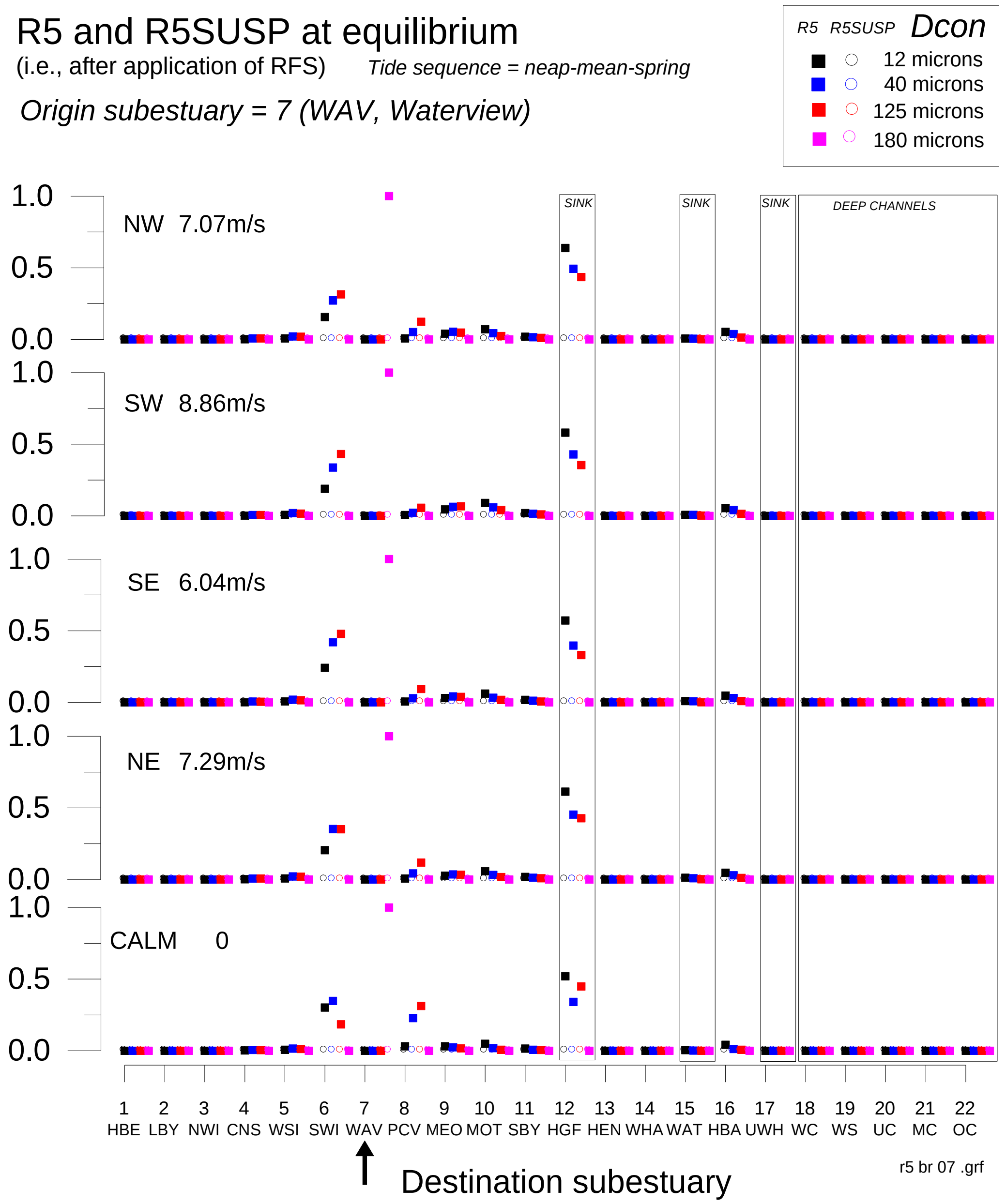
R5 and R5SUSP at equilibrium
(i.e., after application of RFS) Tide sequence = neap-mean-spring
Origin subestuary = 5 (WSI, Western Intertidal)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 7.07m/s
SW 8.86m/s
SE 6.04m/s
NE 7.29m/s
CALM 0
SINK
DEEP CHANNELS
1 HBE 2 LBY 3 NWI 4 CNS 5 WSI 6 SWI 7 WAV 8 PCV 9 MEO 10 MOT 11 SBY 12 HGF 13 HEN 14 WHA 15 WAT 16 HBA 17 UWH 18 WC 19 WS 20 UC 21 MC 22 OC
Destination subestuary
r5 br 05 .grf

Figure 96



R5 and R5SUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = neap-mean-spring
Origin subestuary = 6 (SWI, Southwestern Intertidal)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 7.07m/s
SW 8.86m/s
SE 6.04m/s
NE 7.29m/s
CALM 0
SINK
DEEP CHANNELS
1.0
0.5
0.0
1 HBE 2 LBY 3 NWI 4 CNS 5 WSI 6 SWI 7 WAV 8 PCV 9 MEO 10 MOT 11 SBY 12 HGF 13 HEN 14 WHA 15 WAT 16 HBA 17 UWH 18 WC 19 WS 20 UC 21 MC 22 OC
Destination subestuary
r5 br 06 .grf

Figure 97



R5 and R5SUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = neap-mean-spring
Origin subestuary = 7 (WAV, Waterview)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 7.07m/s
SW 8.86m/s
SE 6.04m/s
NE 7.29m/s
CALM 0
1.0
0.5
0.0
SINK
DEEP CHANNELS
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22
HBE LBY NWI CNS WSI SWI WAV PCV MEO MOT SBY HGF HEN WHA WAT HBA UWH WC WS UC MC OC
Destination subestuary
r5 br 07 .grf

Figure 98

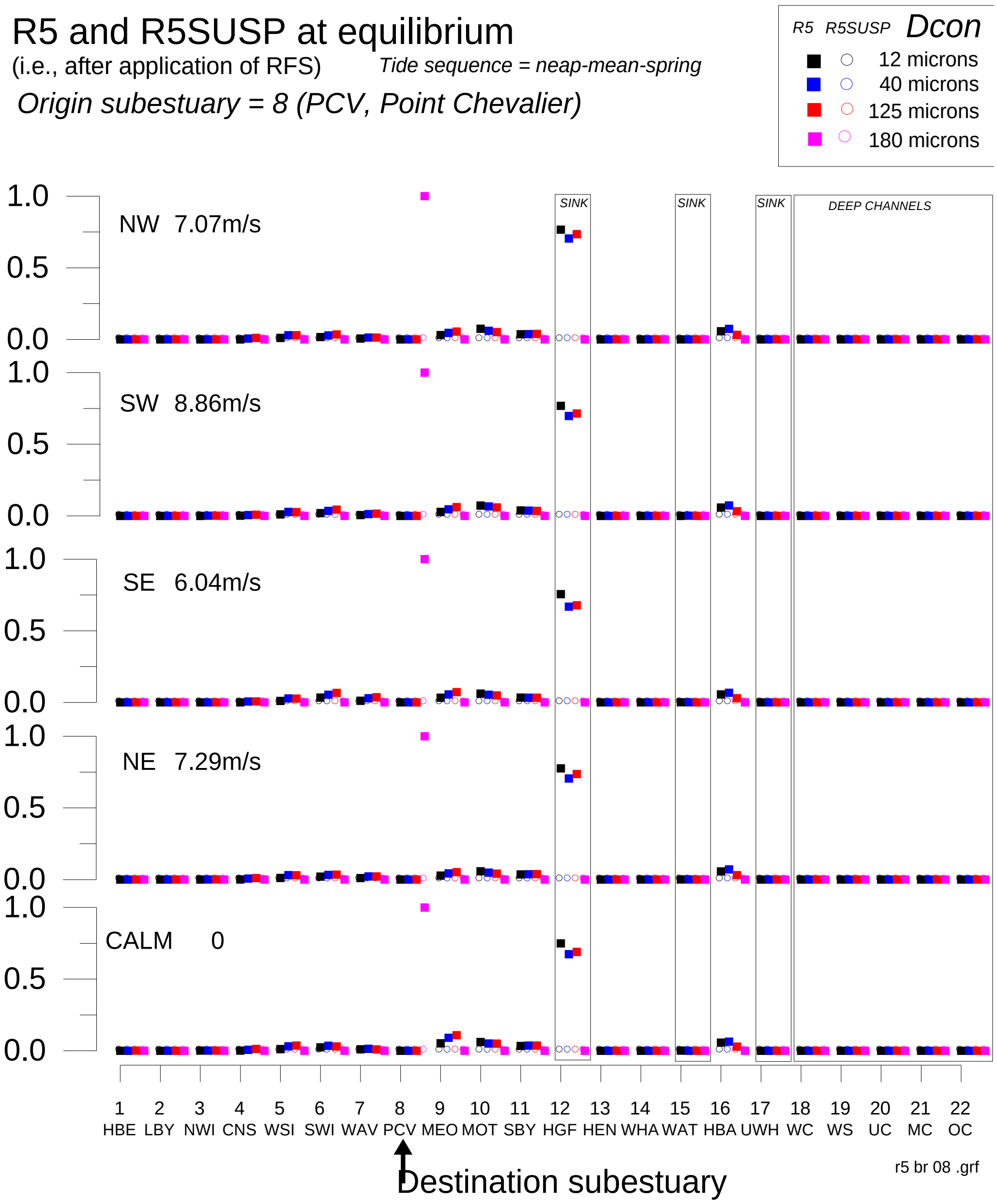

R5 and R5SUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = neap-mean-spring
Origin subestuary = 8 (PCV, Point Chevalier)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 7.07m/s
SW 8.86m/s
SE 6.04m/s
NE 7.29m/s
CALM 0
1.0
0.5
0.0
SINK
DEEP CHANNELS
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r5 br 08 .grf

Figure 99

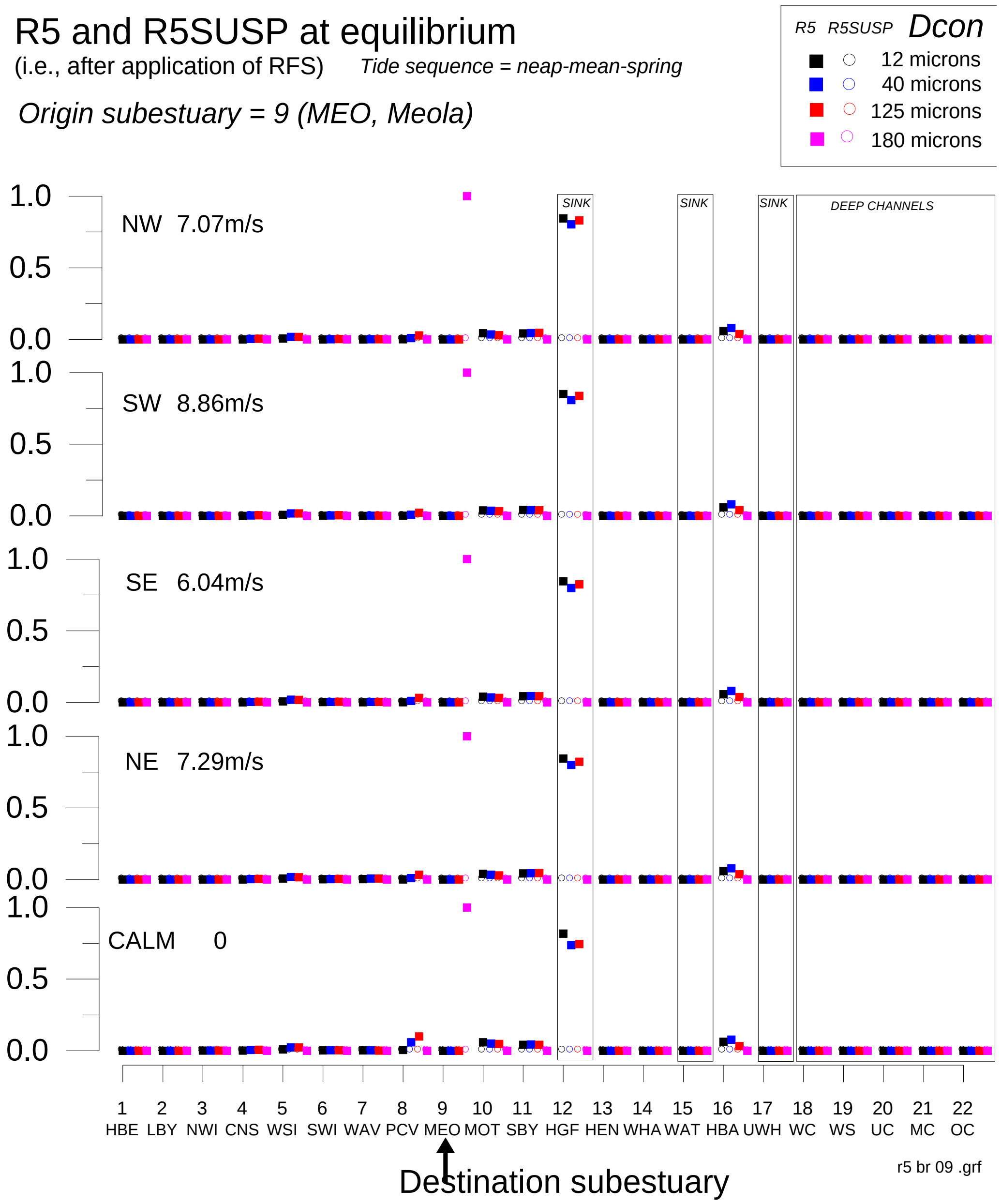

R5 and R5SUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = neap-mean-spring
Origin subestuary = 9 (MEO, Meola)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 7.07m/s
SW 8.86m/s
SE 6.04m/s
NE 7.29m/s
CALM 0
1.0
0.5
0.0
SINK
DEEP CHANNELS
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22
HBE LBY NWI CNS WSI SWI WAV PCV MEO MOT SBY HGF HEN WHA WAT HBA UWH WC WS UC MC OC
Destination subestuary
r5 br 09 .grf

Figure 100

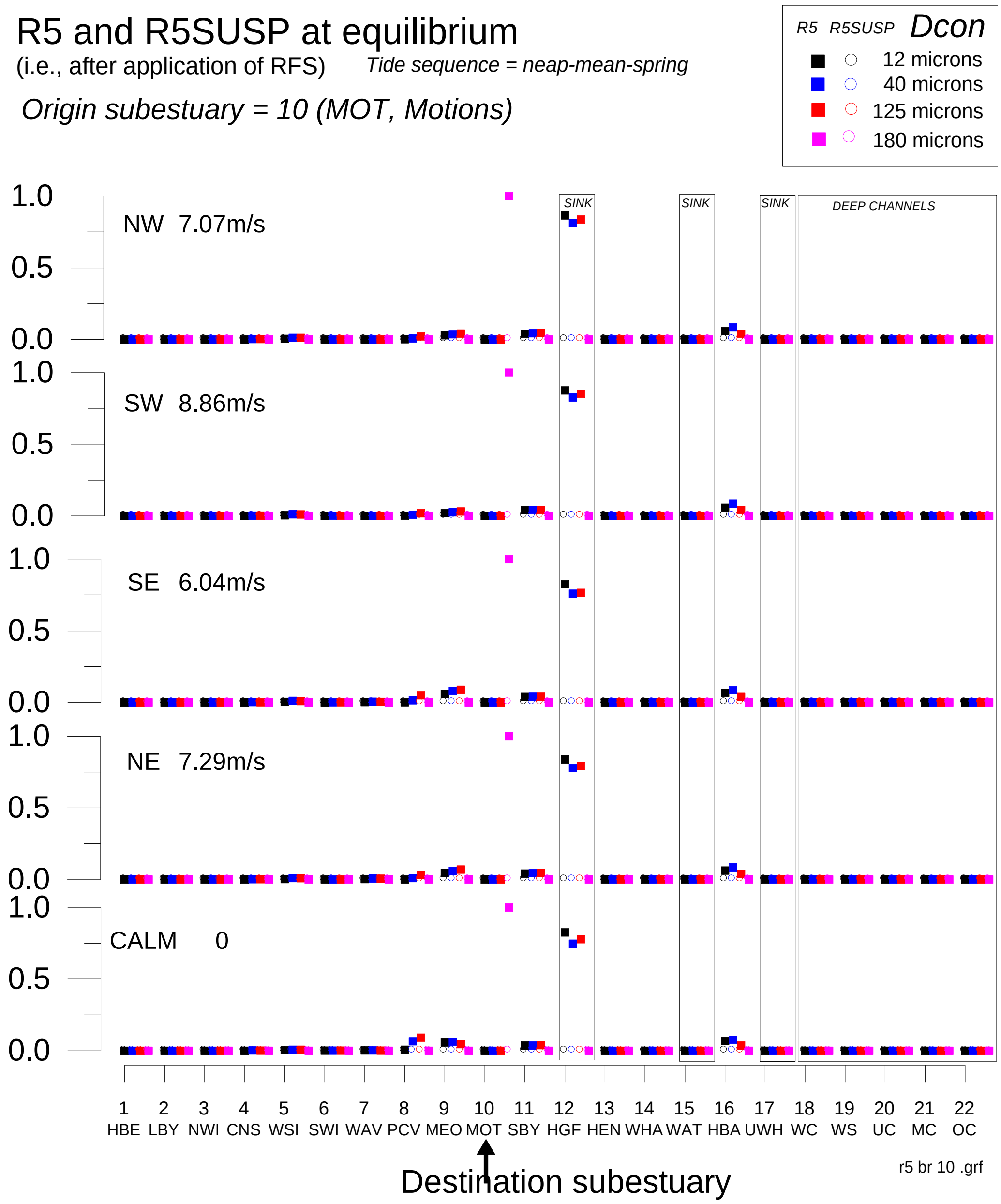
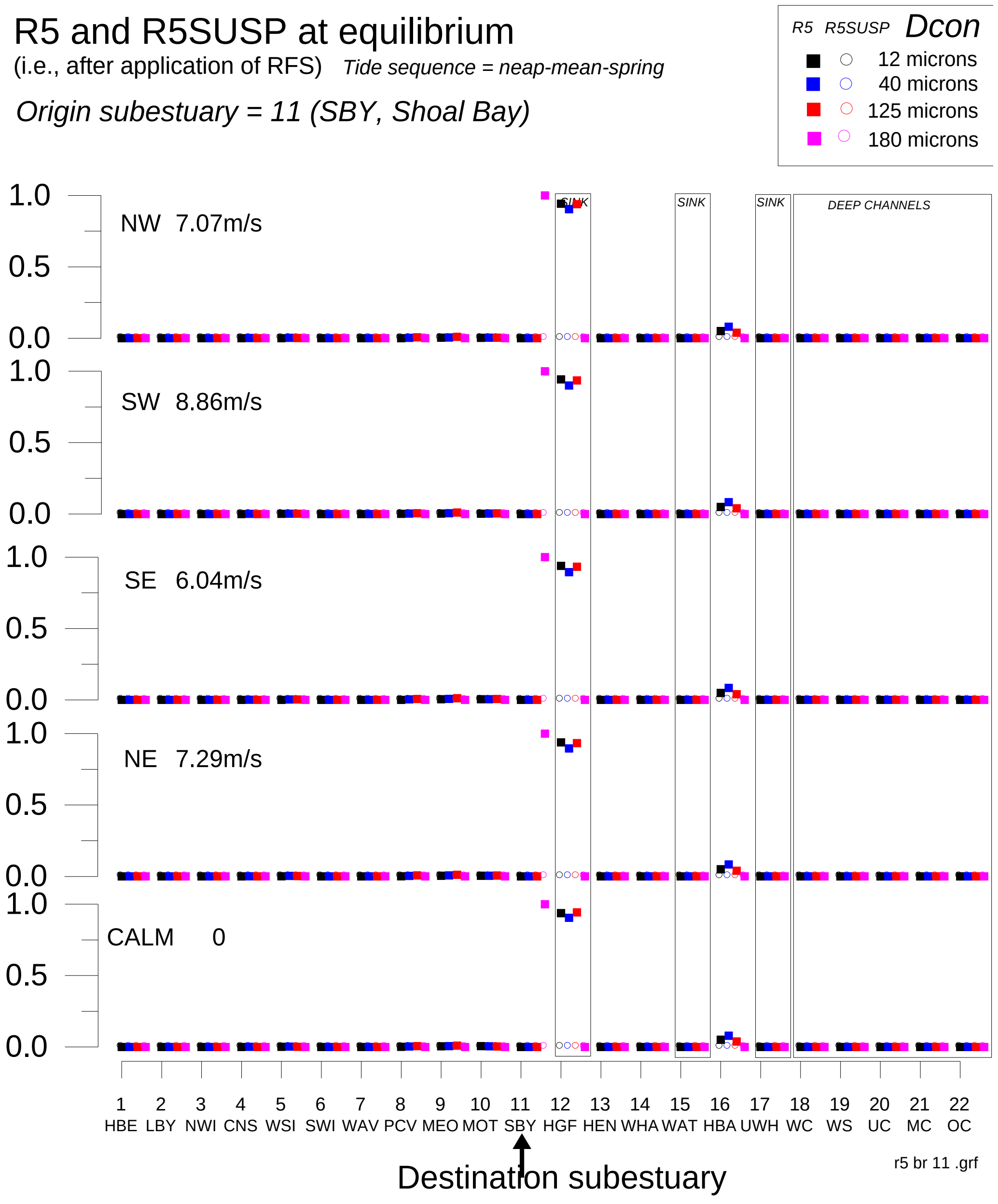

R5 and R5SUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = neap-mean-spring
Origin subestuary = 10 (MOT, Motions)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 7.07m/s
SW 8.86m/s
SE 6.04m/s
NE 7.29m/s
CALM 0
SINK
SINK
SINK
DEEP CHANNELS
1.0
0.5
0.0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22
HBE LBY NWI CNS WSI SWI WAV PCV MEO MOT SBY HGF HEN WHA WAT HBA UWH WC WS UC MC OC
Destination subestuary
r5 br 10 .grf

Figure 101


R5 and R5SUSP at equilibrium
(i.e., after application of RFS) Tide sequence = neap-mean-spring
Origin subestuary = 11 (SBY, Shoal Bay)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 7.07m/s
SW 8.86m/s
SE 6.04m/s
NE 7.29m/s
CALM 0
SINK
SINK
SINK
DEEP CHANNELS
1.0
0.5
0.0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22
HBE LBY NWI CNS WSI SWI WAV PCV MEO MOT SBY HGF HEN WHA WAT HBA UWH WC WS UC MC OC
Destination subestuary
r5 br 11 .grf

## 16.2 Tide sequence mean-spring-neap

**Figure 102**

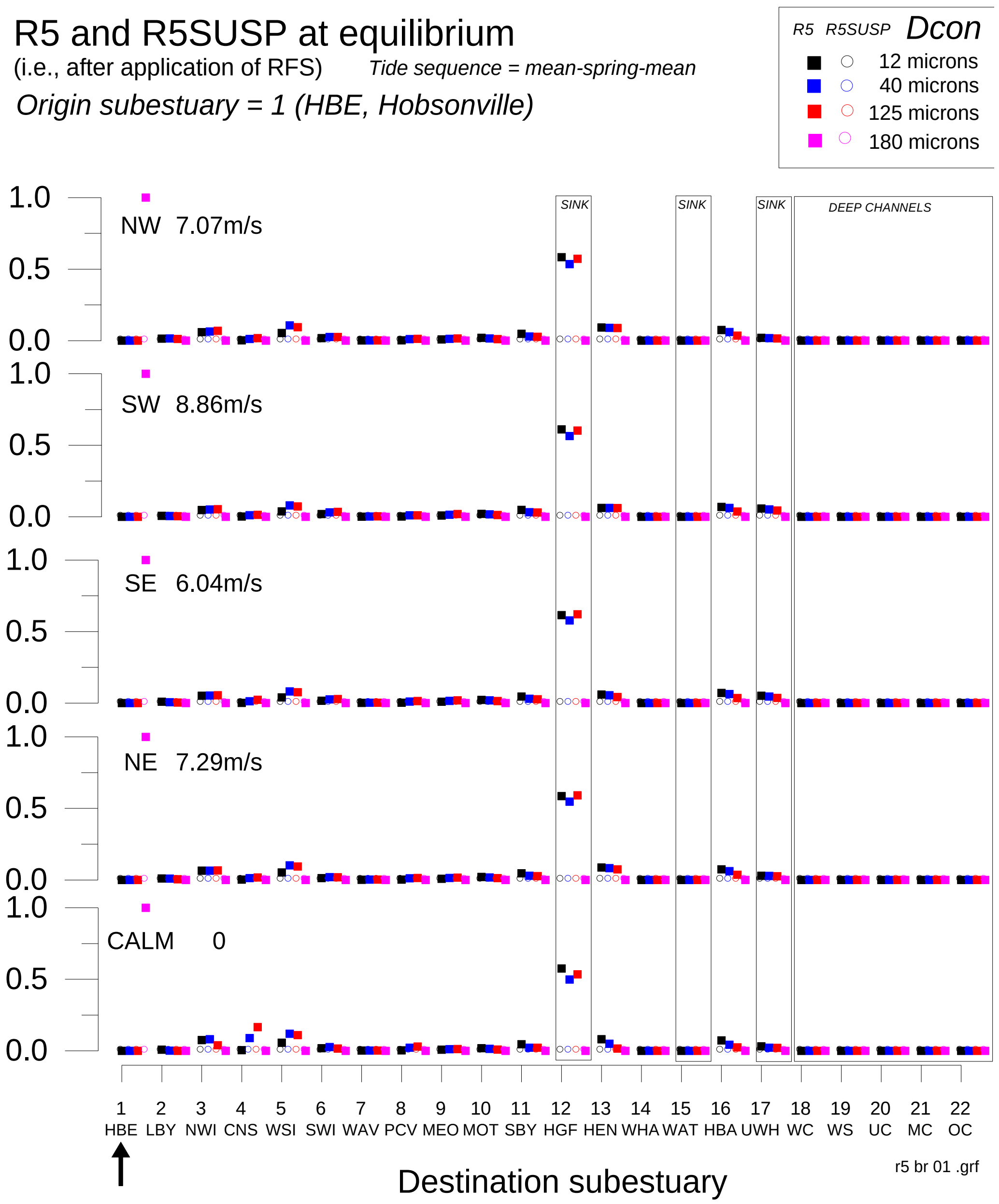


Figure 103

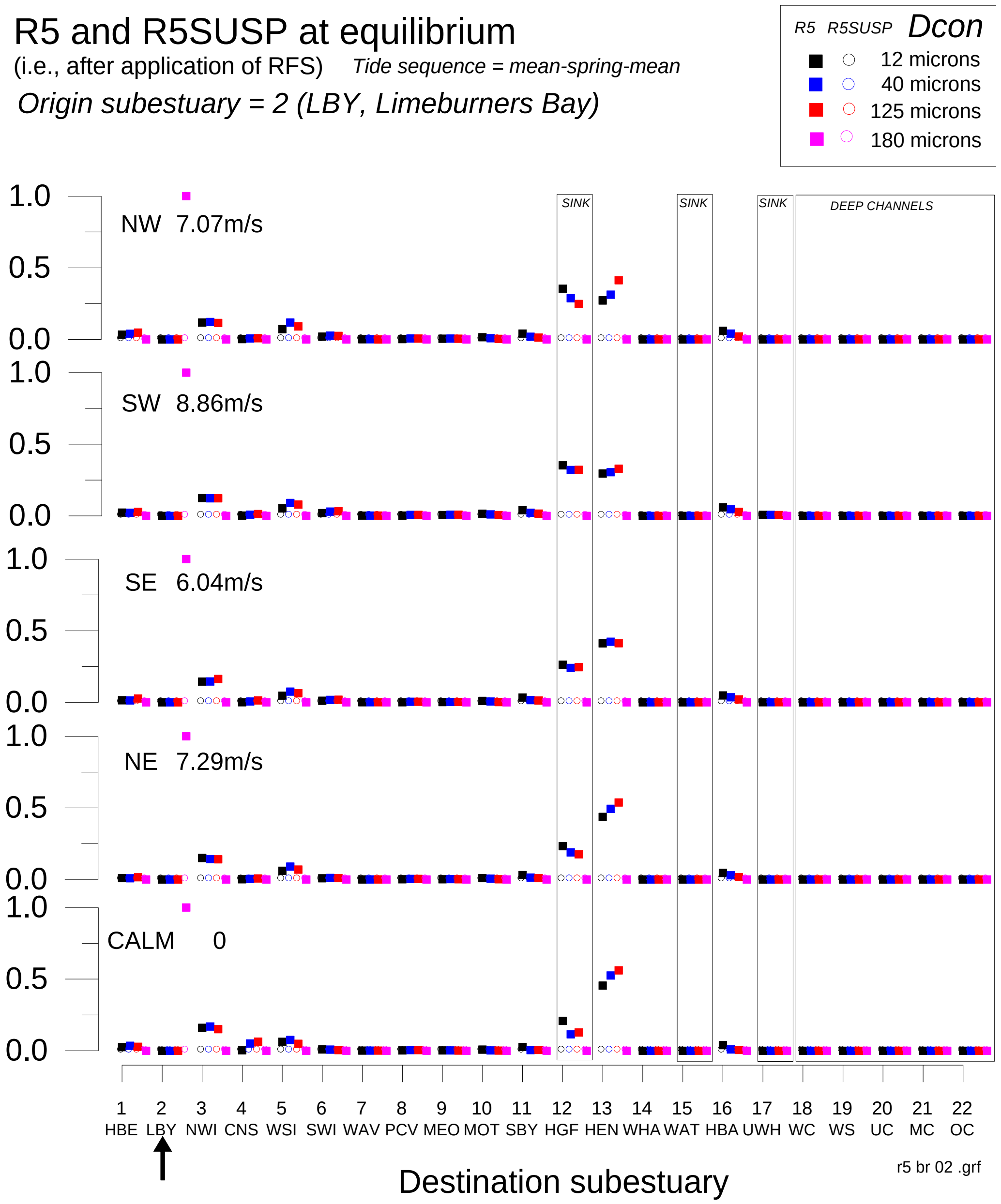

R5 and R5SUSP at equilibrium
(i.e., after application of RFS) Tide sequence = mean-spring-mean
Origin subestuary = 2 (LBY, Limeburners Bay)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 7.07m/s
SW 8.86m/s
SE 6.04m/s
NE 7.29m/s
CALM 0
SINK
SINK
SINK
DEEP CHANNELS
1.0
0.5
0.0
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r5 br 02 .grf

Figure 104

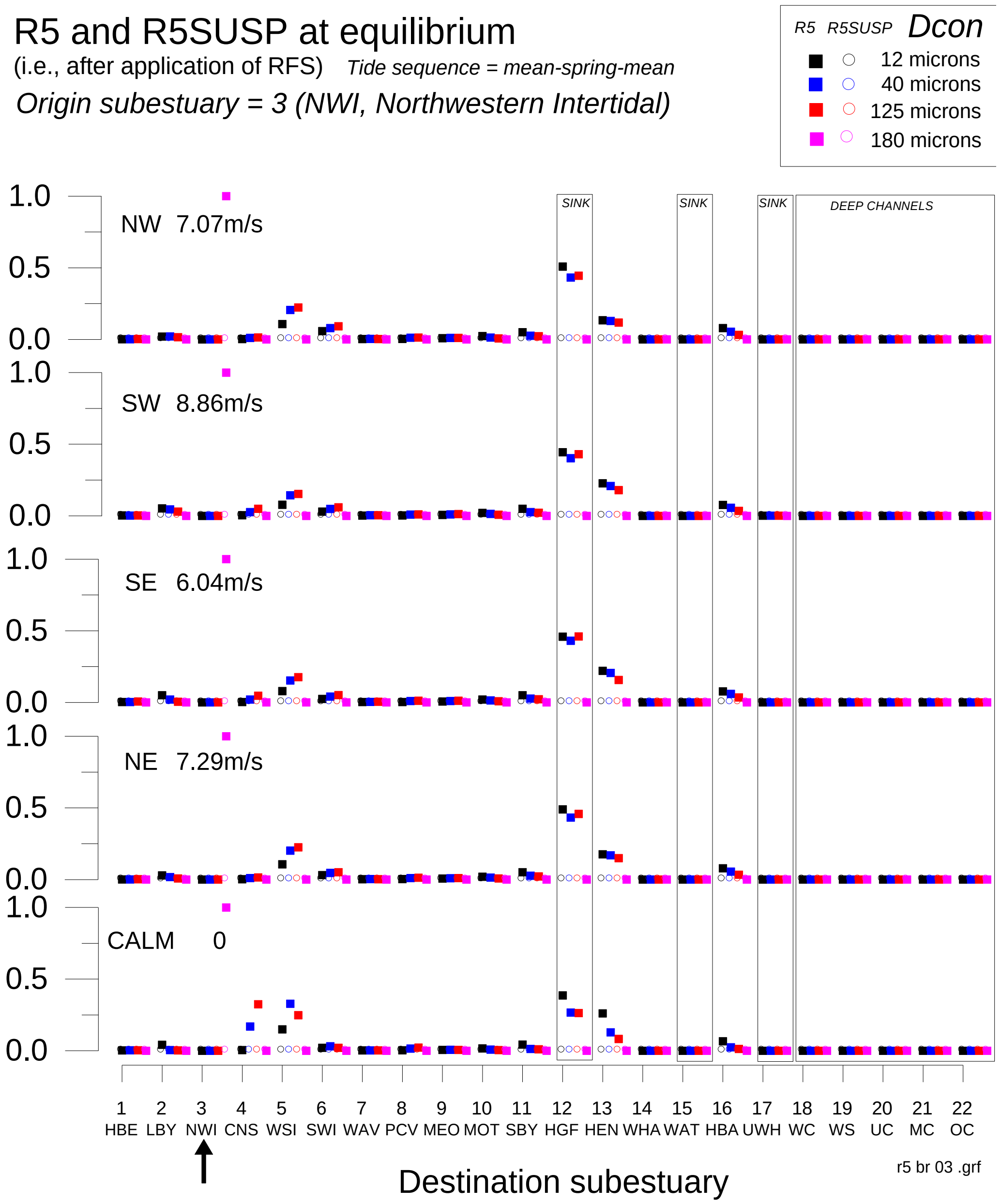
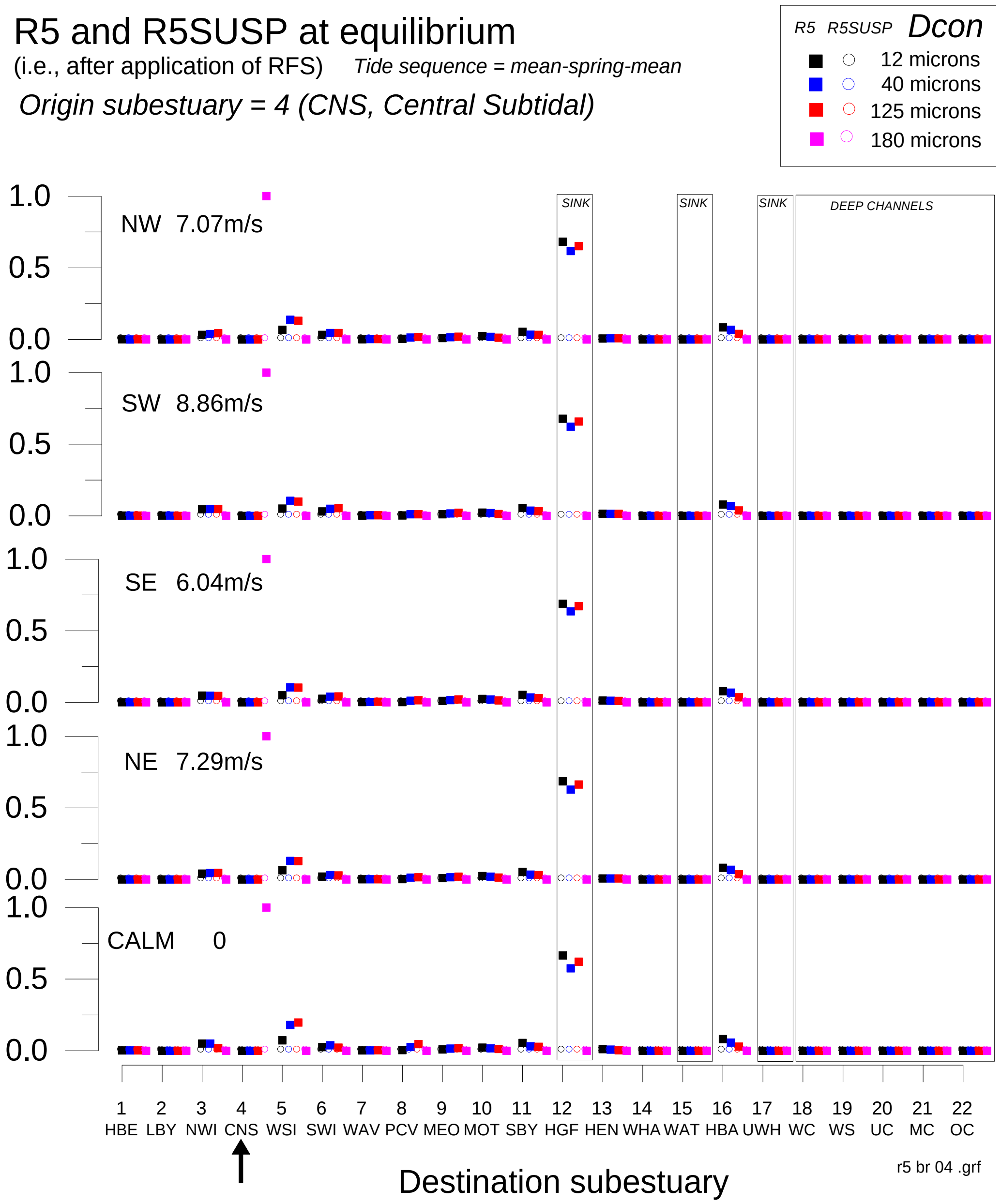
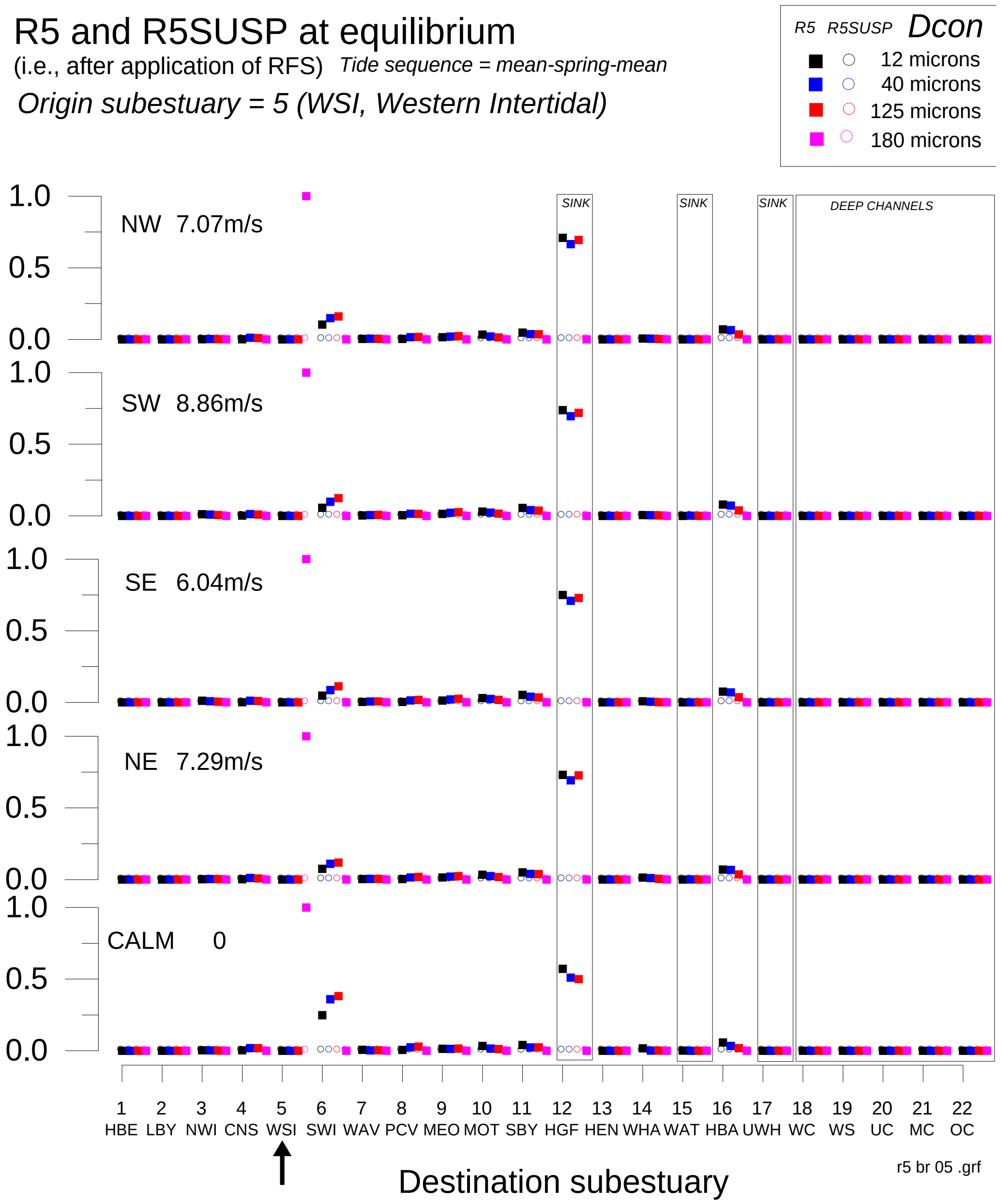

R5 and R5SUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = mean-spring-mean
Origin subestuary = 3 (NWI, Northwestern Intertidal)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 7.07m/s
SW 8.86m/s
SE 6.04m/s
NE 7.29m/s
CALM 0
SINK
SINK
SINK
DEEP CHANNELS
1.0
0.5
0.0
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r5 br 03 .grf

Figure 105



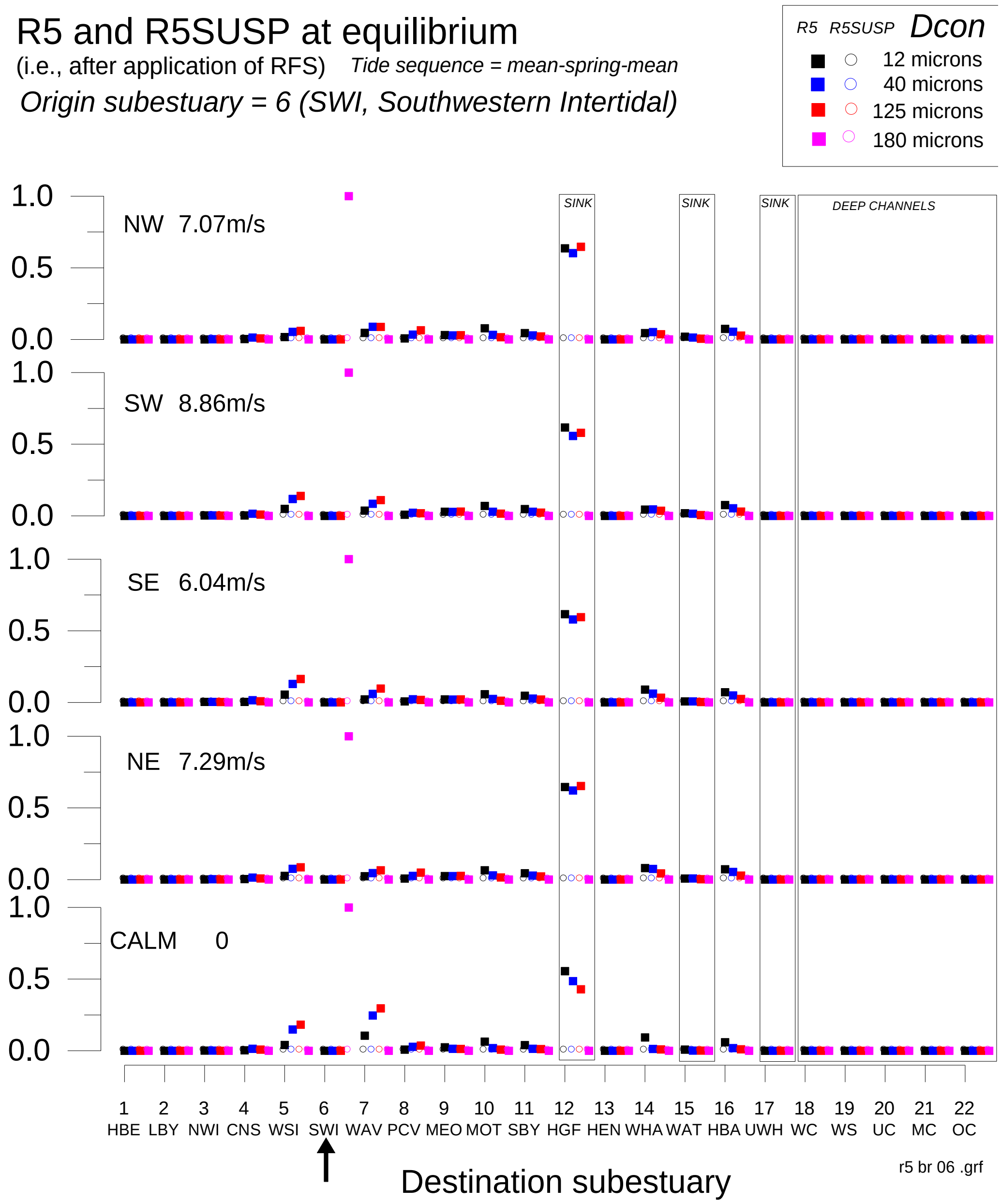
R5 and R5SUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = mean-spring-mean
Origin subestuary = 4 (CNS, Central Subtidal)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 7.07m/s
SW 8.86m/s
SE 6.04m/s
NE 7.29m/s
CALM 0
SINK
SINK
SINK
DEEP CHANNELS
1.0
0.5
0.0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22
HBE LBY NWI CNS WSI SWI WAV PCV MEO MOT SBY HGF HEN WHA WAT HBA UWH WC WS UC MC OC
Destination subestuary
r5 br 04 .grf

Figure 106



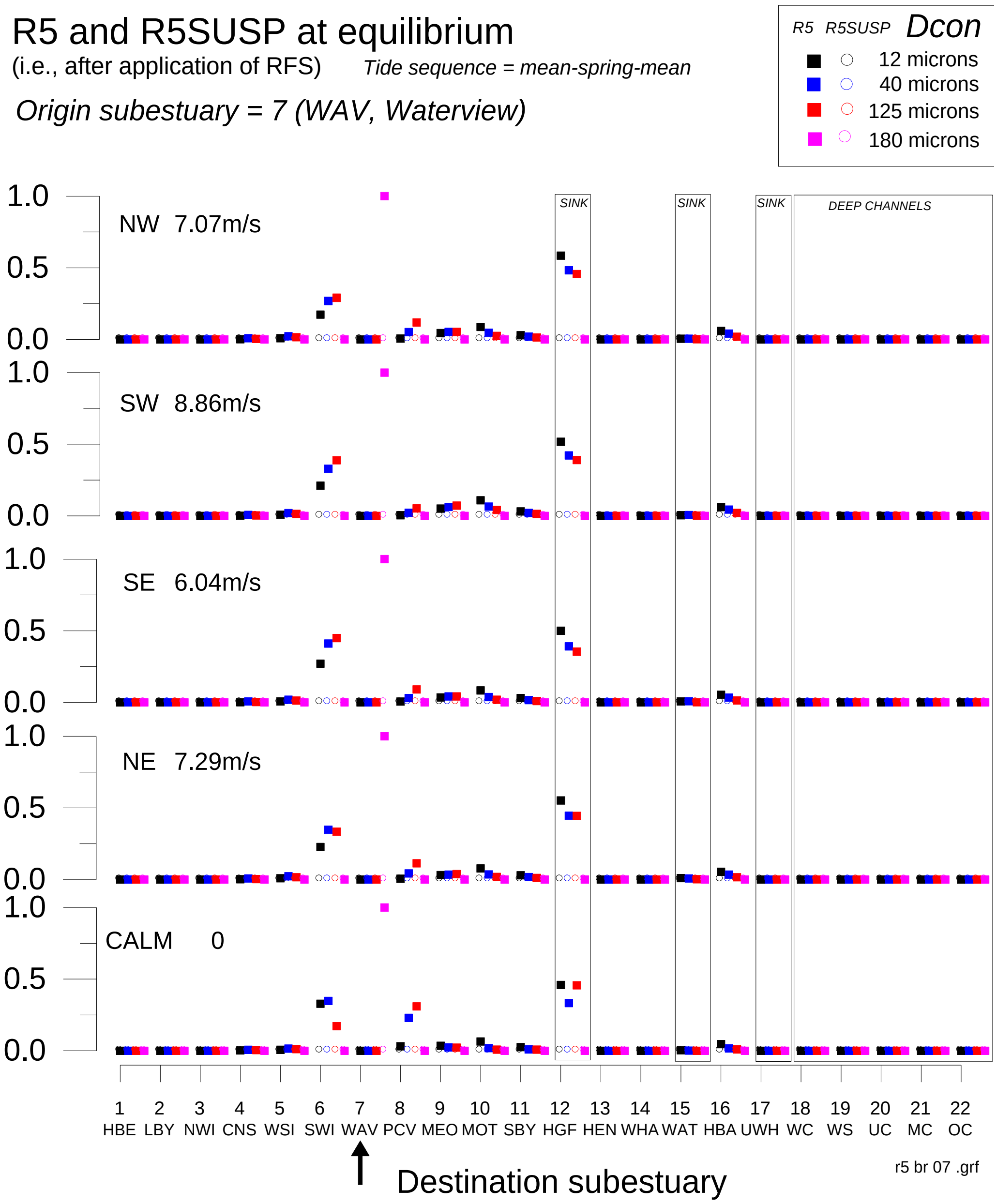
R5 and R5SUSP at equilibrium
(i.e., after application of RFS) Tide sequence = mean-spring-mean
Origin subestuary = 5 (WSI, Western Intertidal)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 7.07m/s
SW 8.86m/s
SE 6.04m/s
NE 7.29m/s
CALM 0
SINK
SINK
SINK
DEEP CHANNELS
1.0
0.5
0.0
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r5 br 05 .grf

**Figure 107**



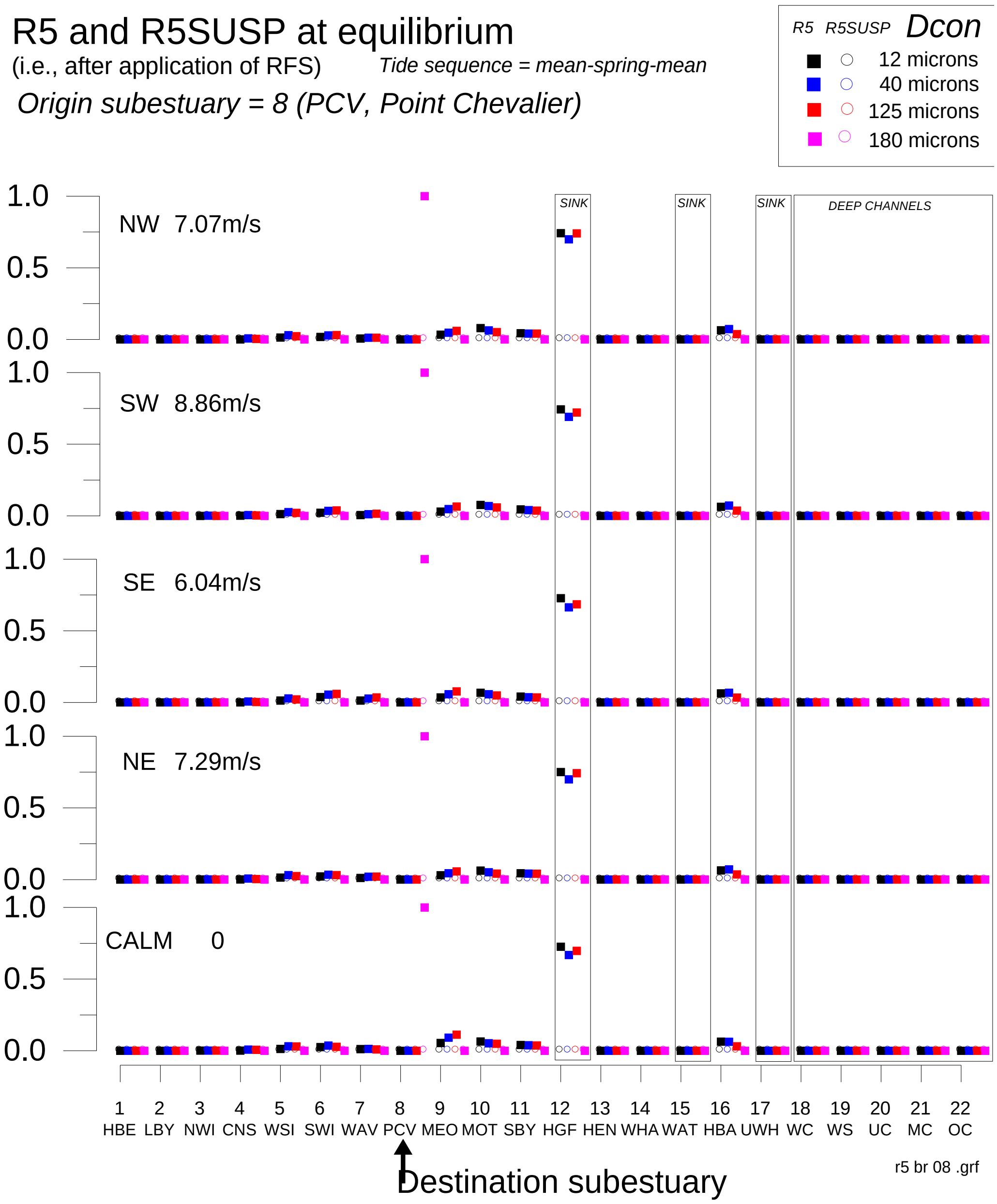
R5 and R5SUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = mean-spring-mean
Origin subestuary = 6 (SWI, Southwestern Intertidal)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 7.07m/s
SW 8.86m/s
SE 6.04m/s
NE 7.29m/s
CALM 0
1.0
0.5
0.0
SINK
DEEP CHANNELS
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r5 br 06 .grf

Figure 108



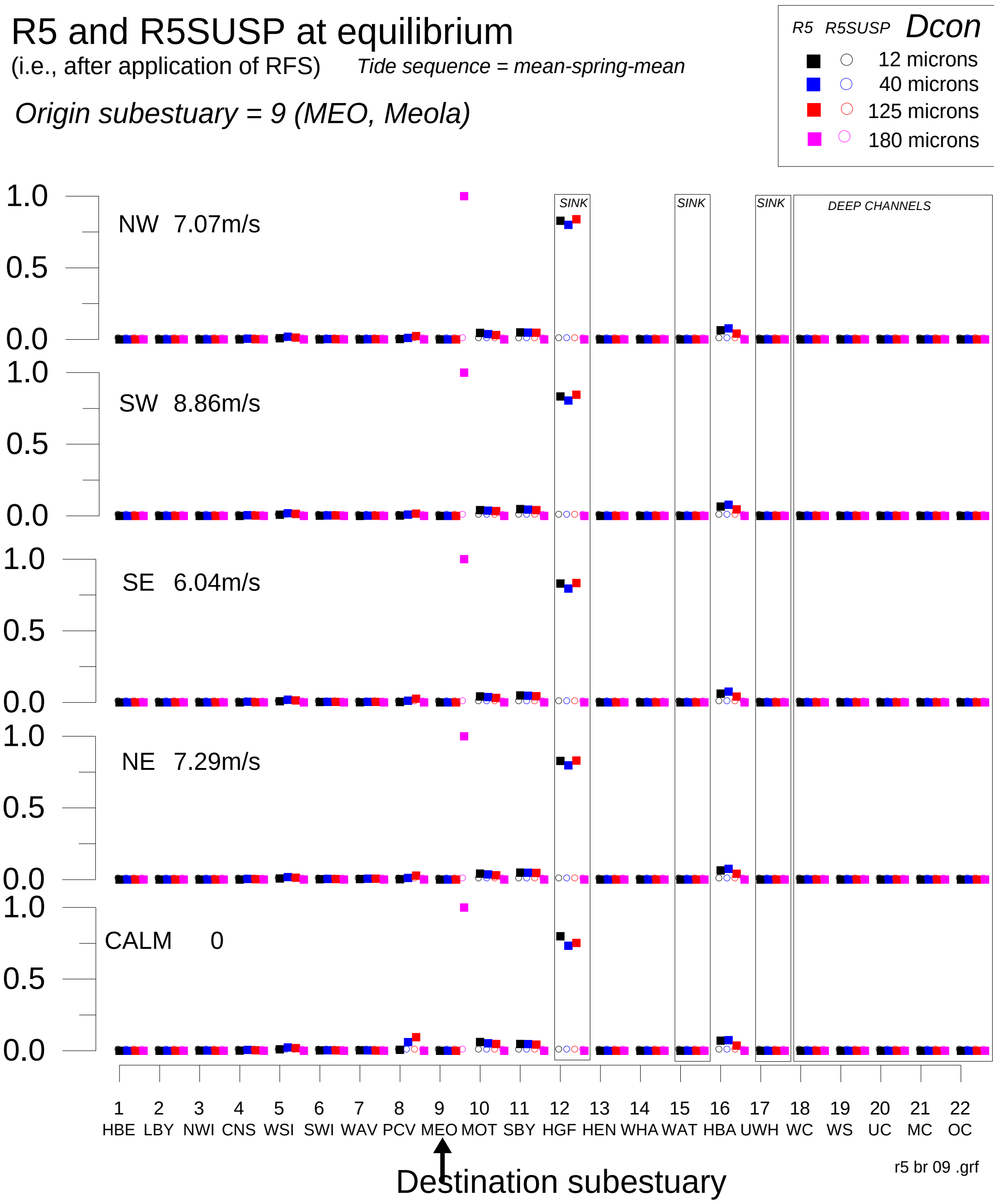
R5 and R5SUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = mean-spring-mean
Origin subestuary = 7 (WAV, Waterview)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 7.07m/s
SW 8.86m/s
SE 6.04m/s
NE 7.29m/s
CALM 0
SINK
SINK
SINK
DEEP CHANNELS
1.0
0.5
0.0
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r5 br 07 .grf

Figure 109



R5 and R5SUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = mean-spring-mean
Origin subestuary = 8 (PCV, Point Chevalier)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
1.0
0.5
0.0
NW 7.07m/s
SW 8.86m/s
SE 6.04m/s
NE 7.29m/s
CALM 0
SINK
SINK
SINK
DEEP CHANNELS
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r5 br 08 .grf

Figure 110



R5 and R5SUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = mean-spring-mean
Origin subestuary = 9 (MEO, Meola)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 7.07m/s
SW 8.86m/s
SE 6.04m/s
NE 7.29m/s
CALM 0
SINK
SINK
SINK
DEEP CHANNELS
1.0
0.5
0.0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22
HBE LBY NWI CNS WSI SWI WAV PCV MEO MOT SBY HGF HEN WHA WAT HBA UWH WC WS UC MC OC
Destination subestuary
r5 br 09 .grf

**Figure 111**

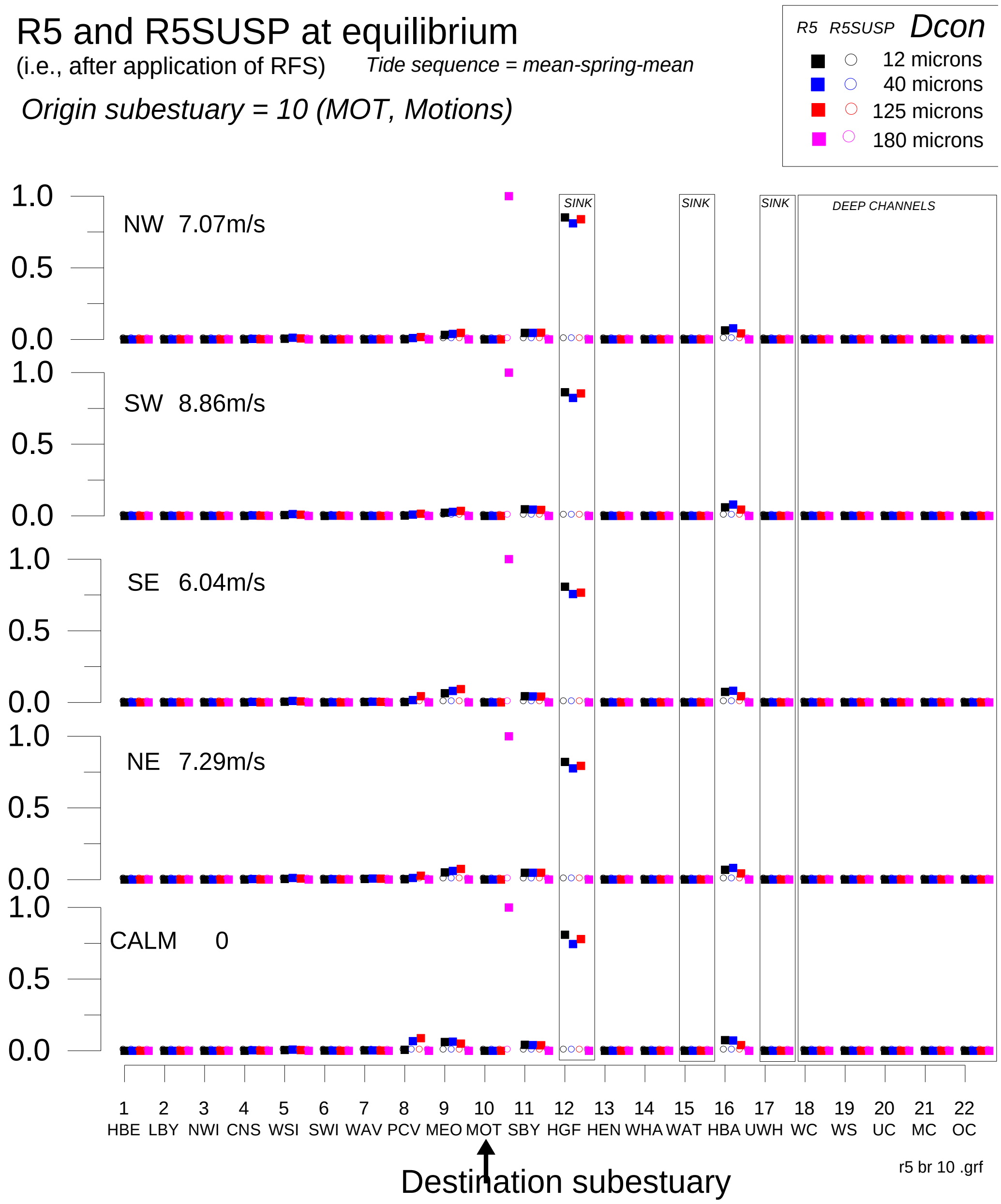

R5 and R5SUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = mean-spring-mean
Origin subestuary = 10 (MOT, Motions)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
1.0
0.5
0.0
NW 7.07m/s
SW 8.86m/s
SE 6.04m/s
NE 7.29m/s
CALM 0
SINK
SINK
SINK
DEEP CHANNELS
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22
HBE LBY NWI CNS WSI SWI WAV PCV MEO MOT SBY HGF HEN WHA WAT HBA UWH WC WS UC MC OC
Destination subestuary
r5 br 10 .grf

Figure 112

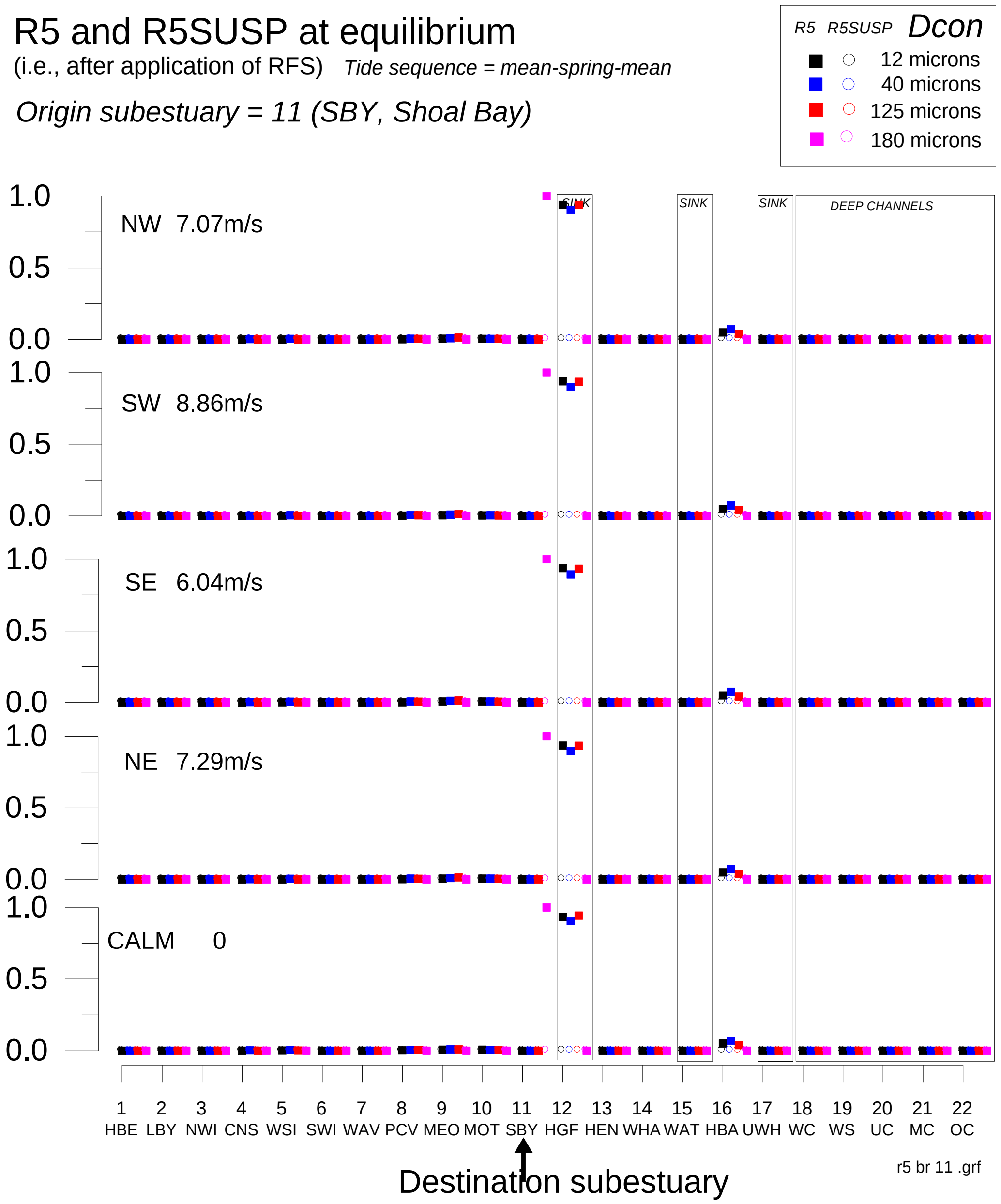

R5 and R5SUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = mean-spring-mean
Origin subestuary = 11 (SBY, Shoal Bay)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 7.07m/s
SW 8.86m/s
SE 6.04m/s
NE 7.29m/s
CALM 0
SINK
SINK
SINK
DEEP CHANNELS
1.0
0.5
0.0
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r5 br 11 .grf

**Figure 113**

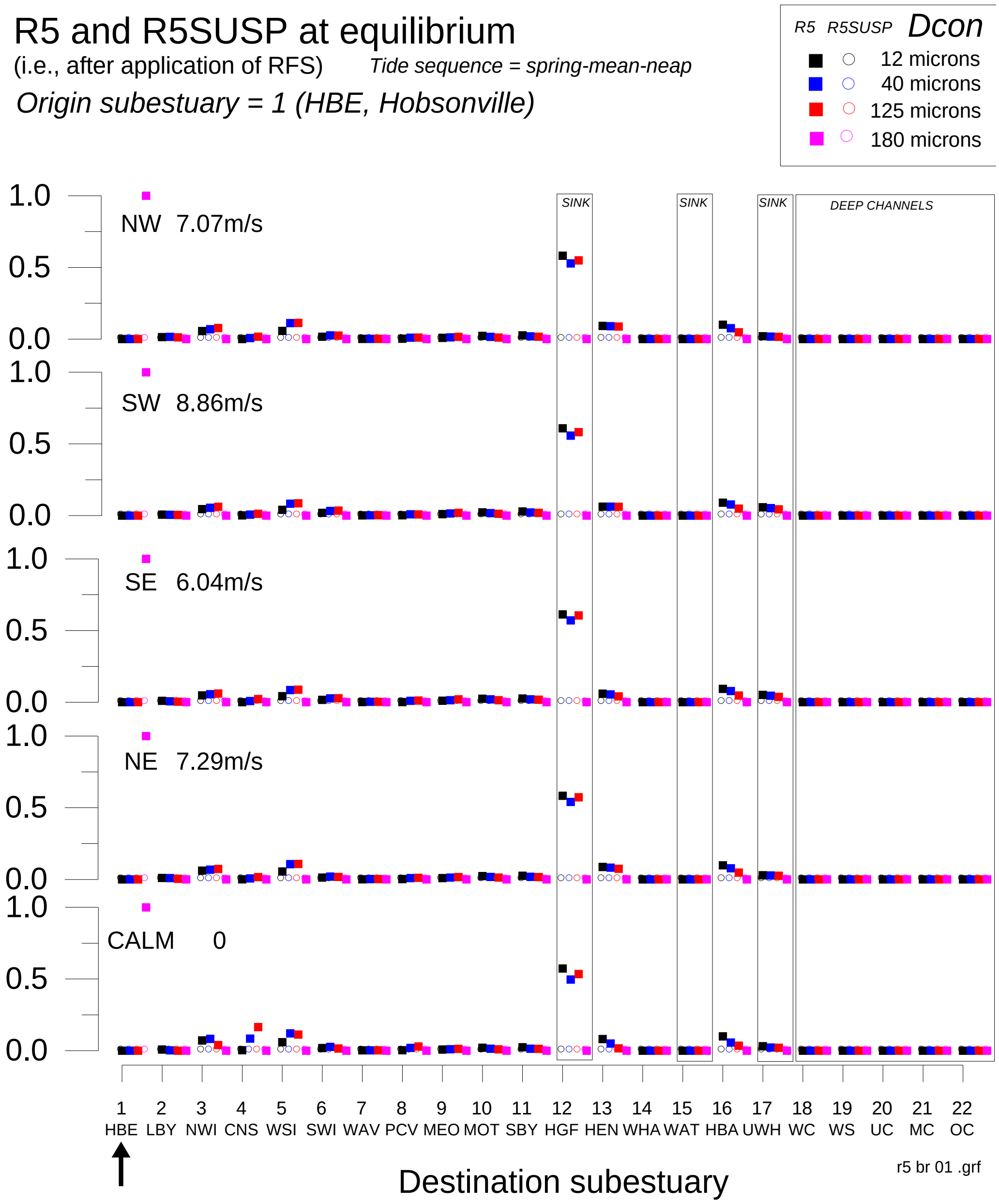

R5 and R5SUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = spring-mean-neap
Origin subestuary = 1 (HBE, Hobsonville)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 7.07m/s
SW 8.86m/s
SE 6.04m/s
NE 7.29m/s
CALM 0
SINK
SINK
SINK
DEEP CHANNELS
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r5 br 01 .grf

Figure 114

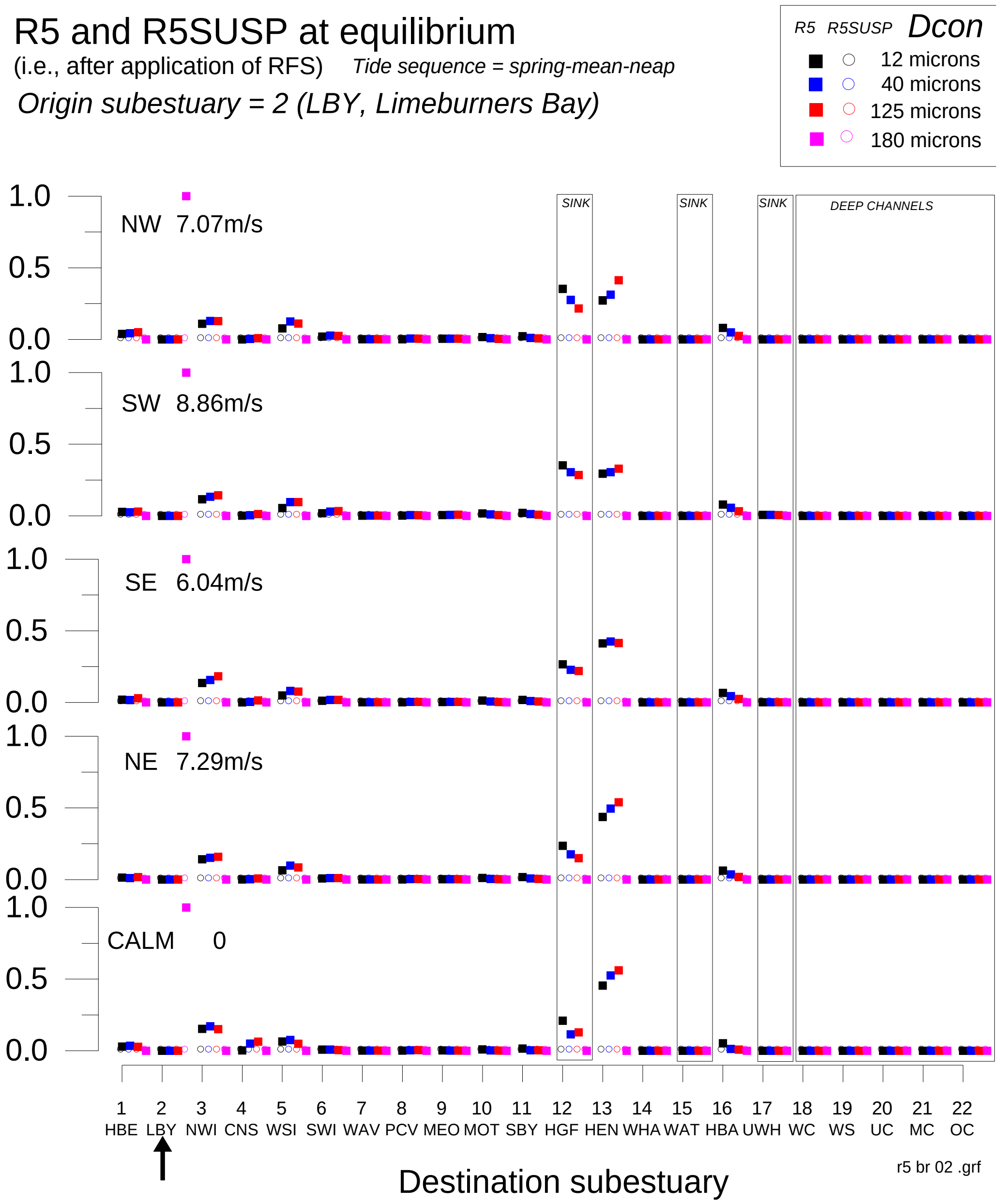

R5 and R5SUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = spring-mean-neap
Origin subestuary = 2 (LBY, Limeburners Bay)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 7.07m/s
SW 8.86m/s
SE 6.04m/s
NE 7.29m/s
CALM 0
1.0
0.5
0.0
SINK
SINK
SINK
DEEP CHANNELS
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r5 br 02 .grf

**Figure 115**

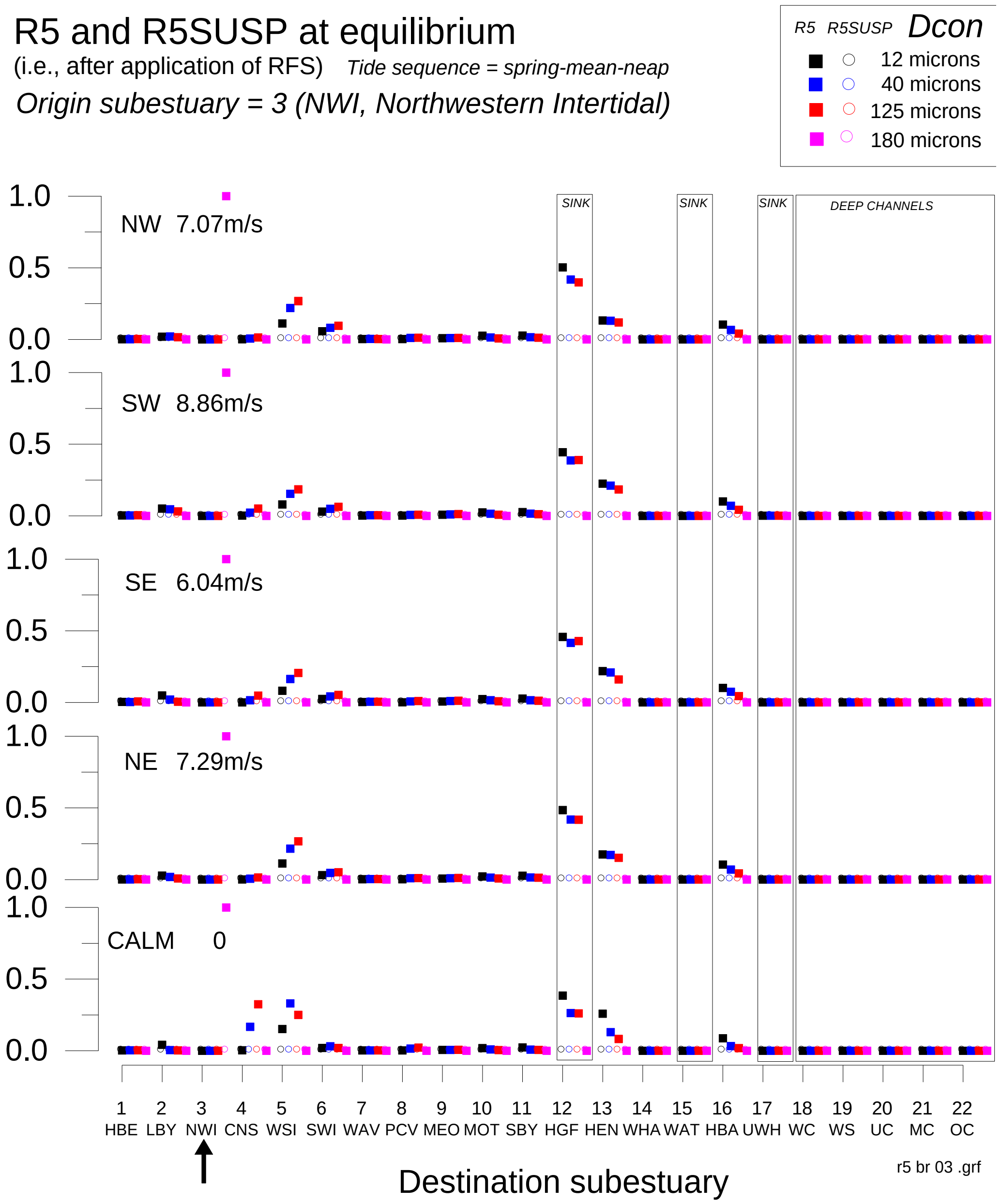

R5 and R5SUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = spring-mean-neap
Origin subestuary = 3 (NWI, Northwestern Intertidal)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 7.07m/s
SW 8.86m/s
SE 6.04m/s
NE 7.29m/s
CALM 0
1.0
0.5
0.0
SINK
SINK
SINK
DEEP CHANNELS
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r5 br 03 .grf

Figure 116

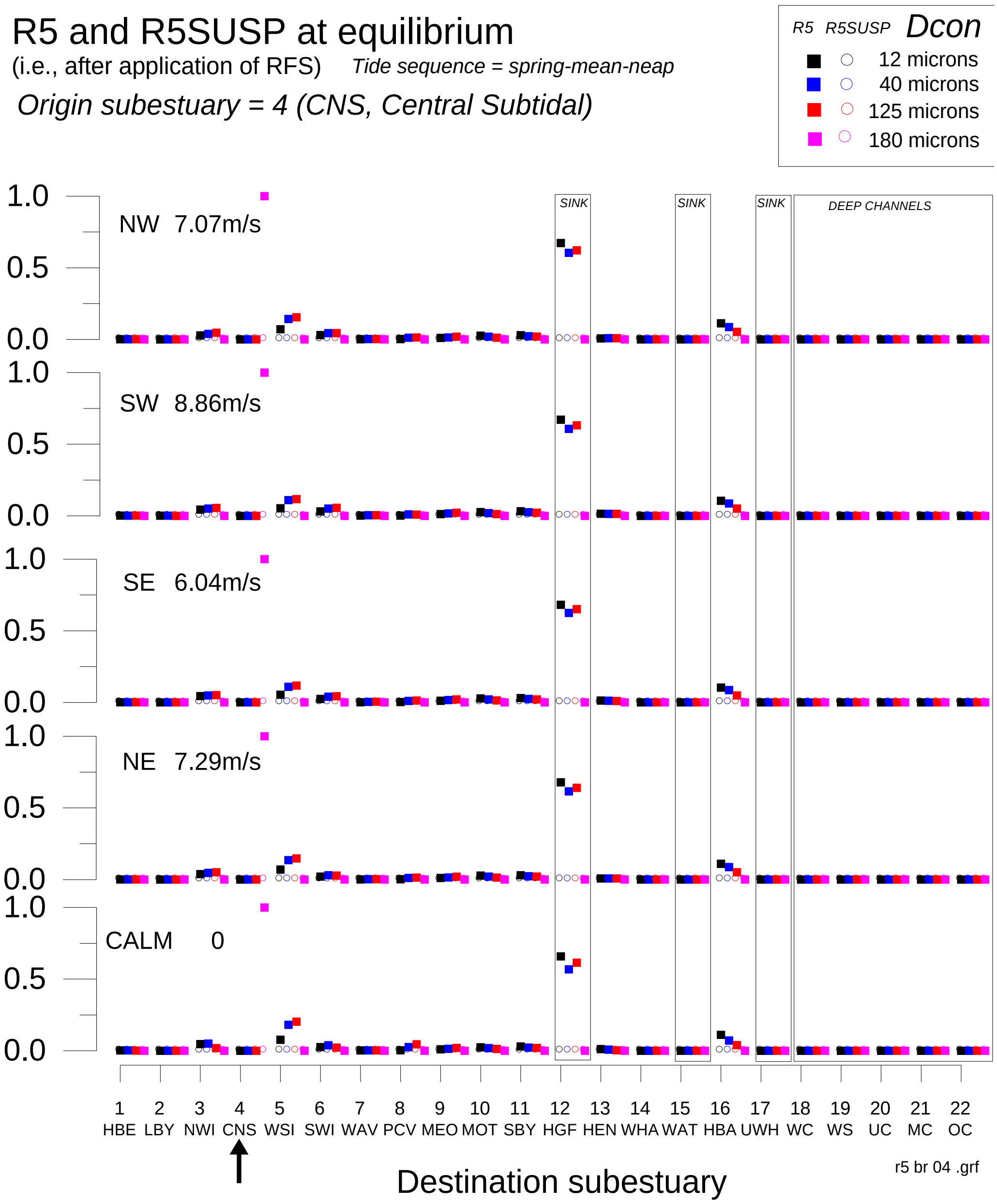
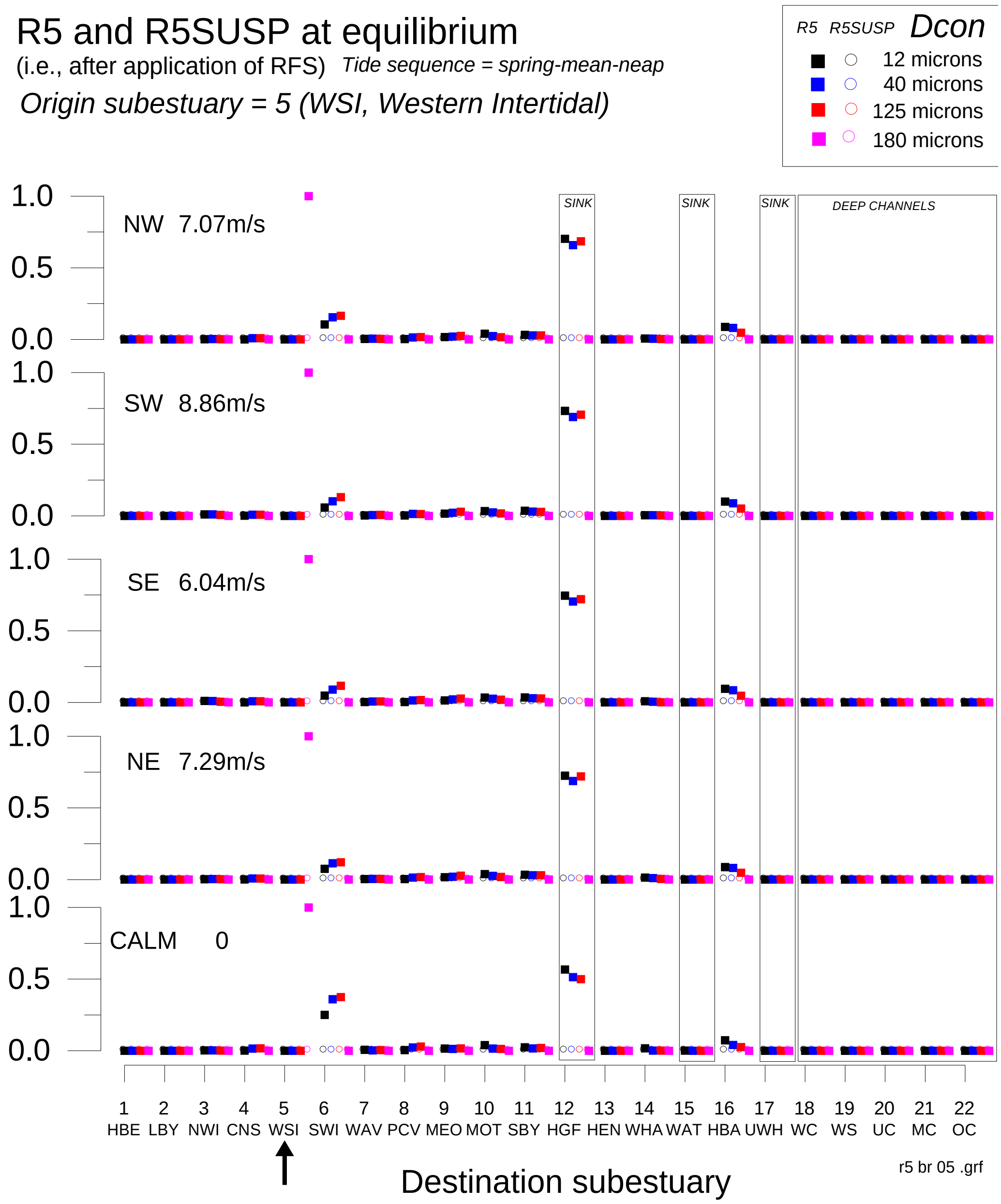
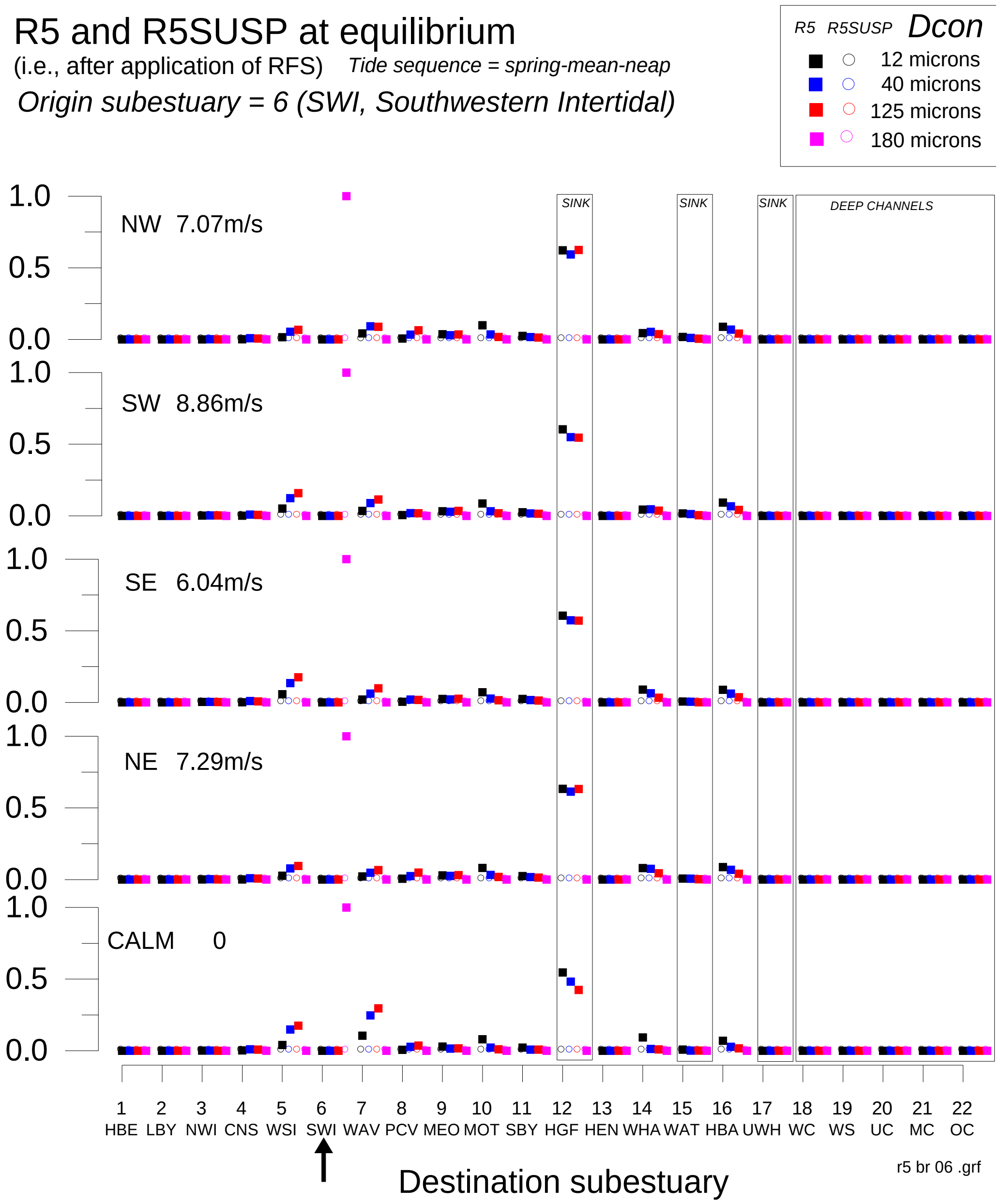

R5 and R5SUSP at equilibrium
(i.e., after application of RFS) Tide sequence = spring-mean-neap
Origin subestuary = 4 (CNS, Central Subtidal)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 7.07m/s
SW 8.86m/s
SE 6.04m/s
NE 7.29m/s
CALM 0
1.0
0.5
0.0
SINK
SINK
SINK
DEEP CHANNELS
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r5 br 04 .grf

Figure 117



R5 and R5SUSP at equilibrium
(i.e., after application of RFS) Tide sequence = spring-mean-neap
Origin subestuary = 5 (WSI, Western Intertidal)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 7.07m/s
SW 8.86m/s
SE 6.04m/s
NE 7.29m/s
CALM 0
1.0
0.5
0.0
SINK
SINK
SINK
DEEP CHANNELS
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r5 br 05 .grf

Figure 118



R5 and R5SUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = spring-mean-neap
Origin subestuary = 6 (SWI, Southwestern Intertidal)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 7.07m/s
SW 8.86m/s
SE 6.04m/s
NE 7.29m/s
CALM 0
1.0
0.5
0.0
SINK
SINK
SINK
DEEP CHANNELS
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r5 br 06 .grf

Figure 119

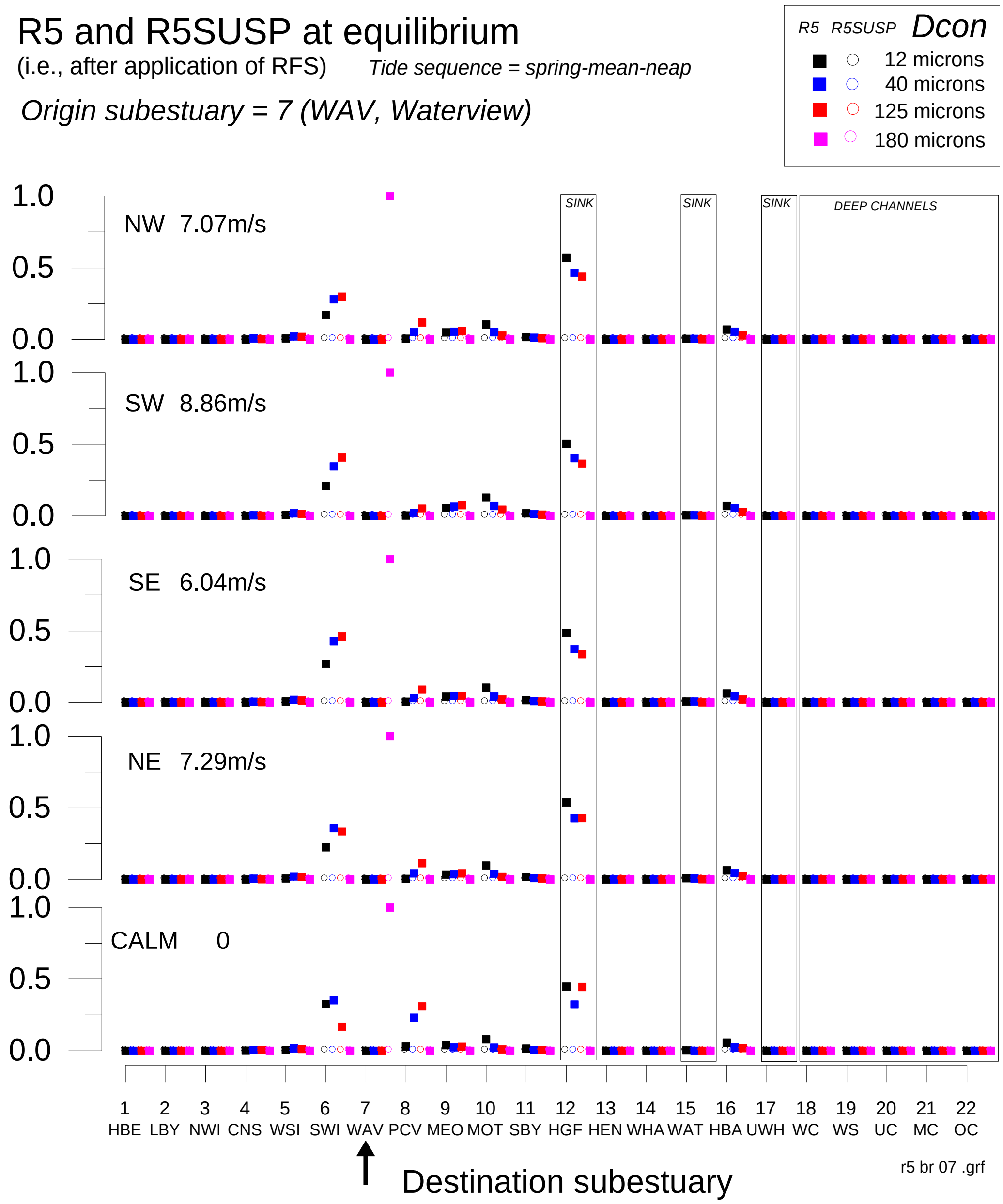

R5 and R5SUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = spring-mean-neap
Origin subestuary = 7 (WAV, Waterview)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 7.07m/s
SW 8.86m/s
SE 6.04m/s
NE 7.29m/s
CALM 0
1.0
0.5
0.0
SINK
SINK
SINK
DEEP CHANNELS
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r5 br 07 .grf

Figure 120

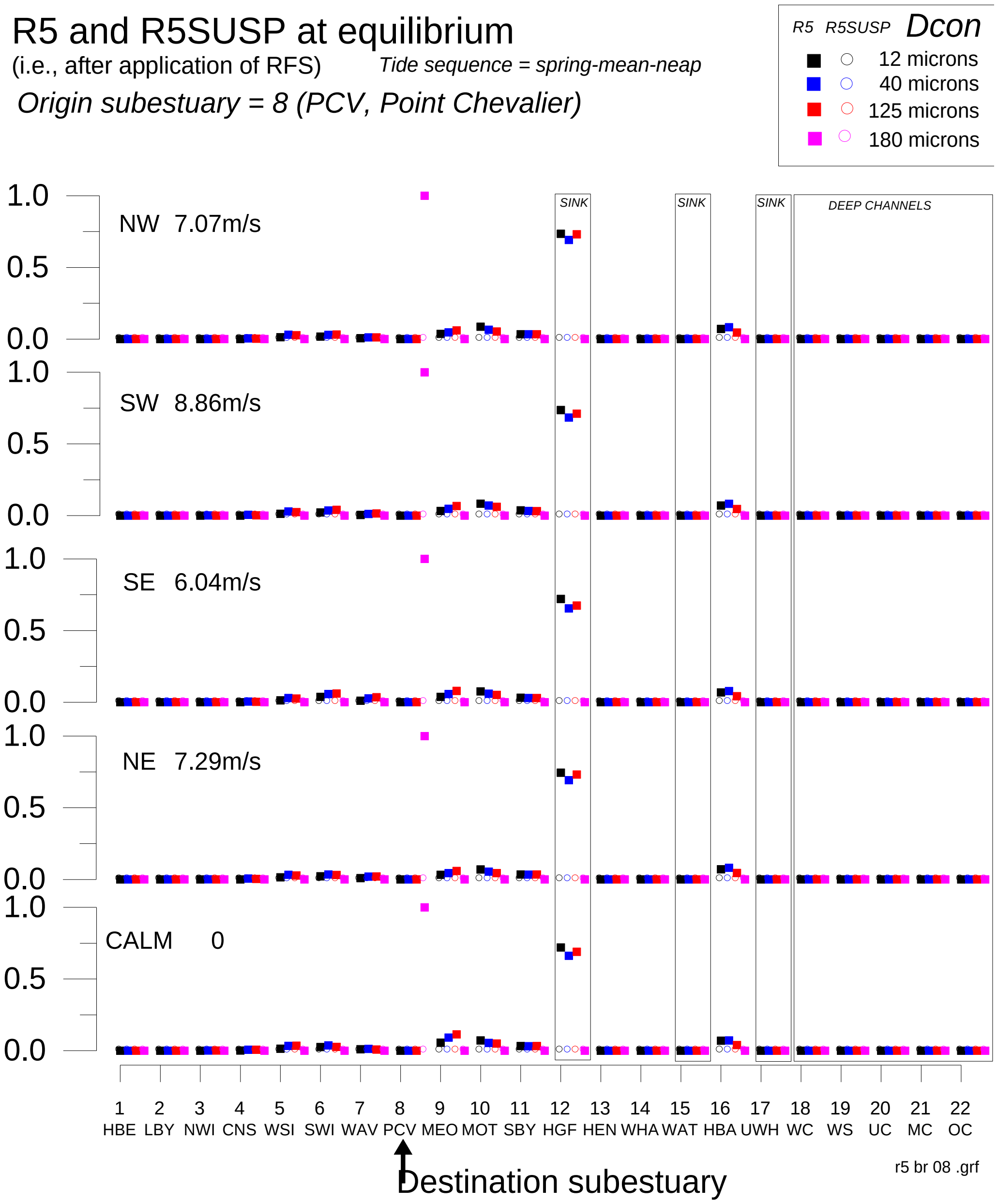

R5 and R5SUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = spring-mean-neap
Origin subestuary = 8 (PCV, Point Chevalier)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 7.07m/s
SW 8.86m/s
SE 6.04m/s
NE 7.29m/s
CALM 0
1.0
0.5
0.0
SINK
SINK
SINK
DEEP CHANNELS
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22
HBE LBY NWI CNS WSI SWI WAV PCV MEO MOT SBY HGF HEN WHA WAT HBA UWH WC WS UC MC OC
Destination subestuary
r5 br 08 .grf

Figure 121

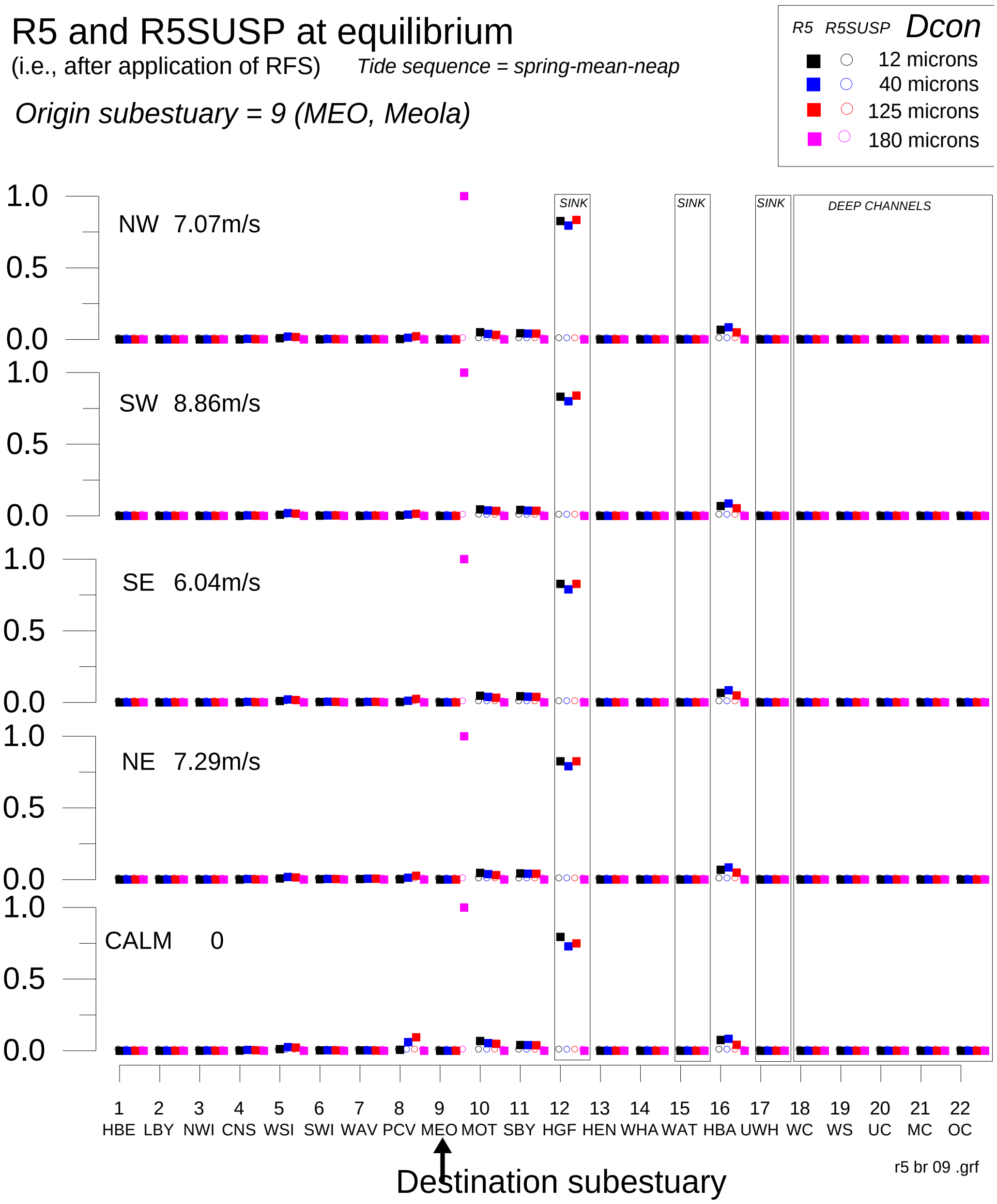

R5 and R5SUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = spring-mean-neap
Origin subestuary = 9 (MEO, Meola)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 7.07m/s
SW 8.86m/s
SE 6.04m/s
NE 7.29m/s
CALM 0
SINK
SINK
SINK
DEEP CHANNELS
1.0
0.5
0.0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22
HBE LBY NWI CNS WSI SWI WAV PCV MEO MOT SBY HGF HEN WHA WAT HBA UWH WC WS UC MC OC
Destination subestuary
r5 br 09 .grf

Figure 122

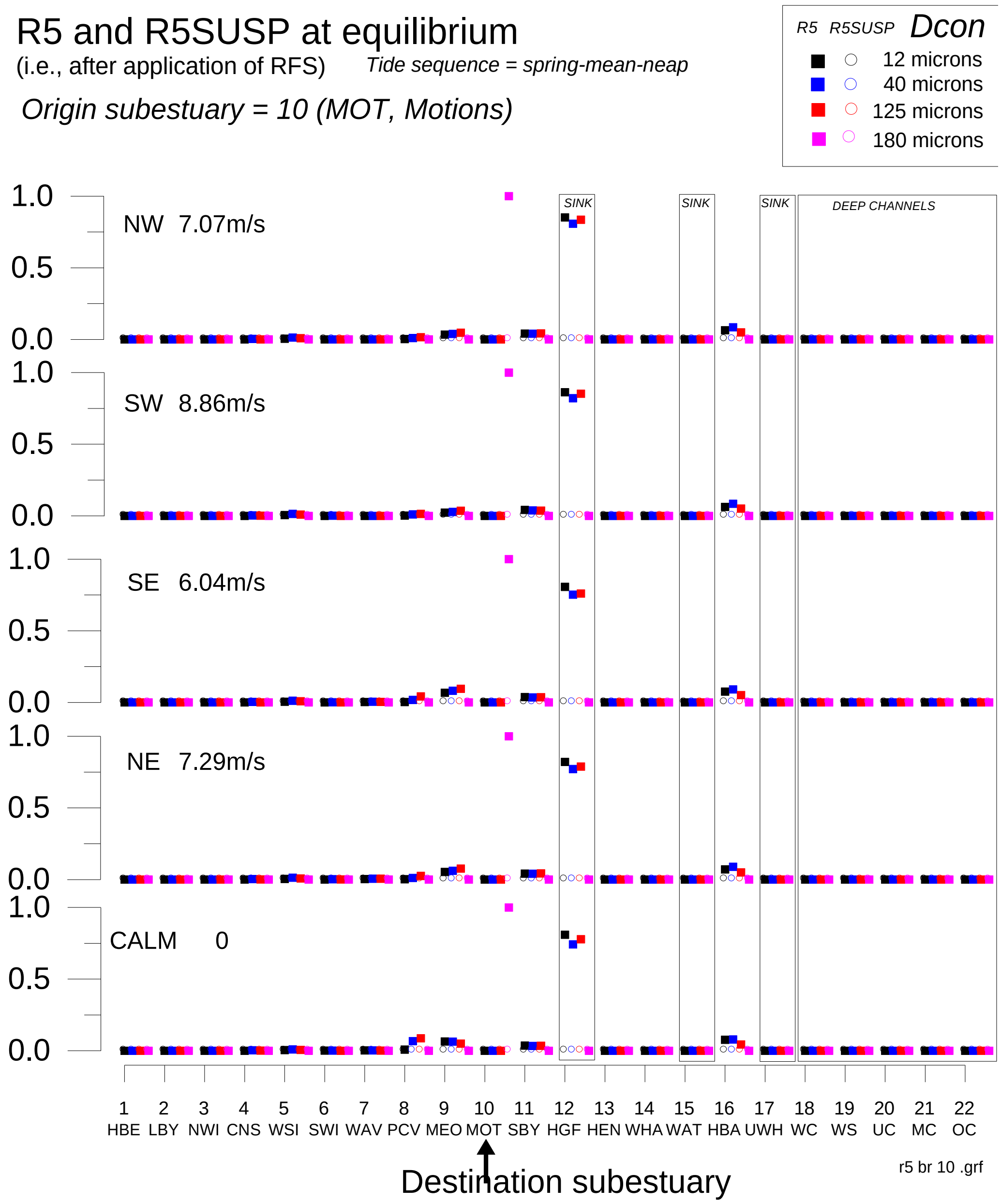

R5 and R5SUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = spring-mean-neap
Origin subestuary = 10 (MOT, Motions)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 7.07m/s
SW 8.86m/s
SE 6.04m/s
NE 7.29m/s
CALM 0
1.0
0.5
0.0
SINK
SINK
SINK
DEEP CHANNELS
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r5 br 10 .grf

**Figure 123**

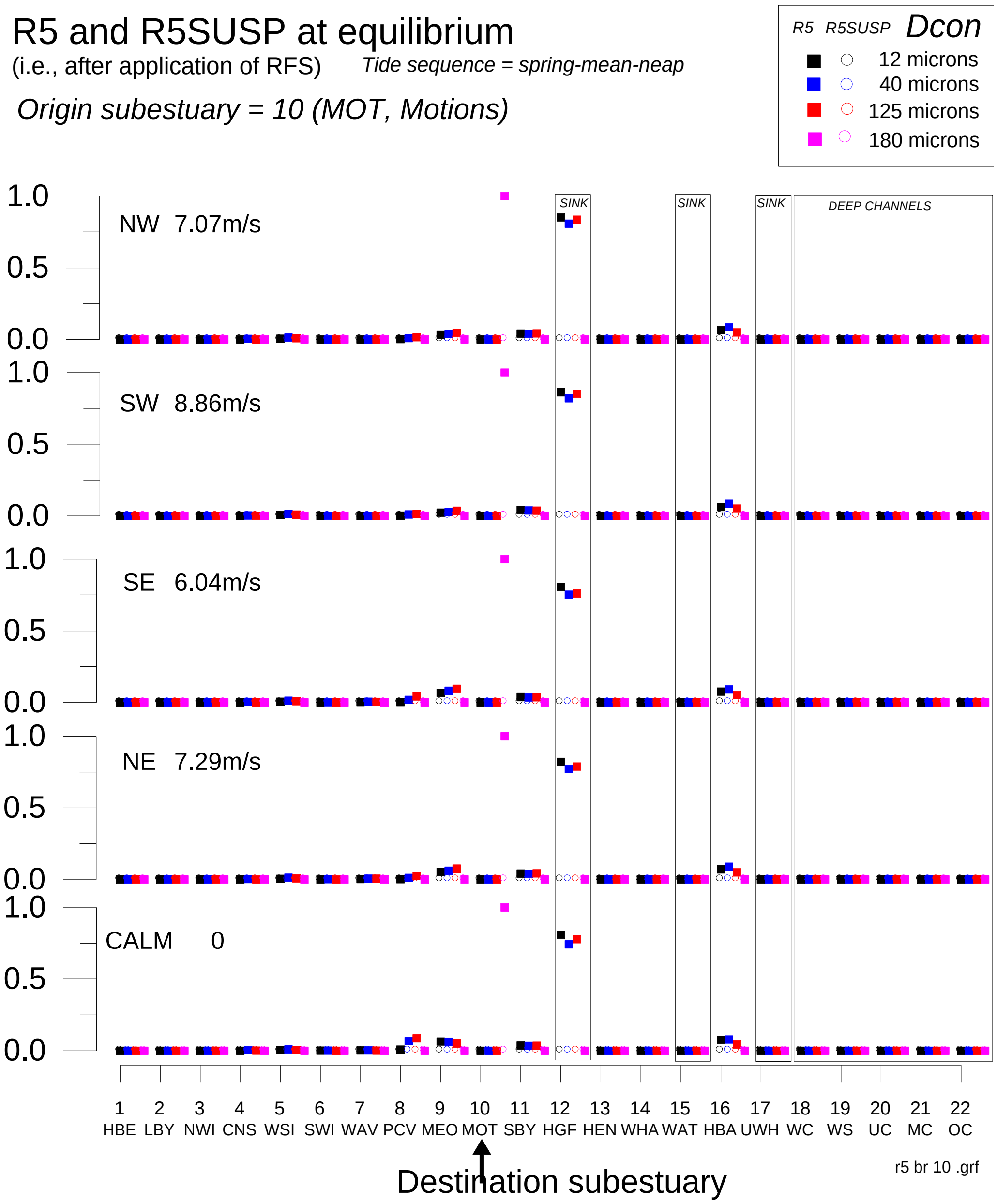

R5 and R5SUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = spring-mean-neap
Origin subestuary = 10 (MOT, Motions)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
SINK
SINK
SINK
DEEP CHANNELS
1.0
0.5
0.0
NW 7.07m/s
SW 8.86m/s
SE 6.04m/s
NE 7.29m/s
CALM 0
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r5 br 10 .grf

**Figure 124**

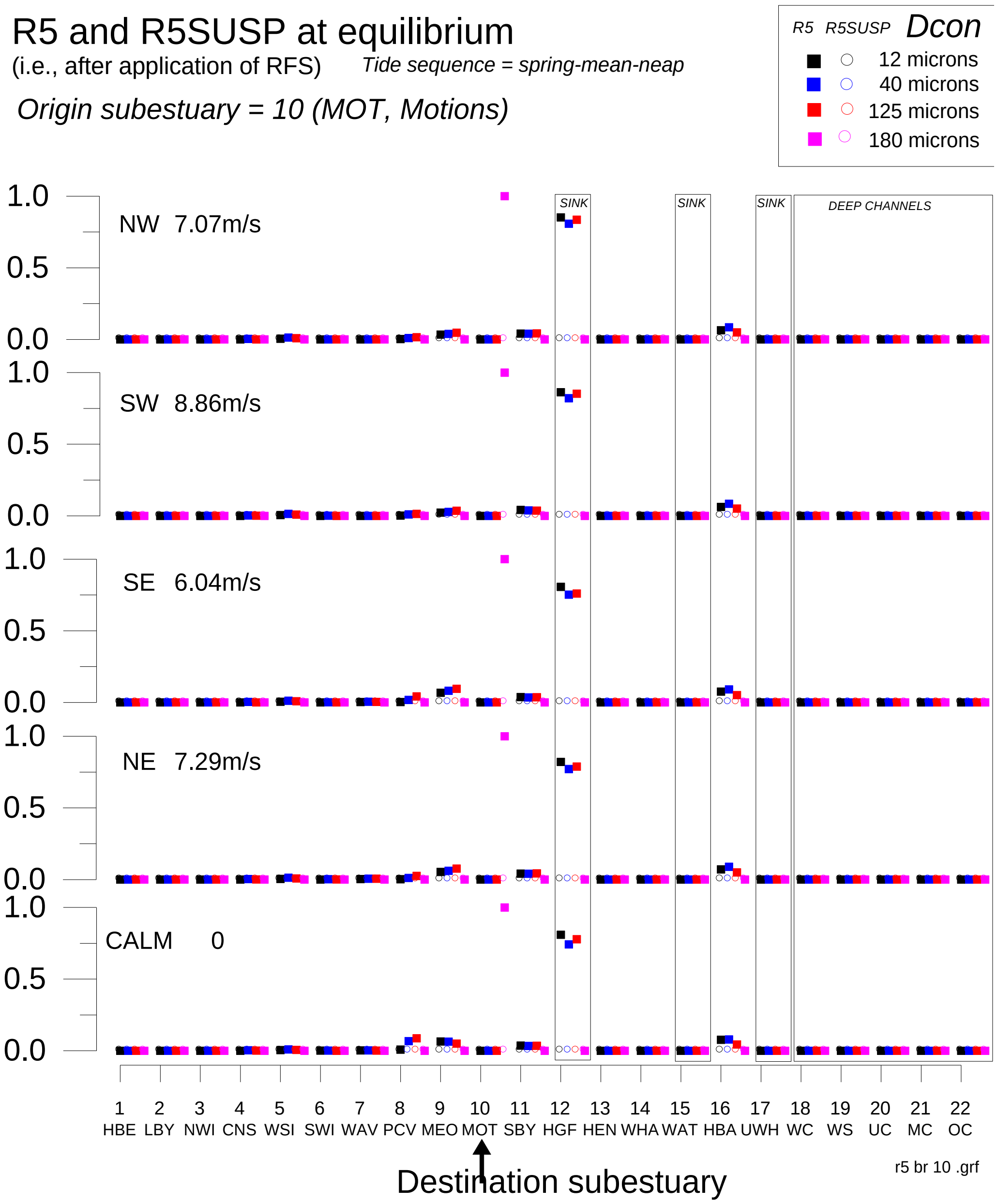

R5 and R5SUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = spring-mean-neap
Origin subestuary = 10 (MOT, Motions)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 7.07m/s
SW 8.86m/s
SE 6.04m/s
NE 7.29m/s
CALM 0
1.0
0.5
0.0
SINK
SINK
SINK
DEEP CHANNELS
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r5 br 10 .grf

Figure 125

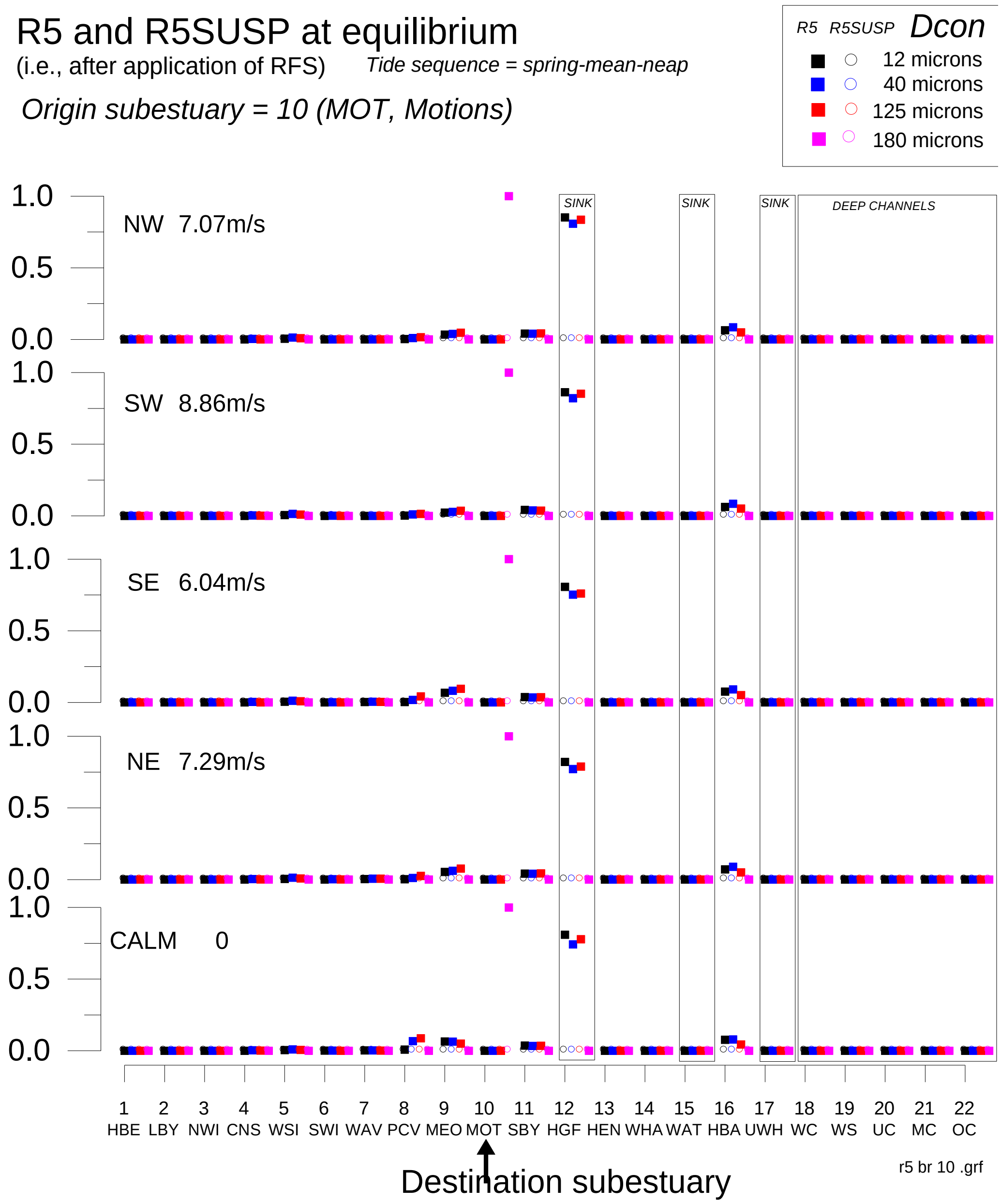

R5 and R5SUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = spring-mean-neap
Origin subestuary = 10 (MOT, Motions)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 7.07m/s
SW 8.86m/s
SE 6.04m/s
NE 7.29m/s
CALM 0
SINK
SINK
SINK
DEEP CHANNELS
1.0
0.5
0.0
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r5 br 10 .grf

Figure 126

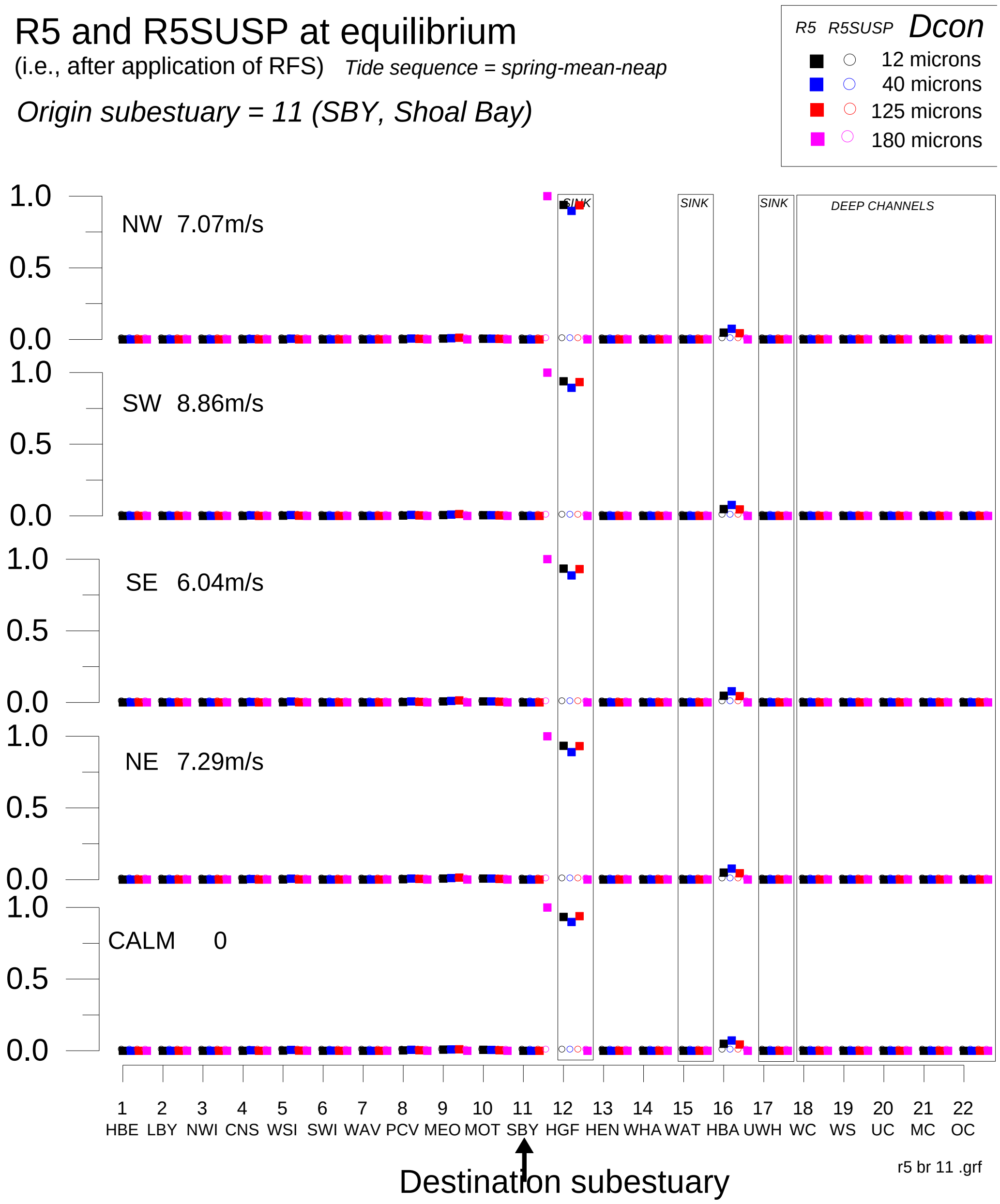

R5 and R5SUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = spring-mean-neap
Origin subestuary = 11 (SBY, Shoal Bay)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
SINK
SINK
SINK
DEEP CHANNELS
NW 7.07m/s
SW 8.86m/s
SE 6.04m/s
NE 7.29m/s
CALM 0
1.0
0.5
0.0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22
HBE LBY NWI CNS WSI SWI WAV PCV MEO MOT SBY HGF HEN WHA WAT HBA UWH WC WS UC MC OC
Destination subestuary
r5 br 11 .grf

**Figure 127**

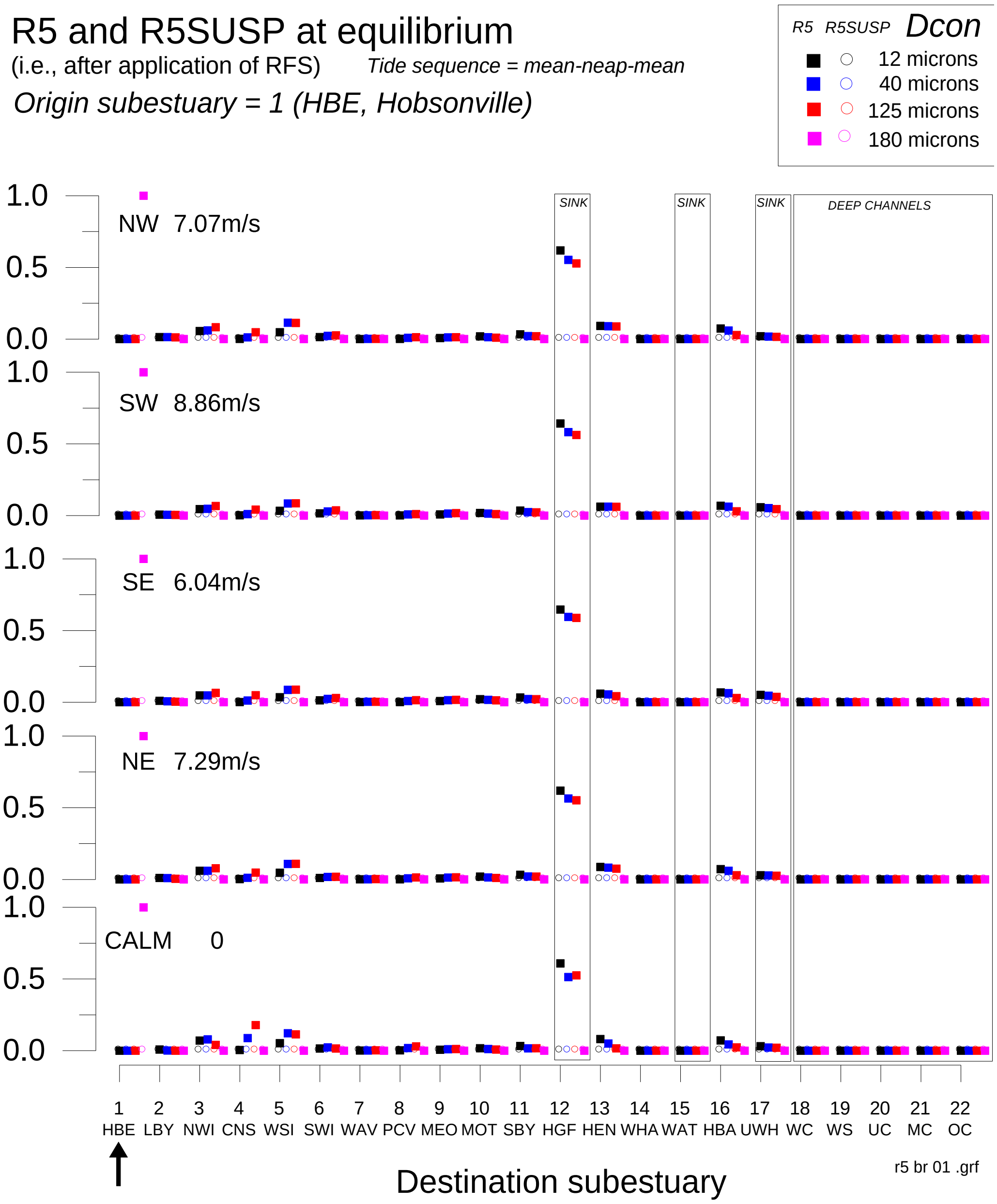

R5 and R5SUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = mean-neap-mean
Origin subestuary = 1 (HBE, Hobsonville)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 7.07m/s
SW 8.86m/s
SE 6.04m/s
NE 7.29m/s
CALM 0
SINK
SINK
SINK
DEEP CHANNELS
1.0
0.5
0.0
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r5 br 01 .grf

Figure 128

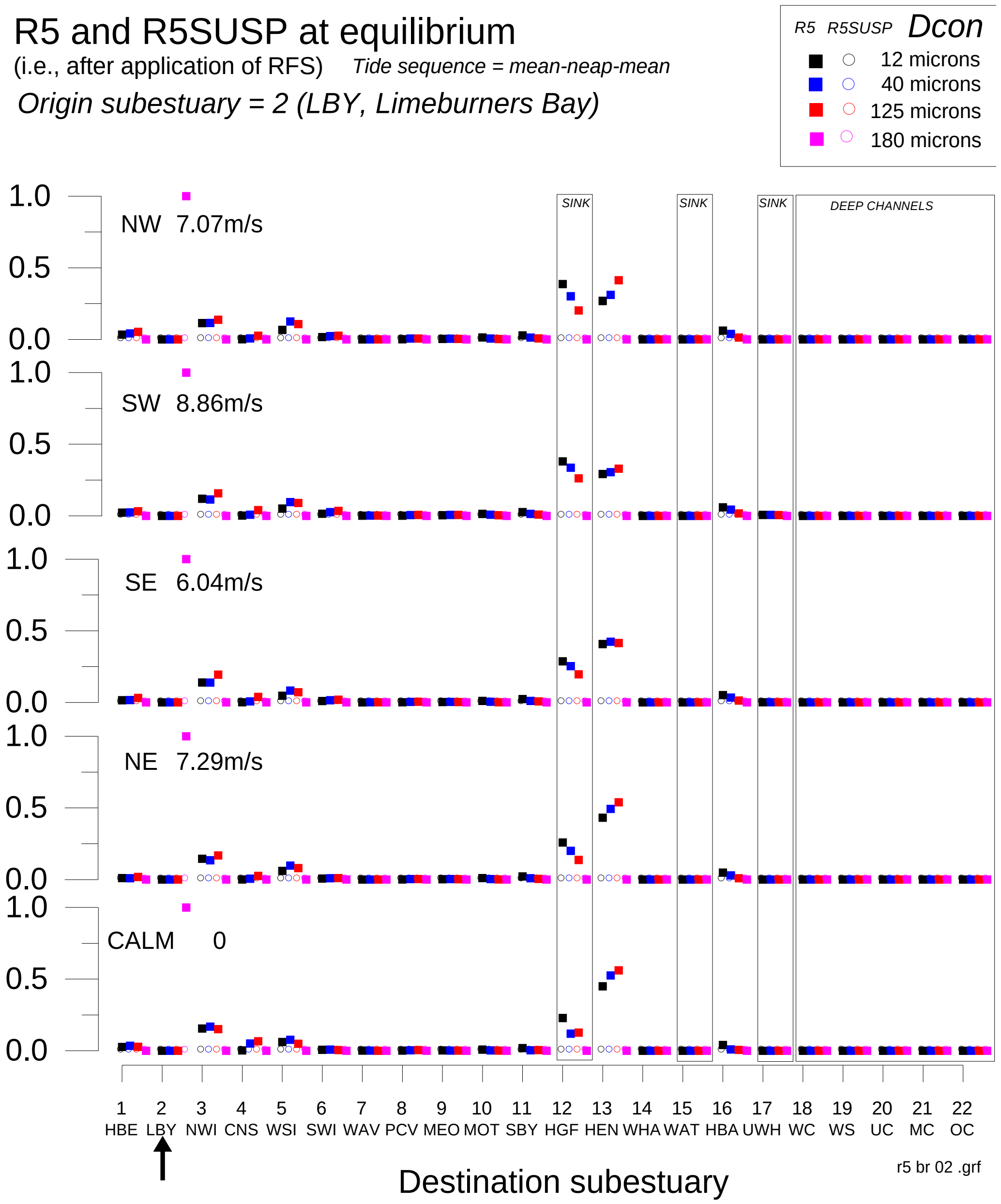

R5 and R5SUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = mean-neap-mean
Origin subestuary = 2 (LBY, Limeburners Bay)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 7.07m/s
SW 8.86m/s
SE 6.04m/s
NE 7.29m/s
CALM 0
SINK
SINK
SINK
DEEP CHANNELS
1.0
0.5
0.0
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r5 br 02 .grf

Figure 129

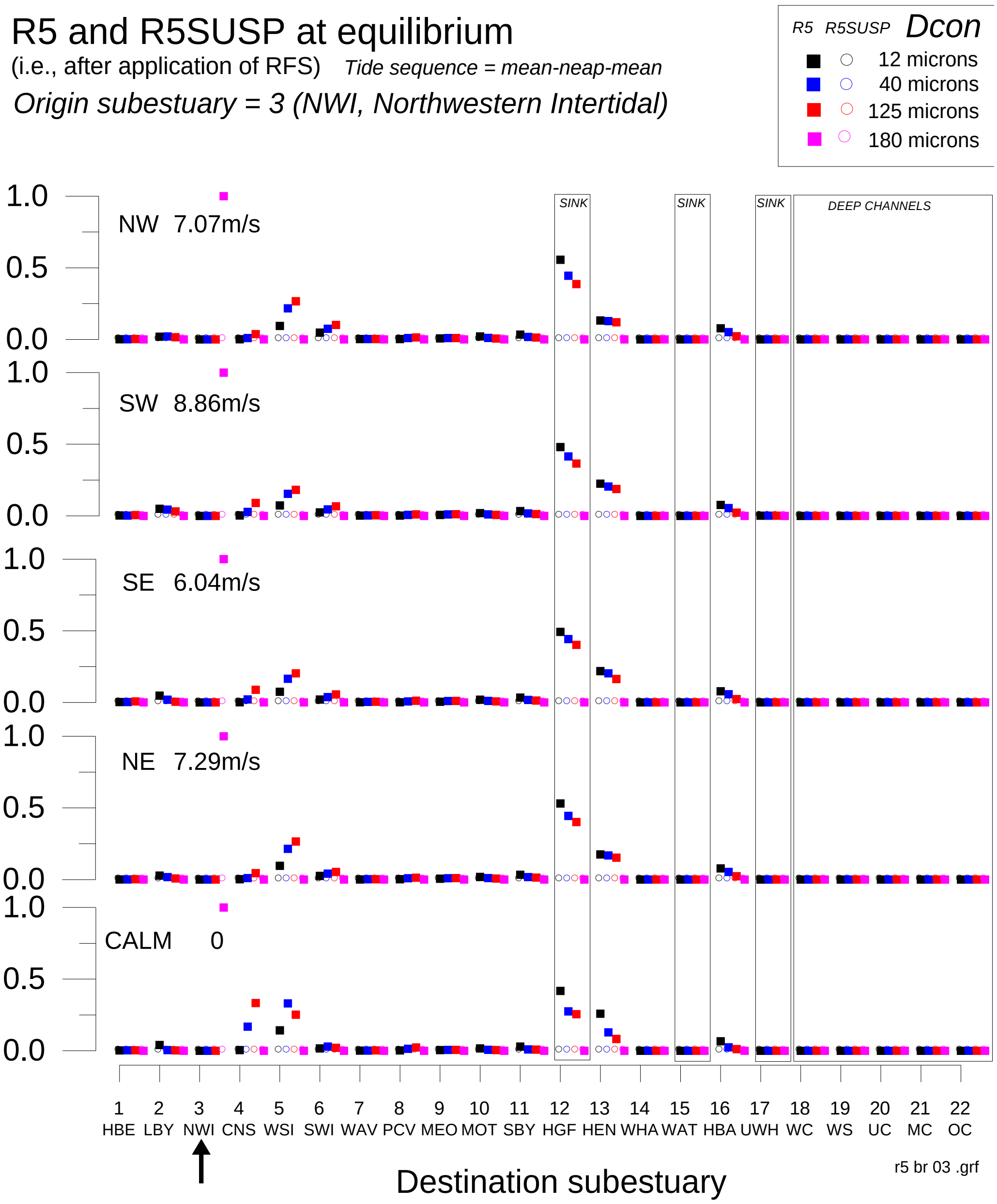

R5 and R5SUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = mean-neap-mean
Origin subestuary = 3 (NWI, Northwestern Intertidal)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 7.07m/s
SW 8.86m/s
SE 6.04m/s
NE 7.29m/s
CALM 0
SINK
SINK
SINK
DEEP CHANNELS
1.0
0.5
0.0
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r5 br 03 .grf

Figure 130

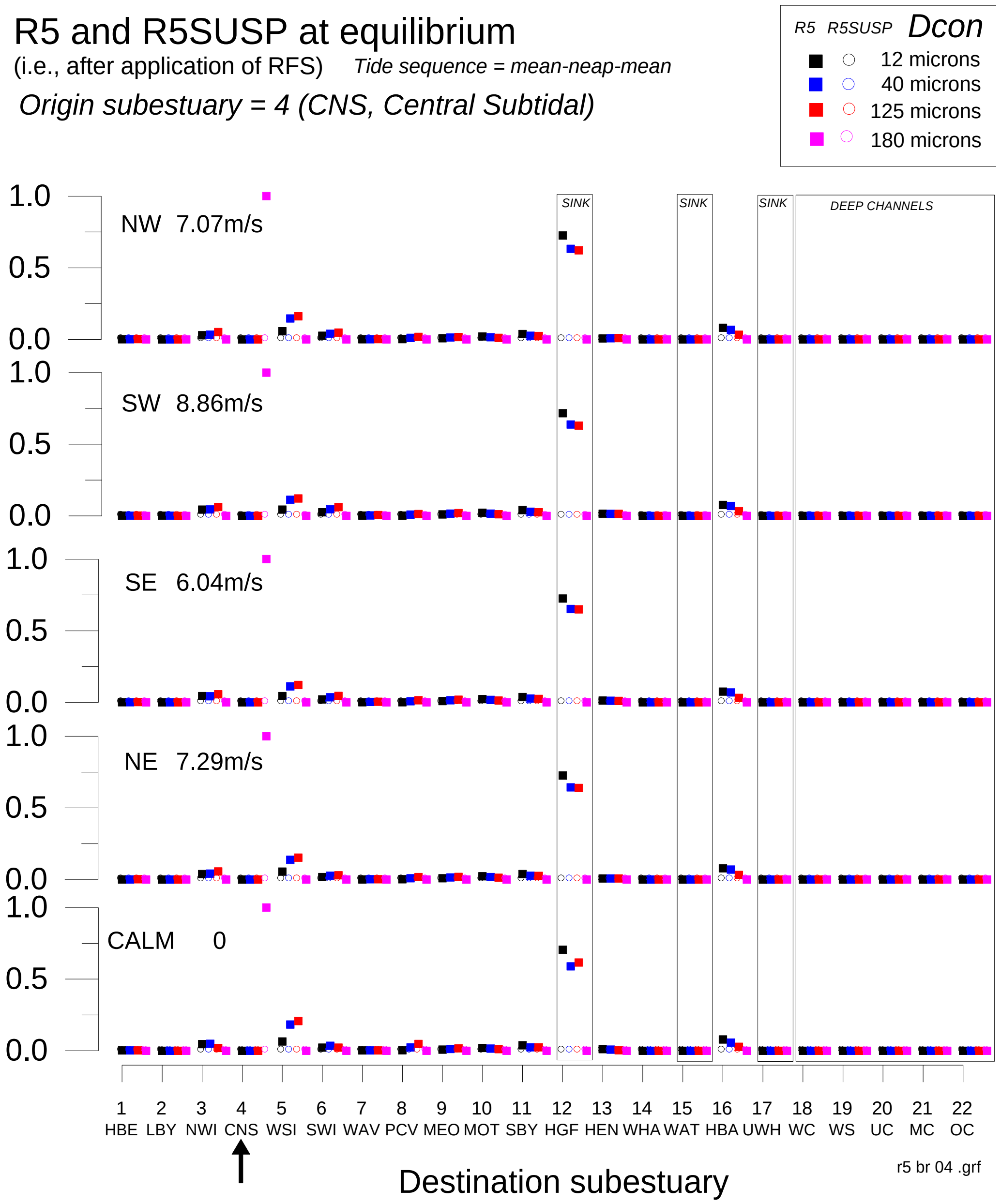
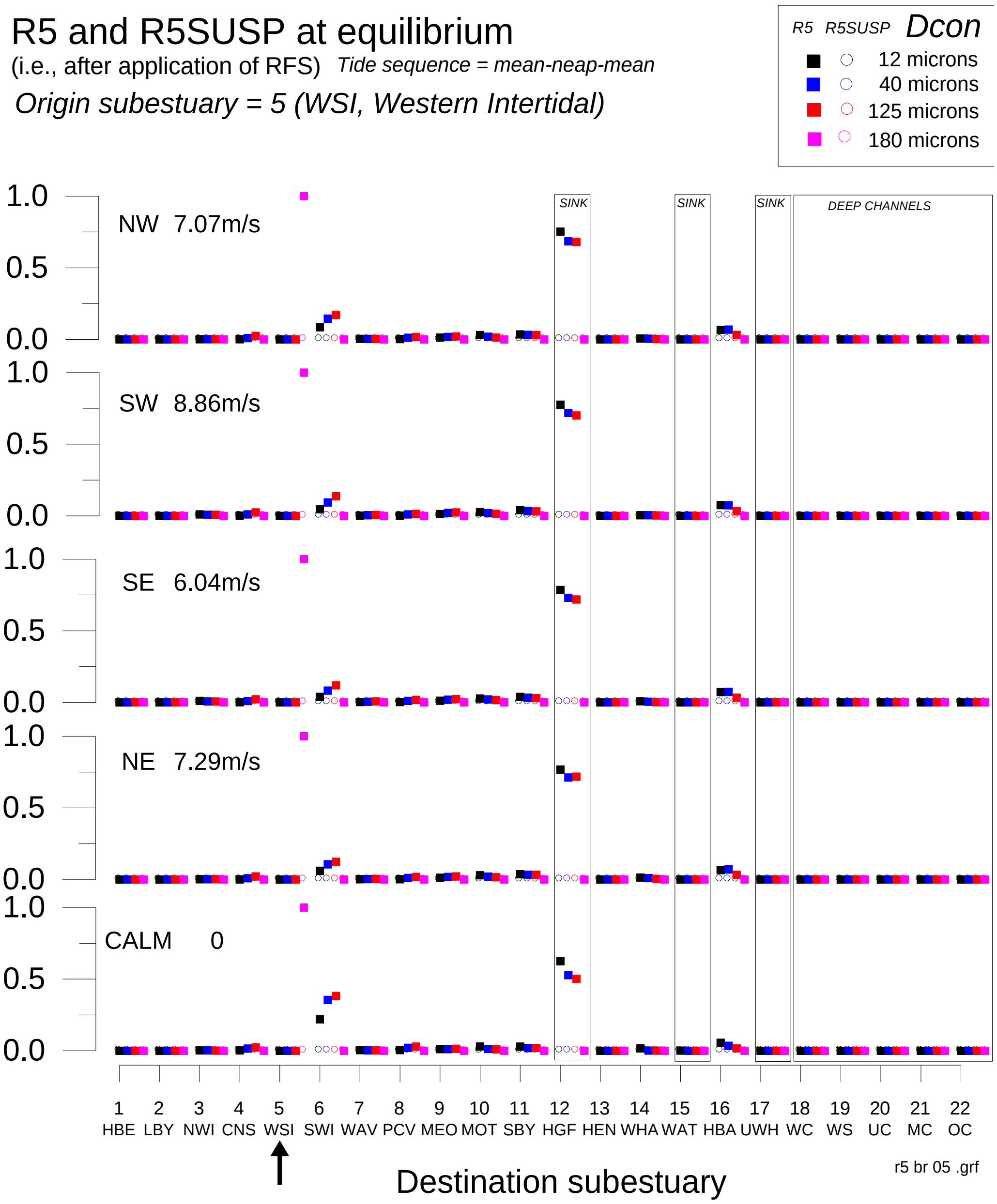
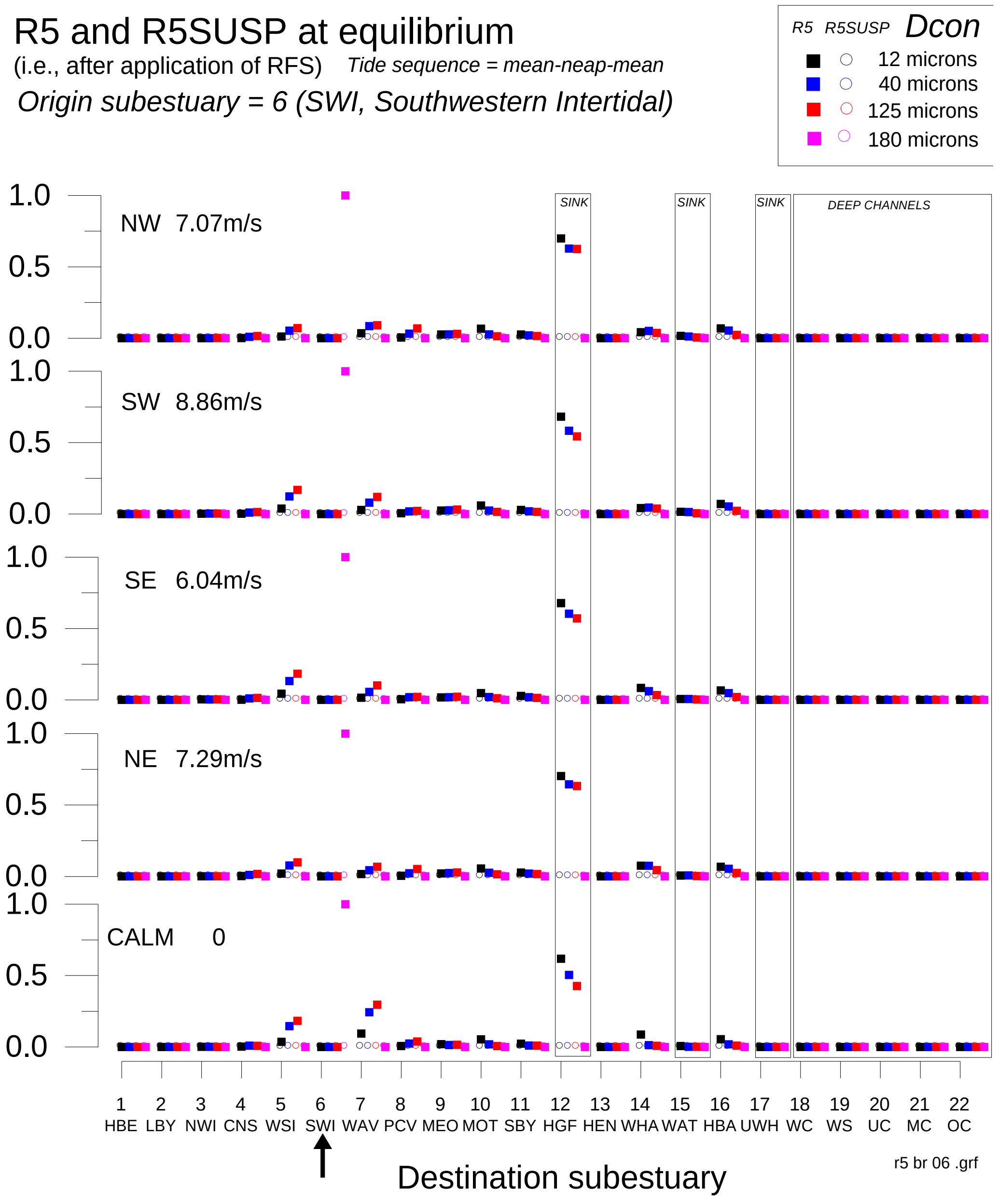

R5 and R5SUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = mean-neap-mean
Origin subestuary = 4 (CNS, Central Subtidal)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 7.07m/s
SW 8.86m/s
SE 6.04m/s
NE 7.29m/s
CALM 0
SINK
SINK
SINK
DEEP CHANNELS
1.0
0.5
0.0
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r5 br 04 .grf

Figure 131



R5 and R5SUSP at equilibrium
(i.e., after application of RFS) Tide sequence = mean-neap-mean
Origin subestuary = 5 (WSI, Western Intertidal)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
1.0
0.5
0.0
NW 7.07m/s
SW 8.86m/s
SE 6.04m/s
NE 7.29m/s
CALM 0
SINK
SINK
SINK
DEEP CHANNELS
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r5 br 05 .grf

Figure 132



R5 and R5SUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = mean-neap-mean
Origin subestuary = 6 (SWI, Southwestern Intertidal)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 7.07m/s
SW 8.86m/s
SE 6.04m/s
NE 7.29m/s
CALM 0
SINK
SINK
SINK
DEEP CHANNELS
1.0
0.5
0.0
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r5 br 06 .grf

Figure 133

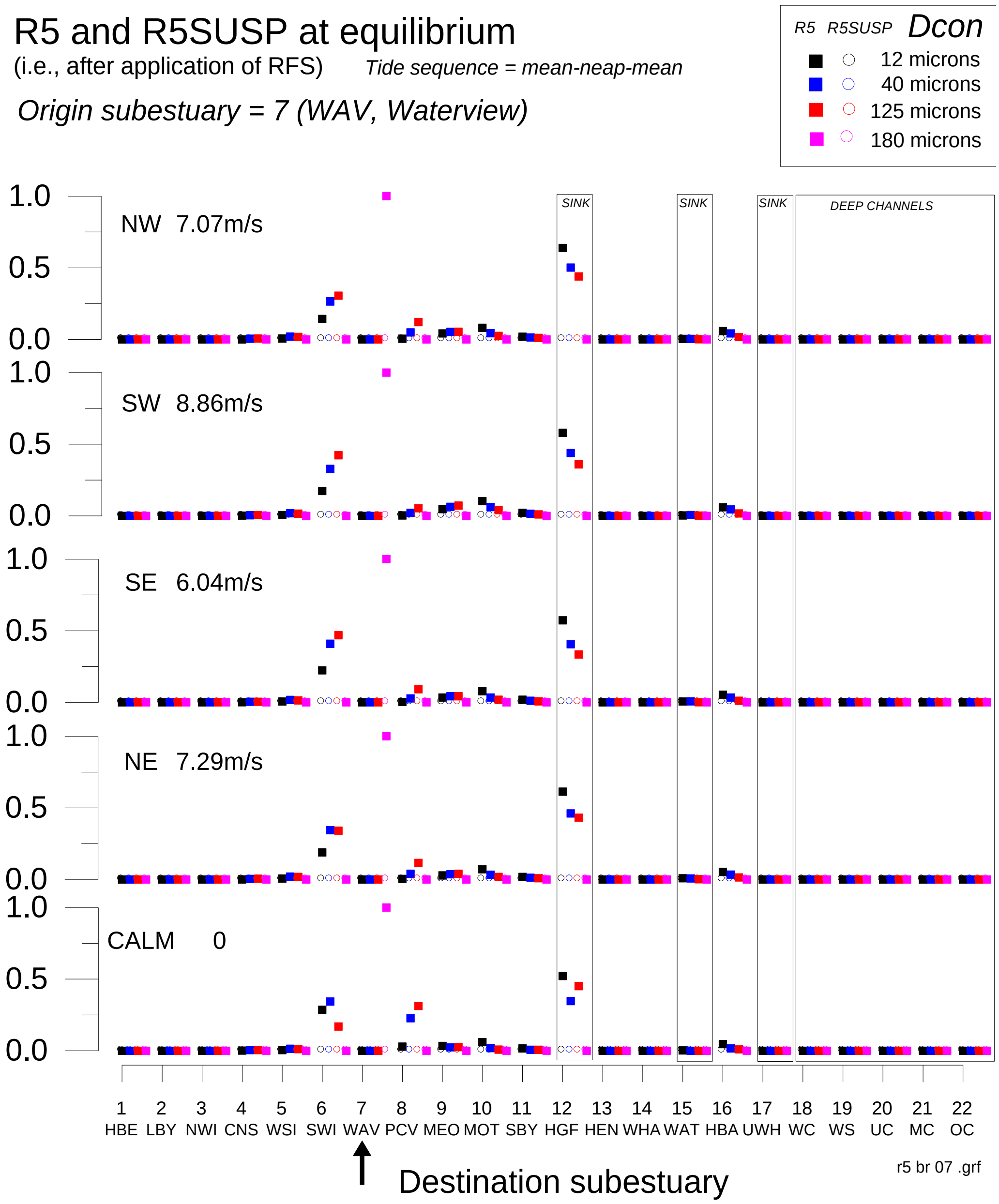
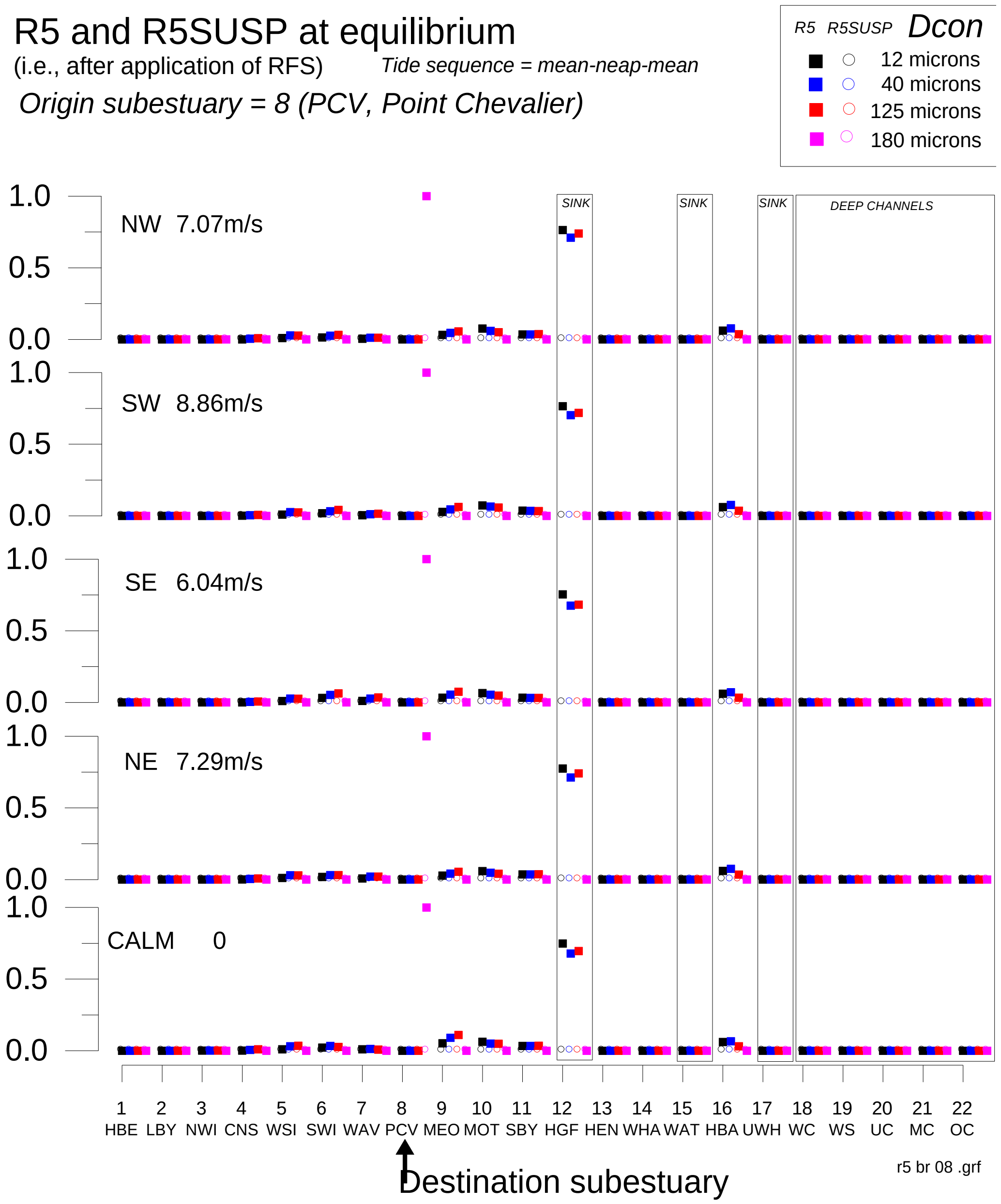

R5 and R5SUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = mean-neap-mean
Origin subestuary = 7 (WAV, Waterview)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 7.07m/s
SW 8.86m/s
SE 6.04m/s
NE 7.29m/s
CALM 0
SINK
SINK
SINK
DEEP CHANNELS
1.0
0.5
0.0
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r5 br 07 .grf

Figure 134



R5 and R5SUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = mean-neap-mean
Origin subestuary = 8 (PCV, Point Chevalier)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
1.0
0.5
0.0
NW 7.07m/s
SW 8.86m/s
SE 6.04m/s
NE 7.29m/s
CALM 0
SINK
SINK
SINK
DEEP CHANNELS
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r5 br 08 .grf

**Figure 135**

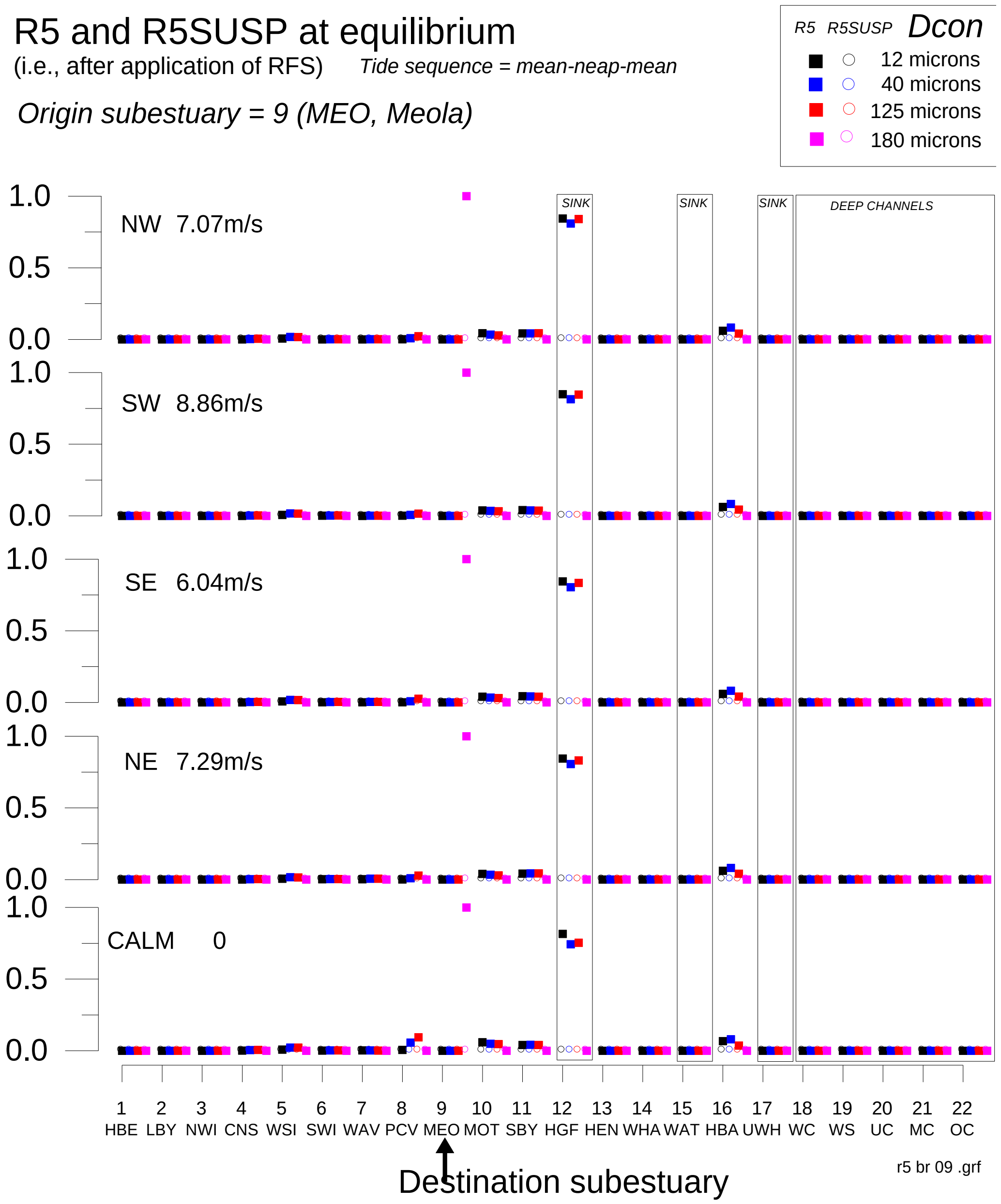
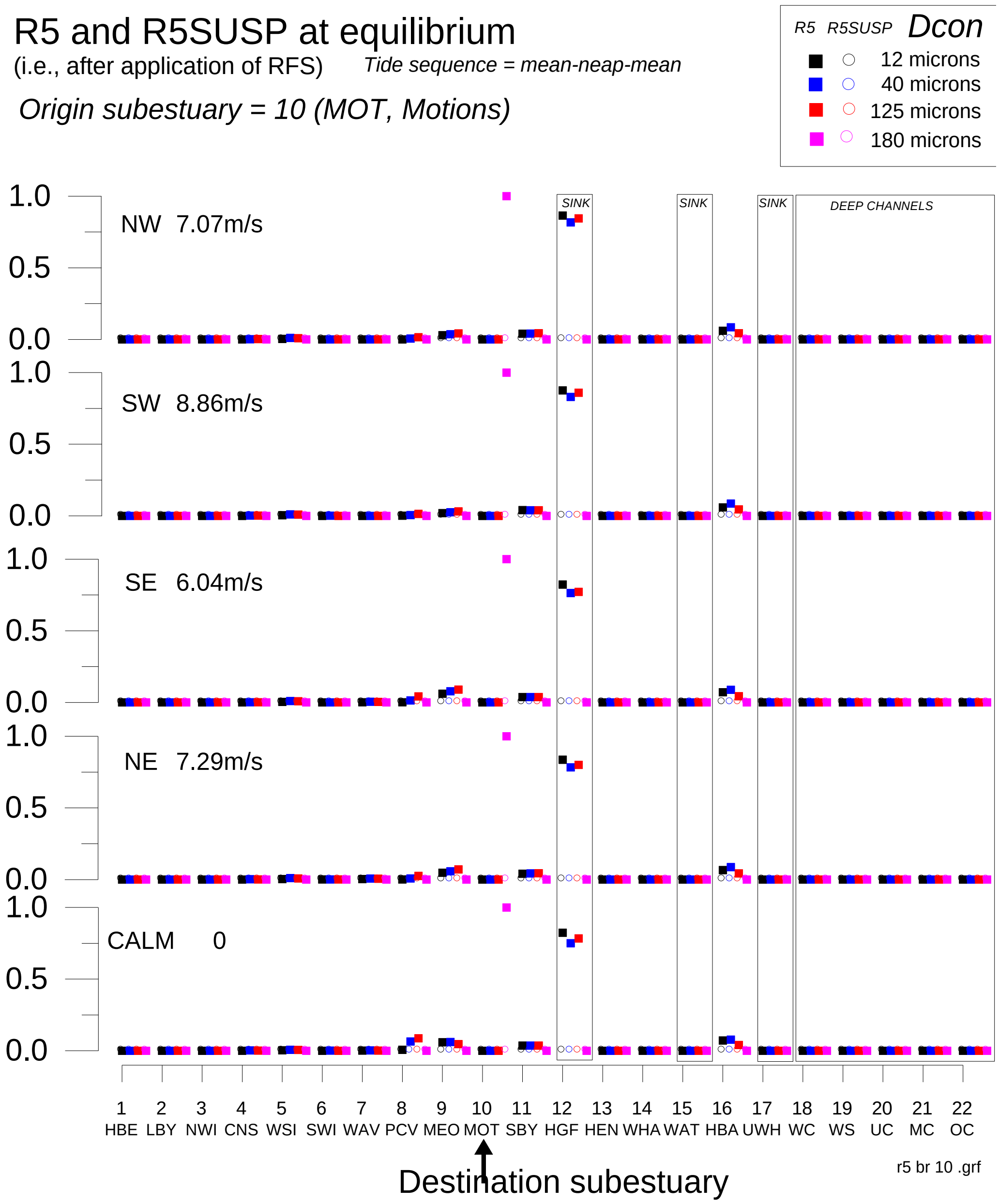
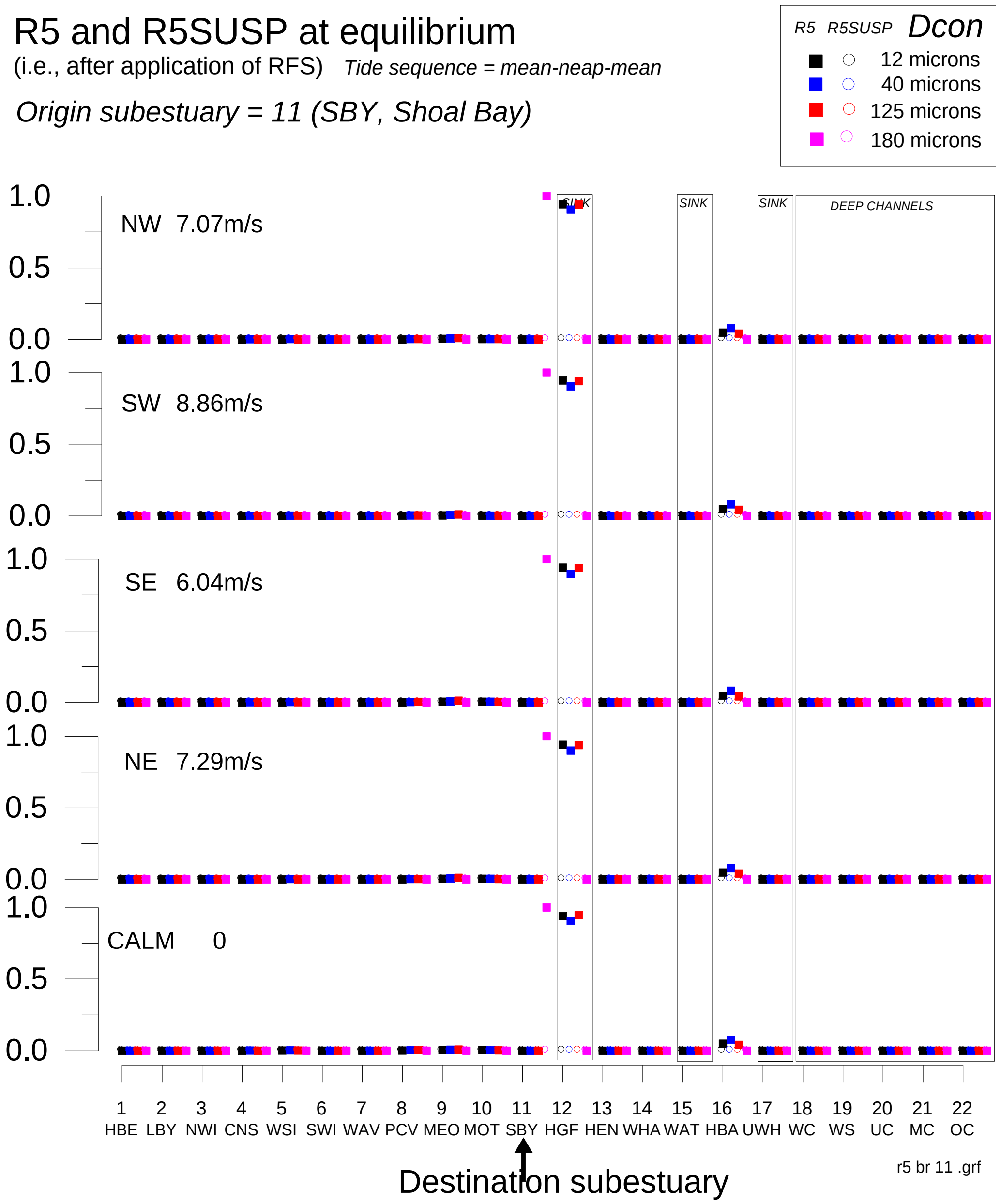

R5 and R5SUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = mean-neap-mean
Origin subestuary = 9 (MEO, Meola)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 7.07m/s
SW 8.86m/s
SE 6.04m/s
NE 7.29m/s
CALM 0
SINK
SINK
SINK
DEEP CHANNELS
1.0
0.5
0.0
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r5 br 09 .grf

Figure 136



R5 and R5SUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = mean-neap-mean
Origin subestuary = 10 (MOT, Motions)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 7.07m/s
SW 8.86m/s
SE 6.04m/s
NE 7.29m/s
CALM 0
1.0
0.5
0.0
SINK
SINK
SINK
DEEP CHANNELS
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r5 br 10 .grf

**Figure 137**


R5 and R5SUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = mean-neap-mean
Origin subestuary = 11 (SBY, Shoal Bay)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
1.0
0.5
0.0
NW 7.07m/s
SW 8.86m/s
SE 6.04m/s
NE 7.29m/s
CALM 0
SINK
SINK
SINK
DEEP CHANNELS
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22
HBE LBY NWI CNS WSI SWI WAV PCV MEO MOT SBY HGF HEN WHA WAT HBA UWH WC WS UC MC OC
Destination subestuary
r5 br 11 .grf

# 17 Appendix 8: R5 and R5SUSP (Equilibrium), Raining

## 17.1 Tide sequence neap-mean-spring

**Figure 138**

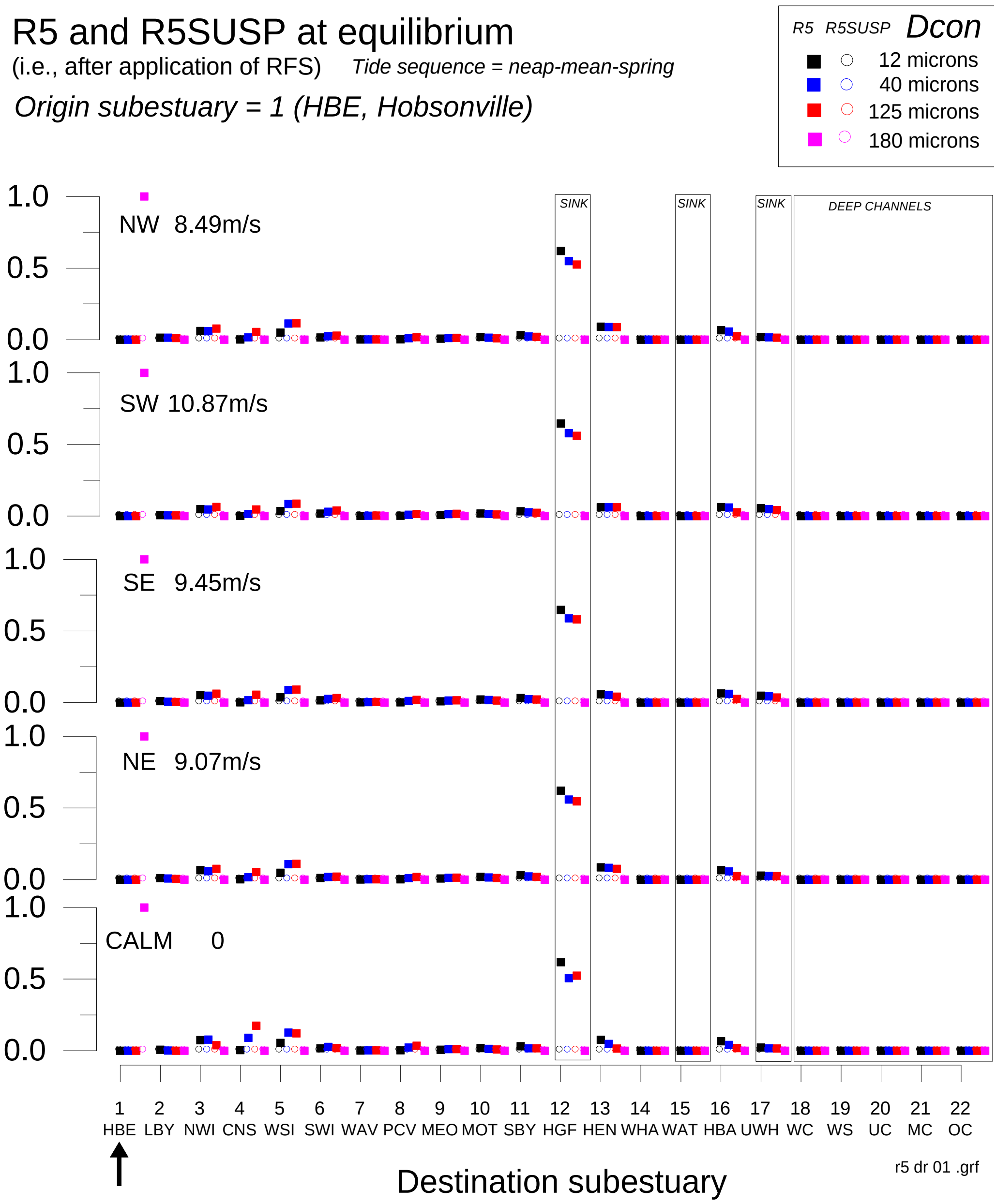


Figure 139

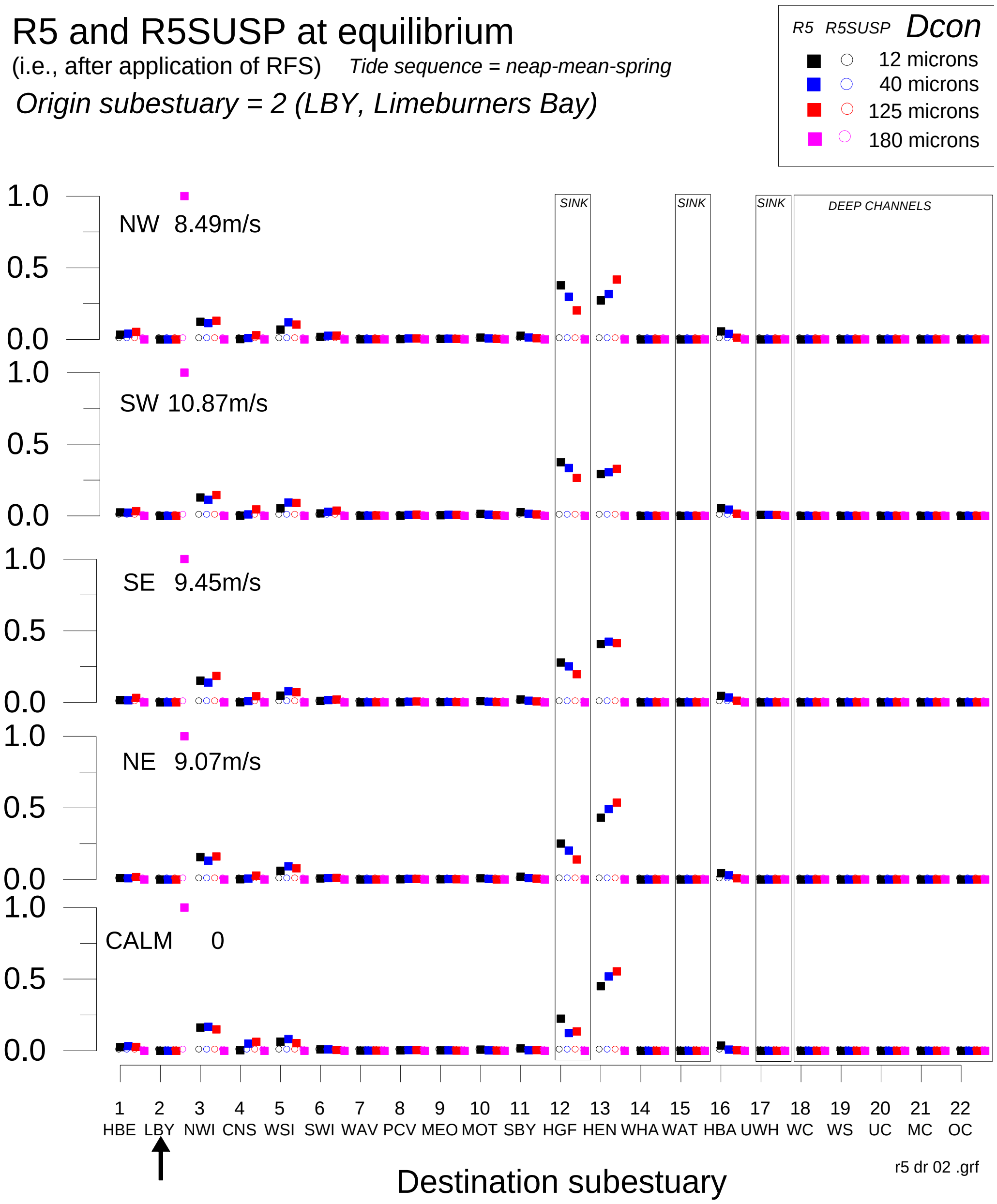
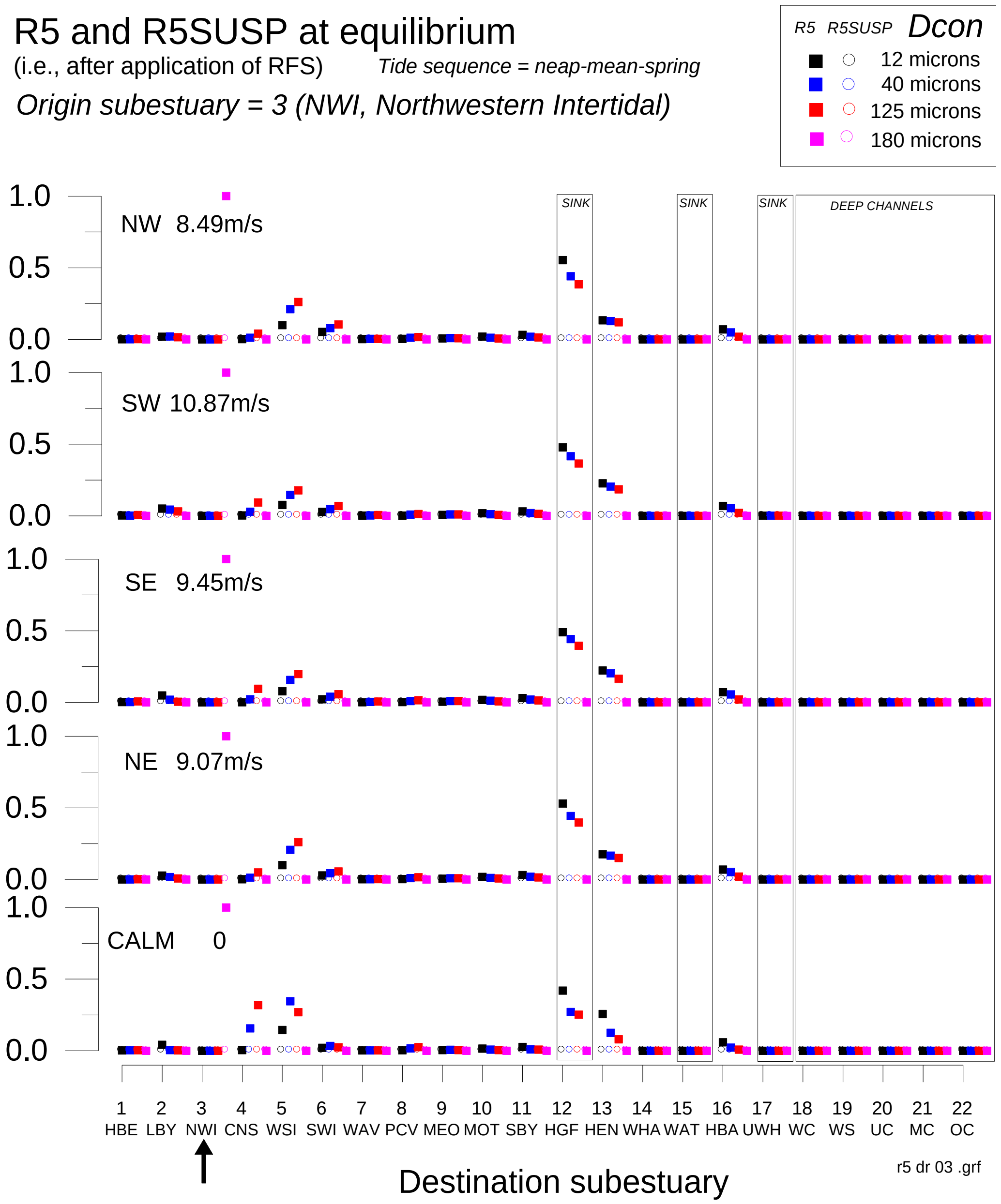

R5 and R5SUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = neap-mean-spring
Origin subestuary = 2 (LBY, Limeburners Bay)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
1.0
0.5
0.0
SINK
SINK
SINK
DEEP CHANNELS
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r5 dr 02 .grf

Figure 140



R5 and R5SUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = neap-mean-spring
Origin subestuary = 3 (NWI, Northwestern Intertidal)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
SINK
SINK
SINK
DEEP CHANNELS
1.0
0.5
0.0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22
HBE LBY NWI CNS WSI SWI WAV PCV MEO MOT SBY HGF HEN WHA WAT HBA UWH WC WS UC MC OC
r5 dr 03 .grf
Destination subestuary

Figure 141

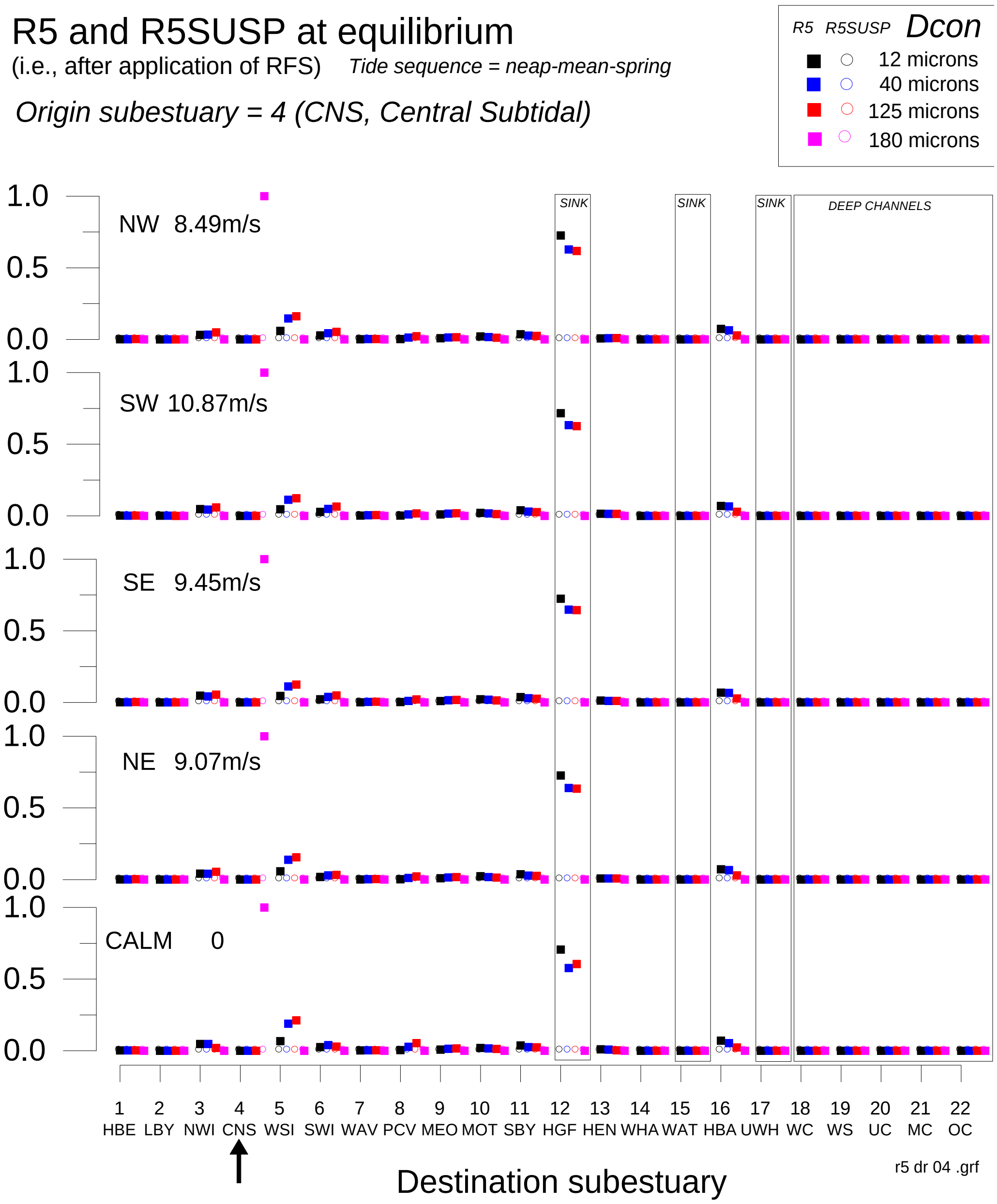
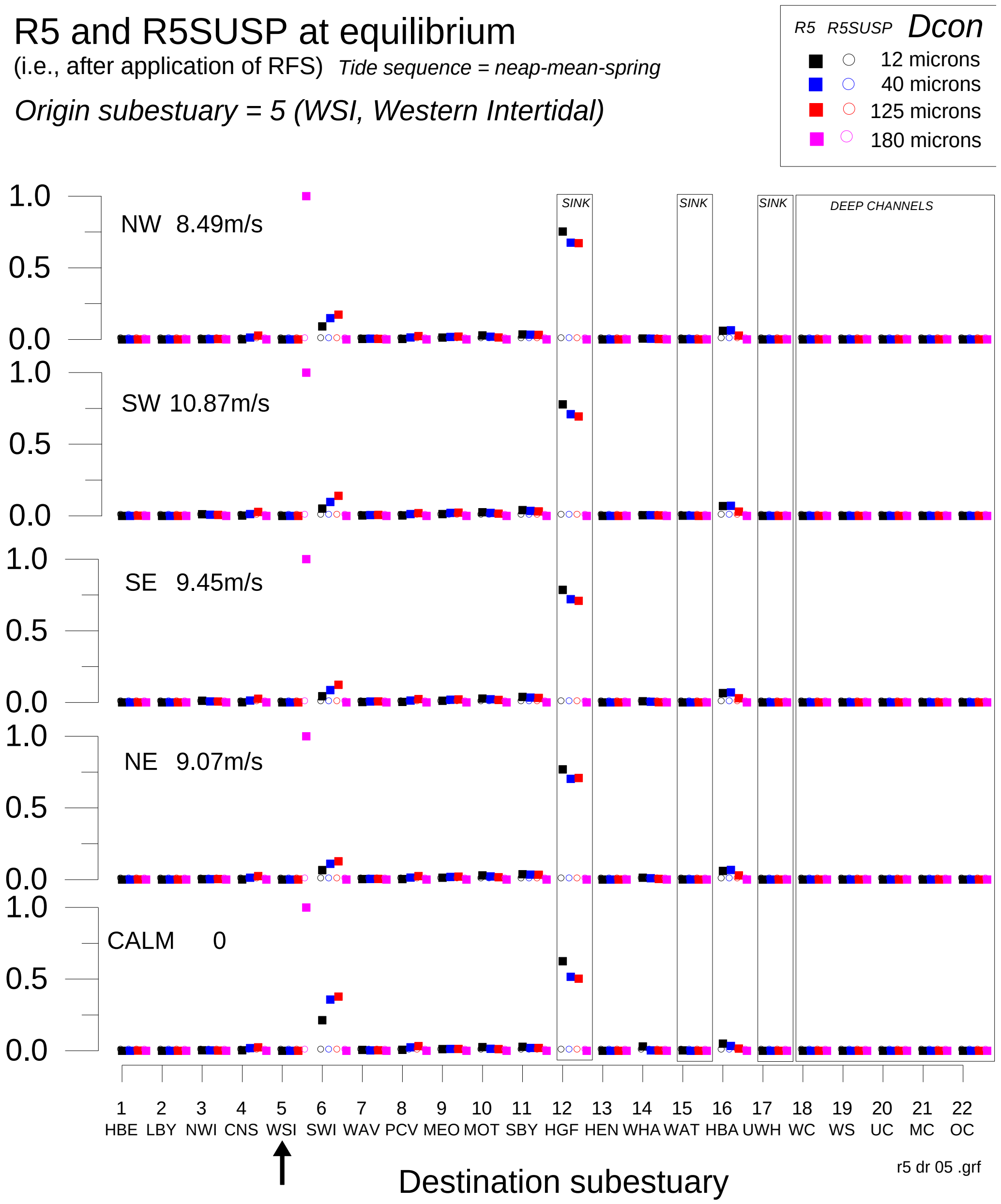
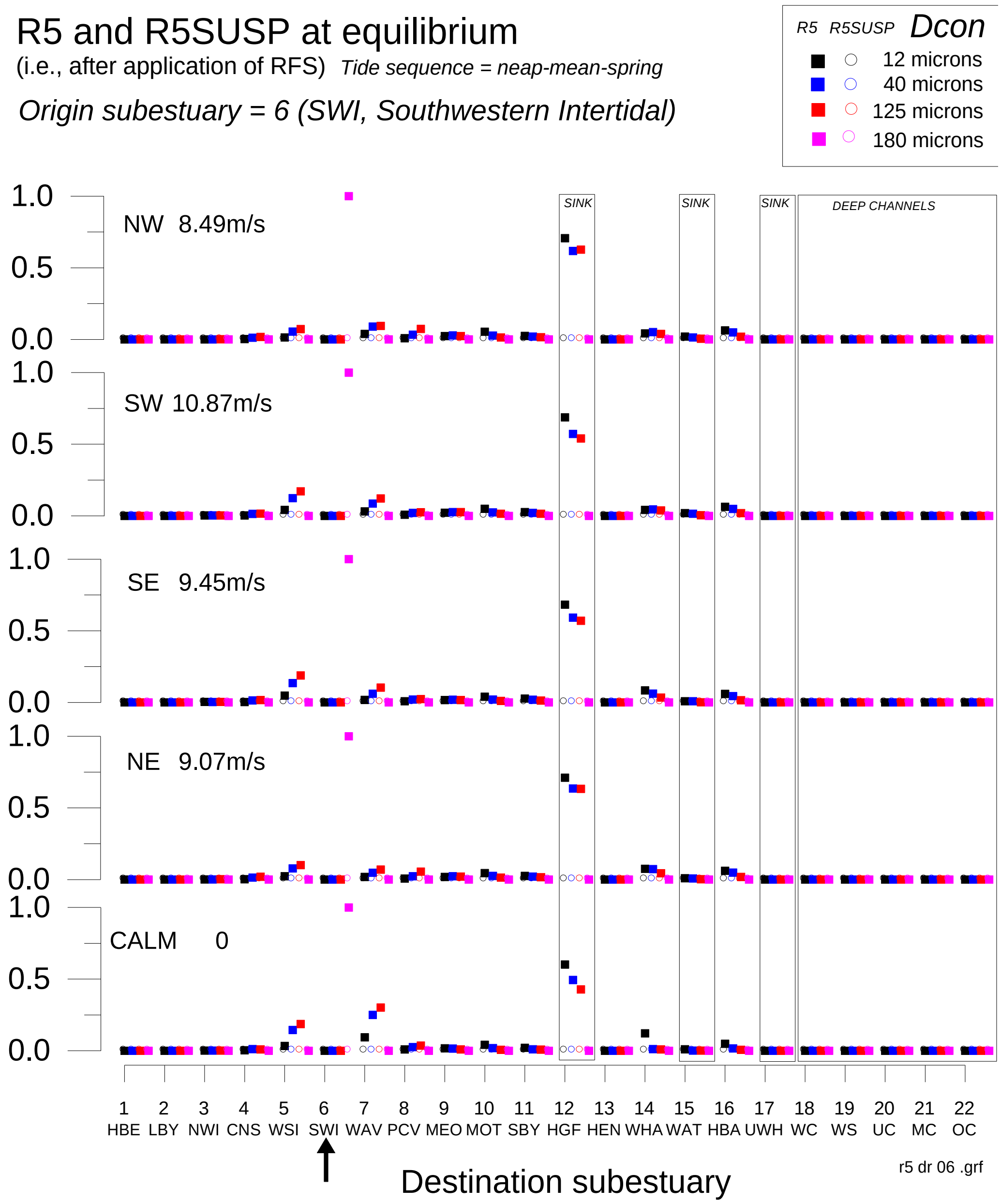

R5 and R5SUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = neap-mean-spring
Origin subestuary = 4 (CNS, Central Subtidal)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
1.0
0.5
0.0
SINK
SINK
SINK
DEEP CHANNELS
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22
HBE LBY NWI CNS WSI SWI WAV PCV MEO MOT SBY HGF HEN WHA WAT HBA UWH WC WS UC MC OC
Destination subestuary
r5 dr 04 .grf

Figure 142



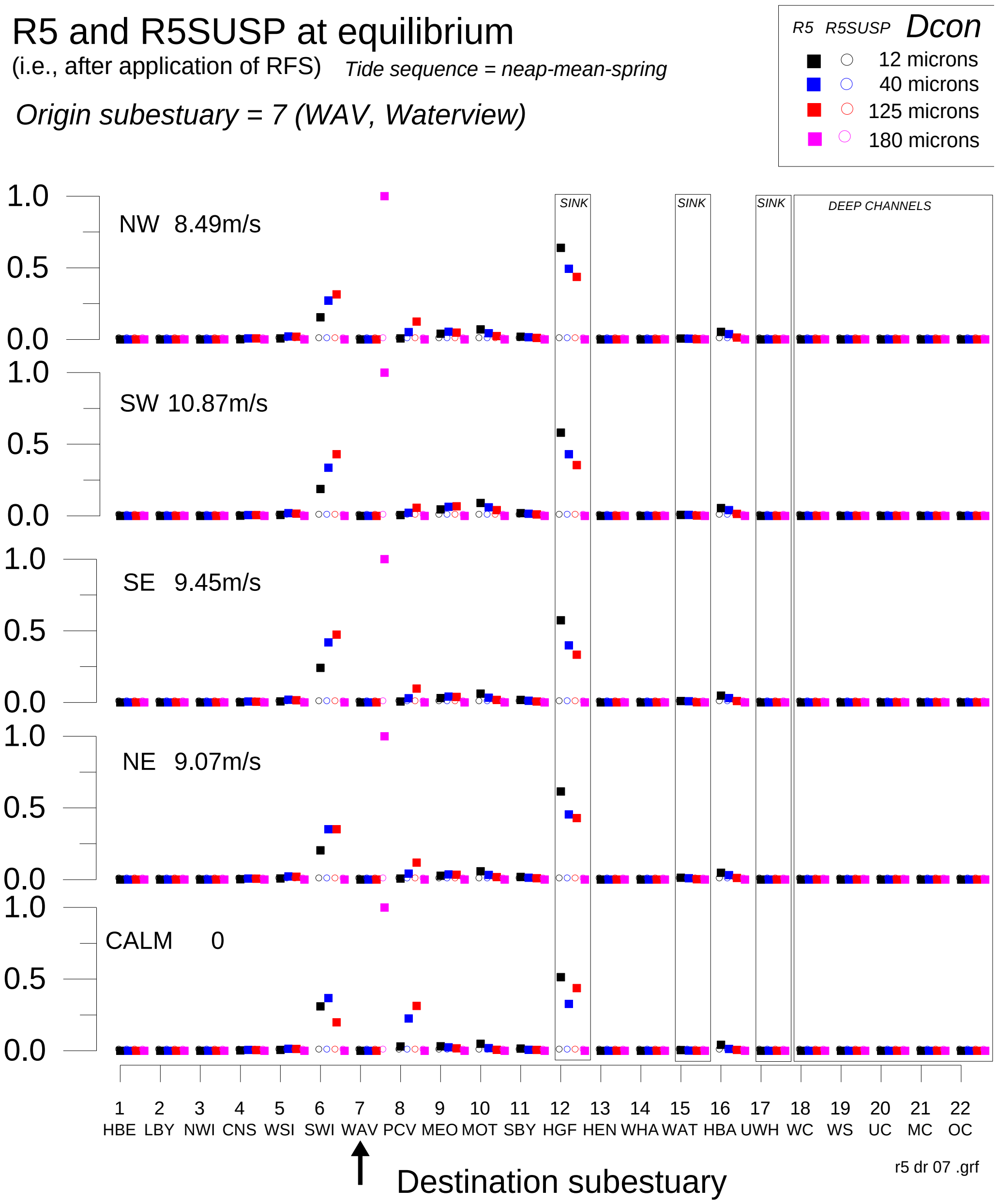
R5 and R5SUSP at equilibrium
(i.e., after application of RFS) Tide sequence = neap-mean-spring
Origin subestuary = 5 (WSI, Western Intertidal)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
1.0
0.5
0.0
SINK
SINK
SINK
DEEP CHANNELS
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r5 dr 05 .grf

Figure 143



R5 and R5SUSP at equilibrium
(i.e., after application of RFS) Tide sequence = neap-mean-spring
Origin subestuary = 6 (SWI, Southwestern Intertidal)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
SINK
SINK
SINK
DEEP CHANNELS
1.0
0.5
0.0
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r5 dr 06 .grf

Figure 144



R5 and R5SUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = neap-mean-spring
Origin subestuary = 7 (WAV, Waterview)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
1.0
0.5
0.0
SINK
SINK
SINK
DEEP CHANNELS
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22
HBE LBY NWI CNS WSI SWI WAV PCV MEO MOT SBY HGF HEN WHA WAT HBA UWH WC WS UC MC OC
Destination subestuary
r5 dr 07 .grf

Figure 145

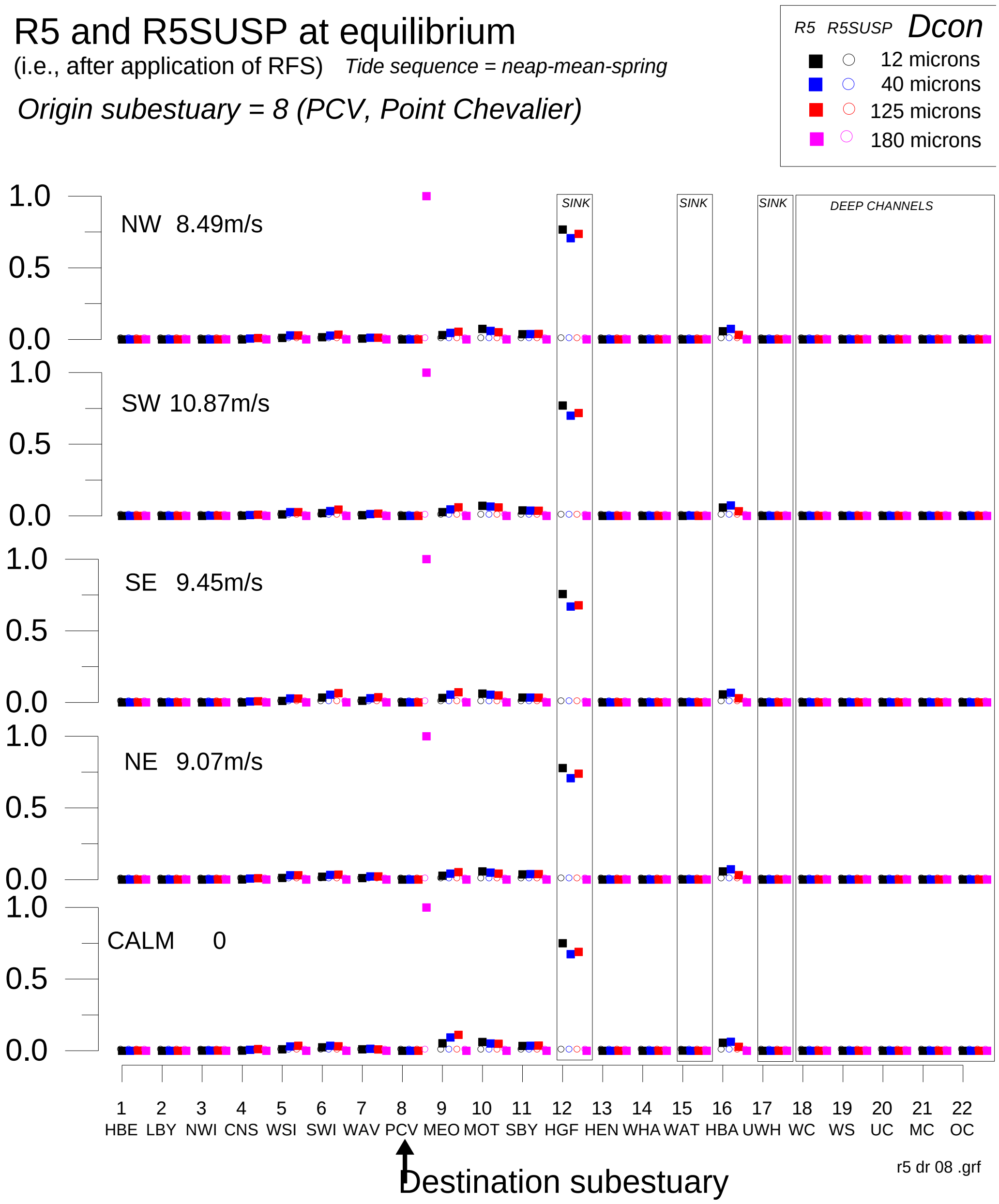
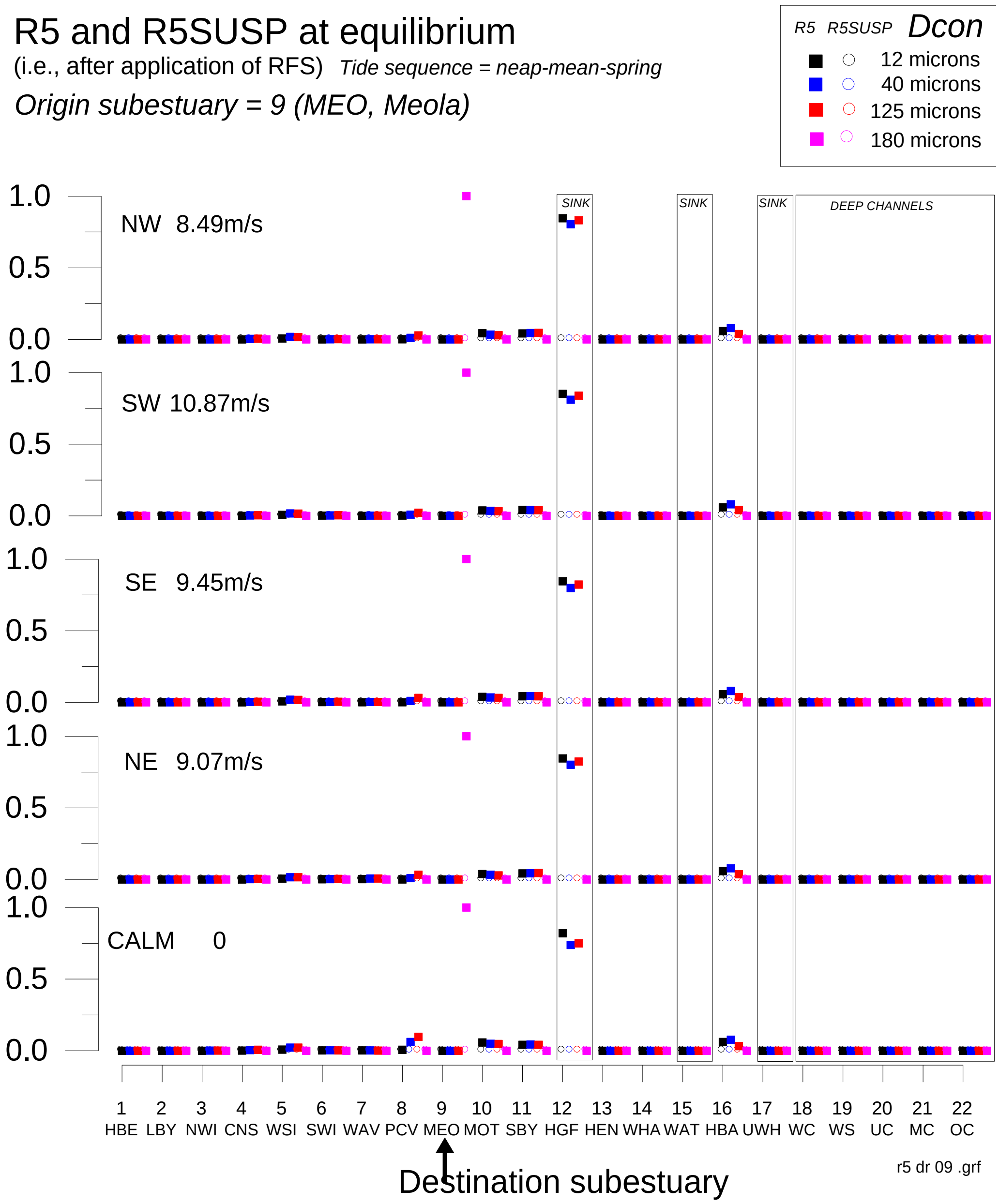
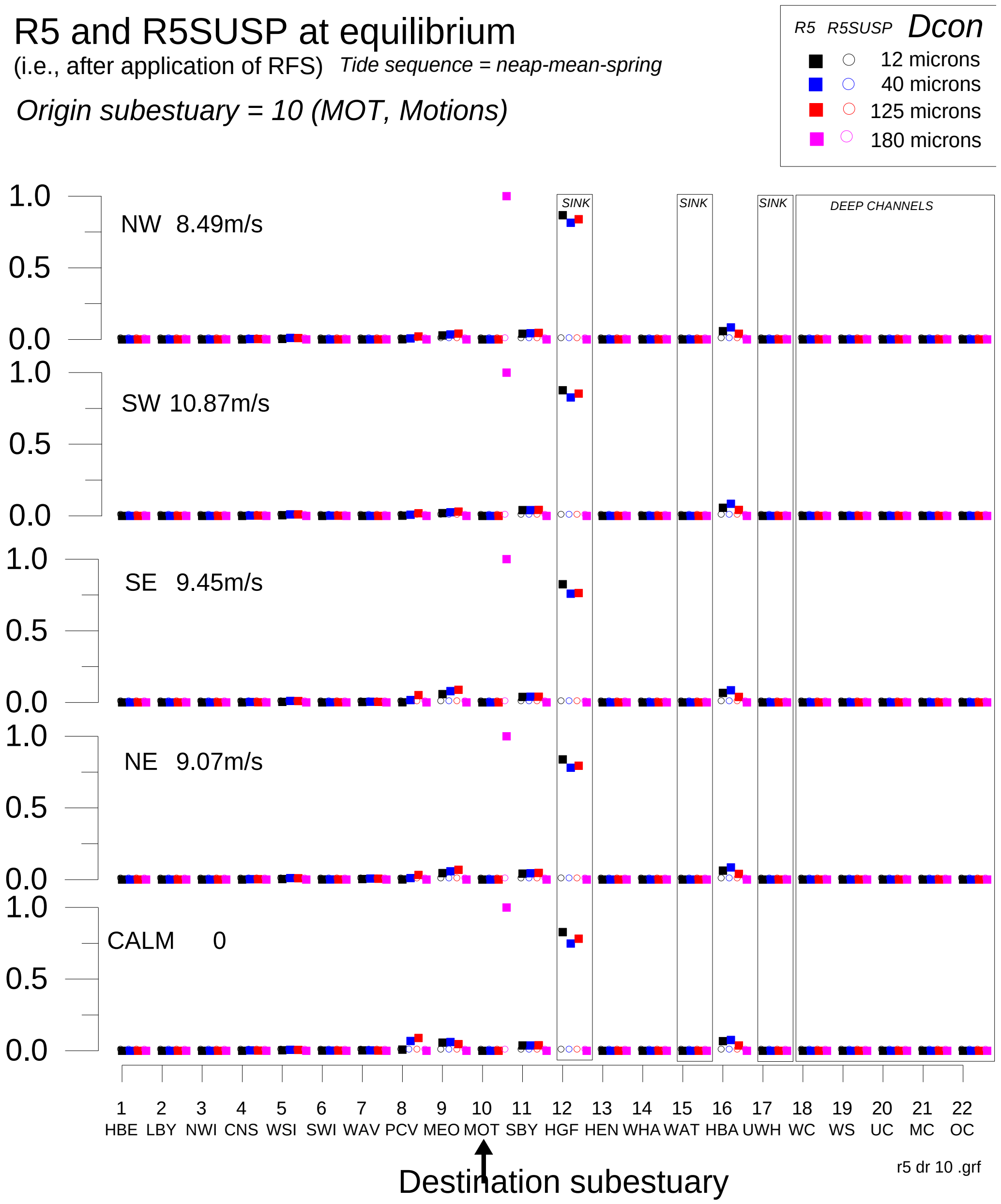

R5 and R5SUSP at equilibrium
(i.e., after application of RFS) Tide sequence = neap-mean-spring
Origin subestuary = 8 (PCV, Point Chevalier)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
1.0
0.5
0.0
SINK
SINK
SINK
DEEP CHANNELS
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r5 dr 08 .grf

**Figure 146**



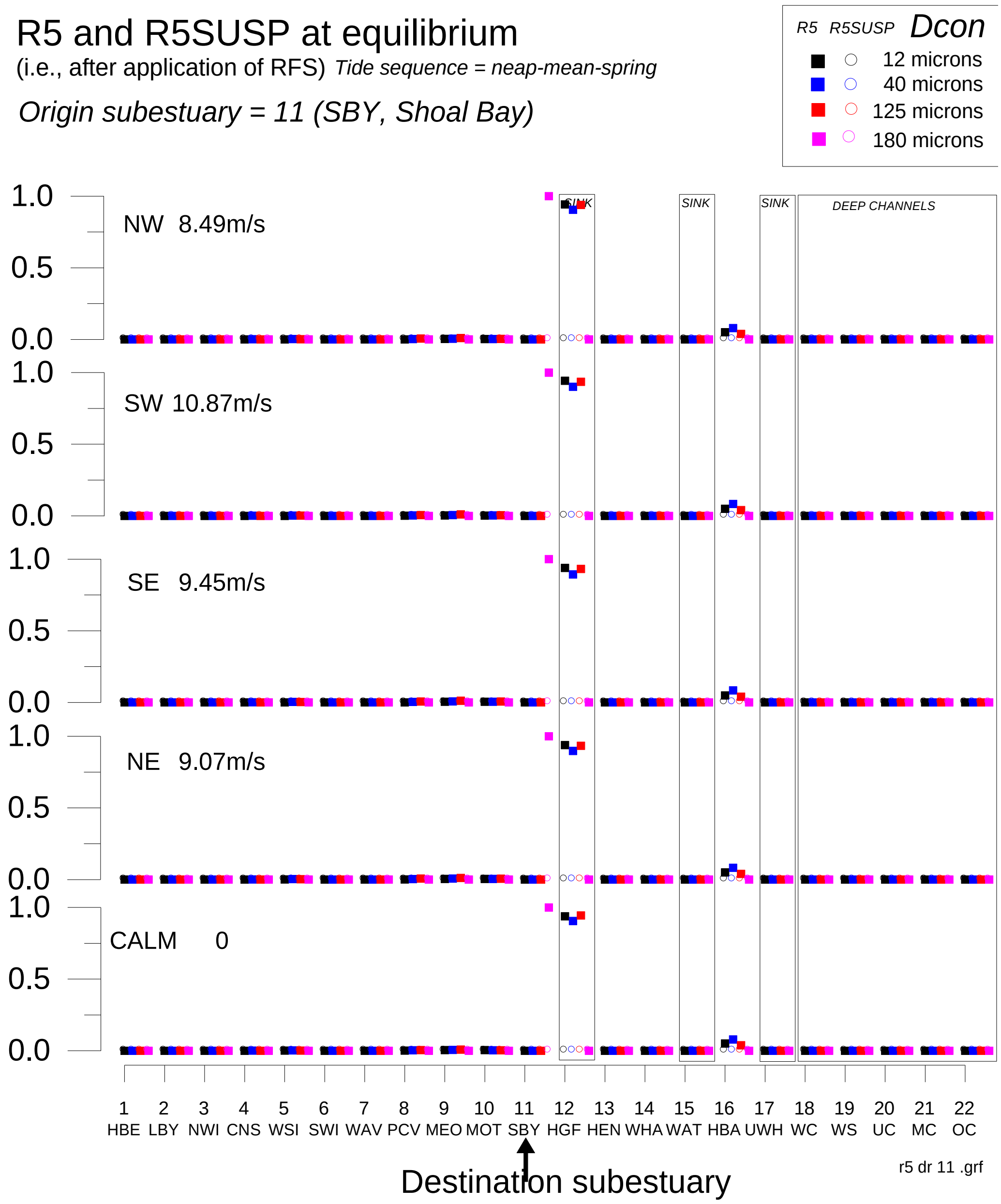
R5 and R5SUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = neap-mean-spring
Origin subestuary = 9 (MEO, Meola)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
1.0
0.5
0.0
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
SINK
SINK
SINK
DEEP CHANNELS
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r5 dr 09 .grf

**Figure 147**



R5 and R5SUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = neap-mean-spring
Origin subestuary = 10 (MOT, Motions)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
1.0
0.5
0.0
SINK
SINK
SINK
DEEP CHANNELS
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r5 dr 10 .grf

Figure 148


R5 and R5SUSP at equilibrium
(i.e., after application of RFS) Tide sequence = neap-mean-spring
Origin subestuary = 11 (SBY, Shoal Bay)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
1.0
0.5
0.0
SINK
SINK
SINK
DEEP CHANNELS
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22
HBE LBY NWI CNS WSI SWI WAV PCV MEO MOT SBY HGF HEN WHA WAT HBA UWH WC WS UC MC OC
Destination subestuary
r5 dr 11 .grf

## 17.2 Tide sequence mean-spring-neap

**Figure 149**

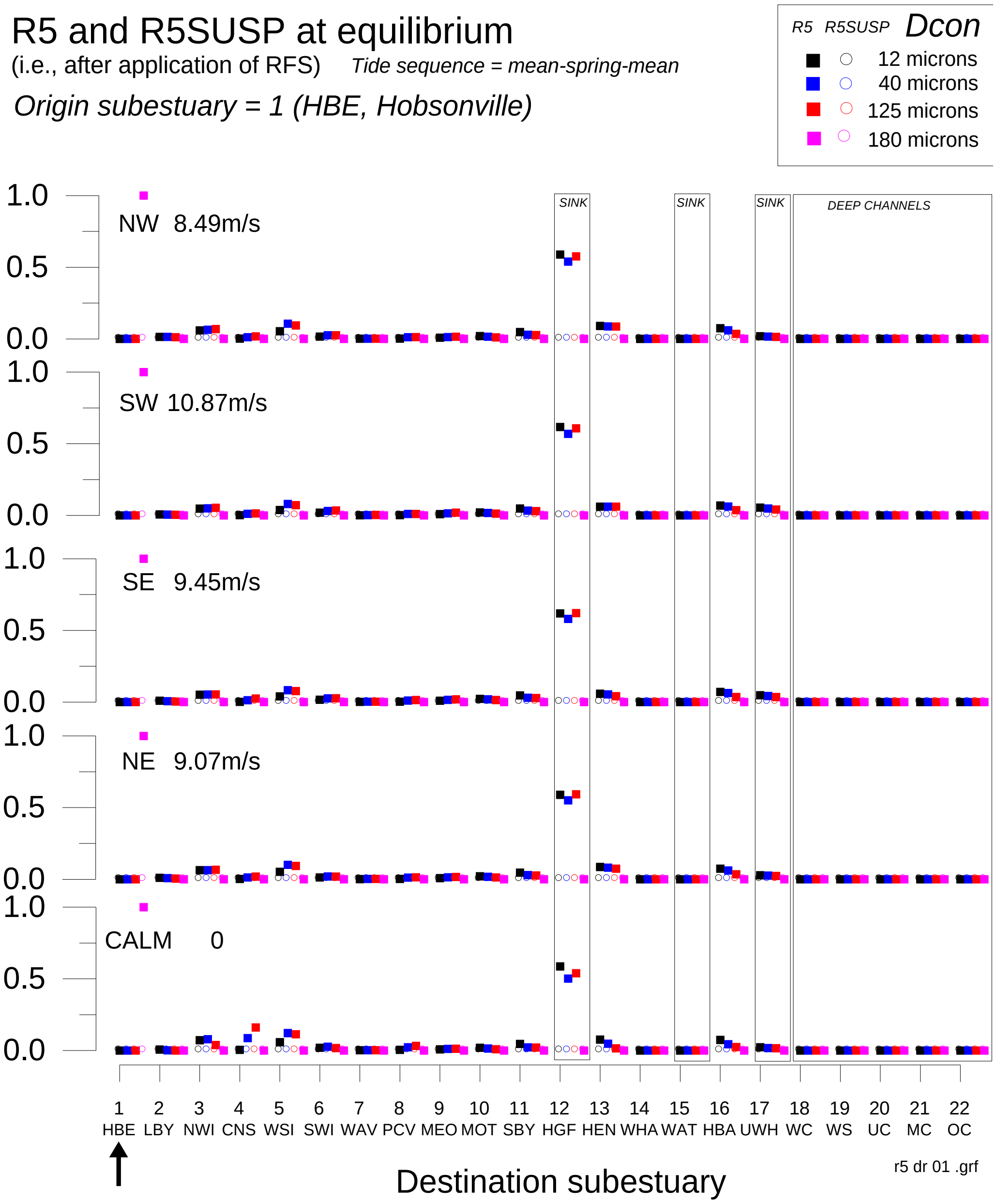
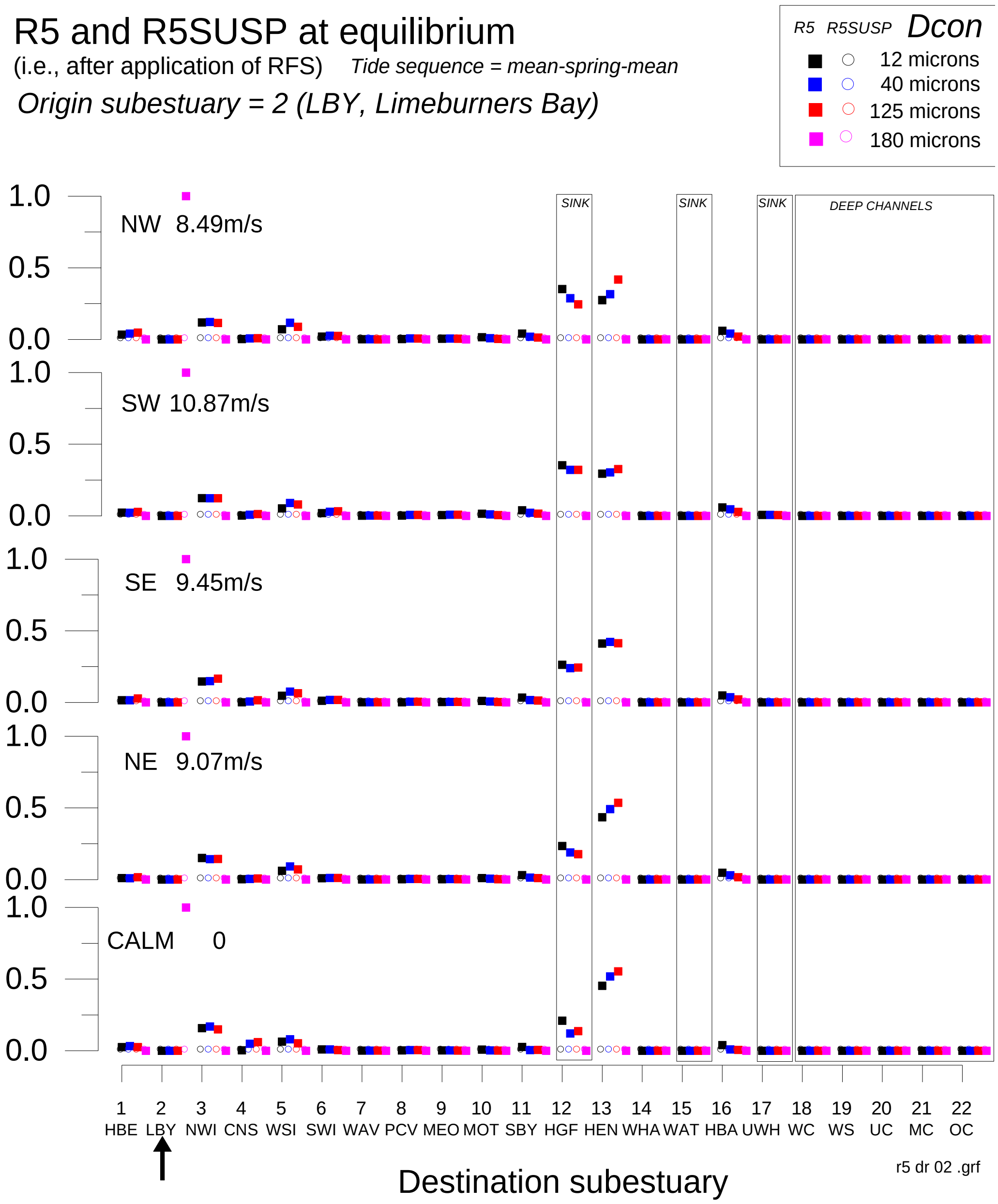
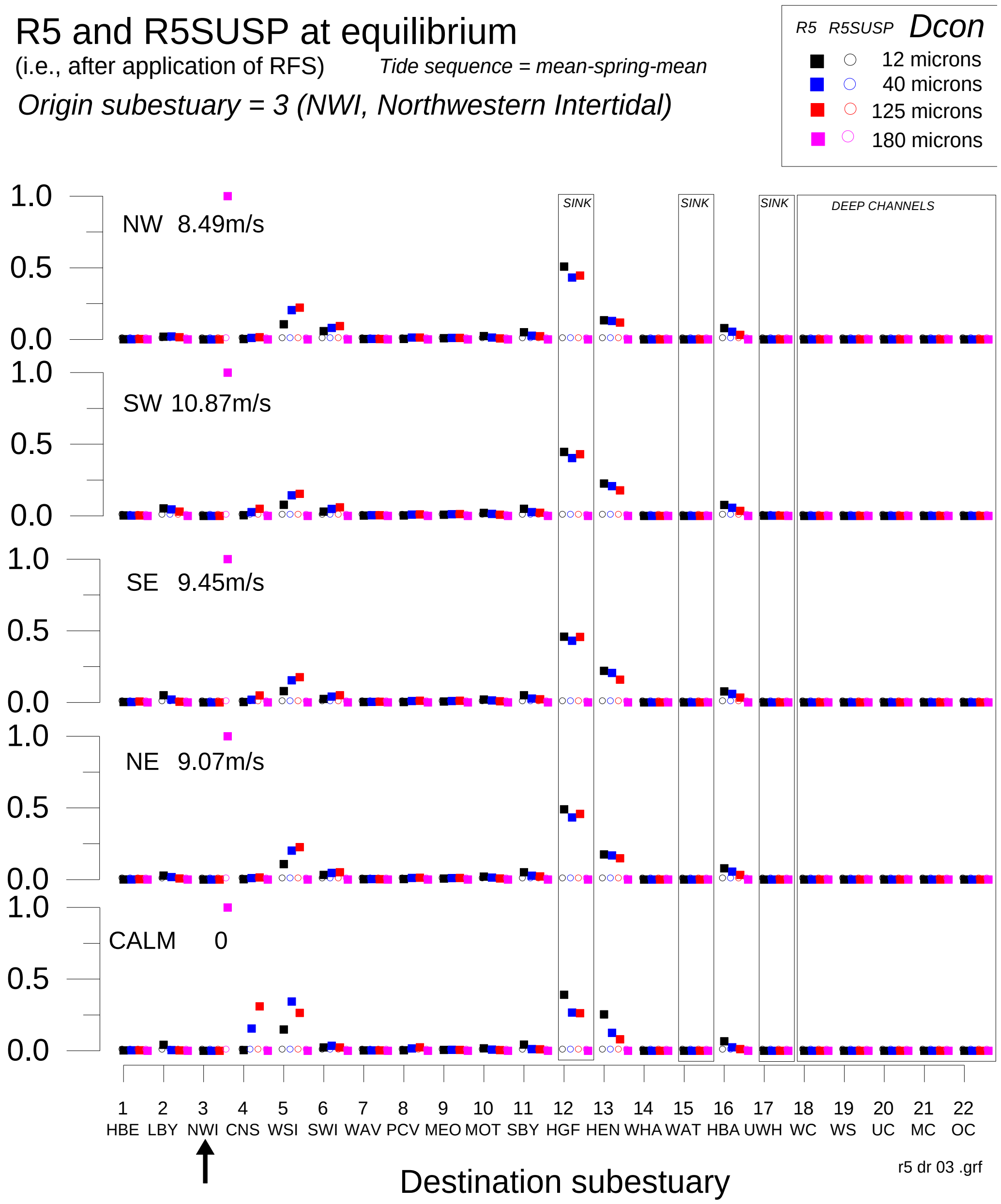


Figure 150



R5 and R5SUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = mean-spring-mean
Origin subestuary = 2 (LBY, Limeburners Bay)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
SINK
SINK
SINK
DEEP CHANNELS
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r5 dr 02 .grf

Figure 151



R5 and R5SUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = mean-spring-mean
Origin subestuary = 3 (NWI, Northwestern Intertidal)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
1.0
0.5
0.0
SINK
SINK
SINK
DEEP CHANNELS
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r5 dr 03 .grf

Figure 152

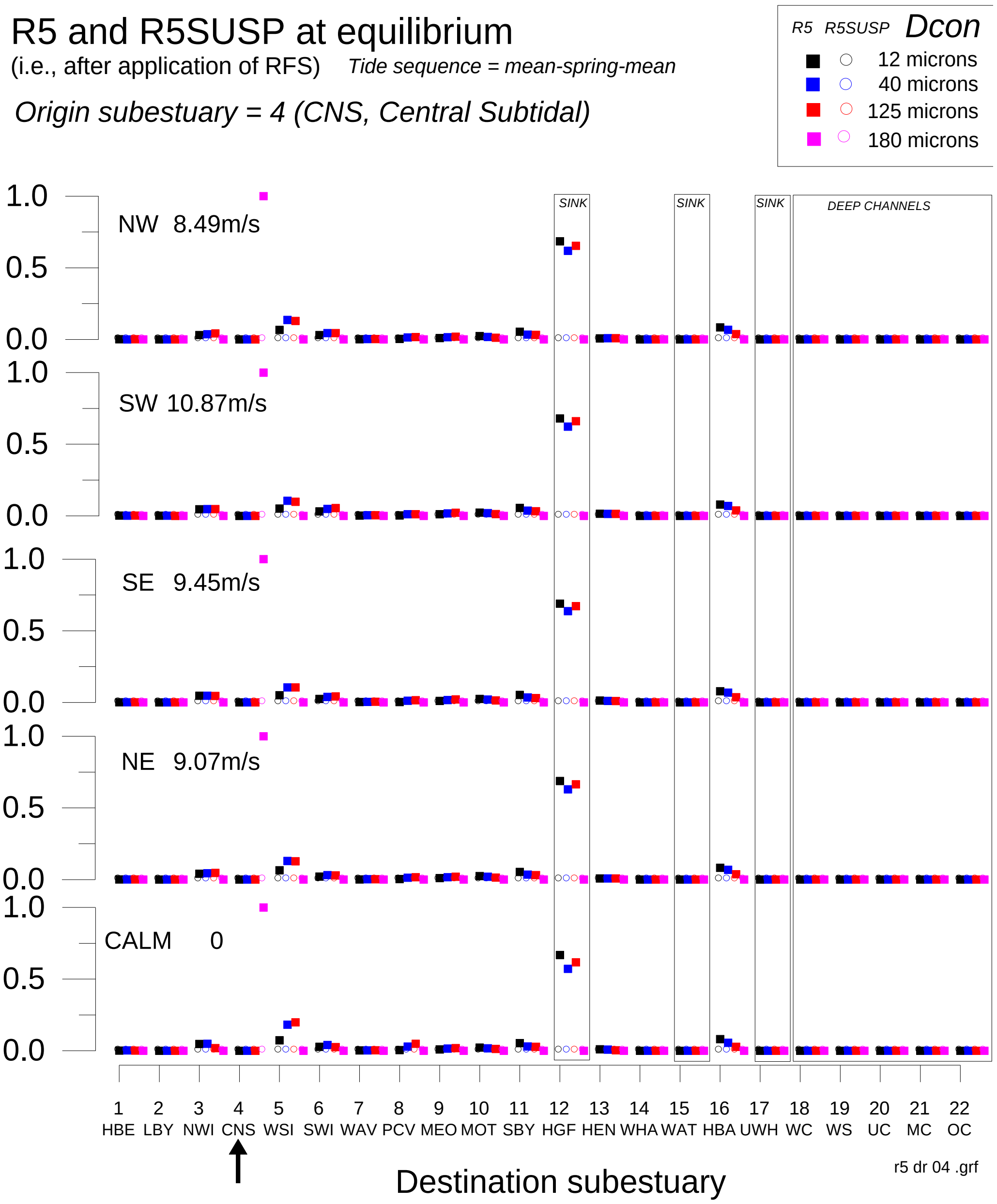
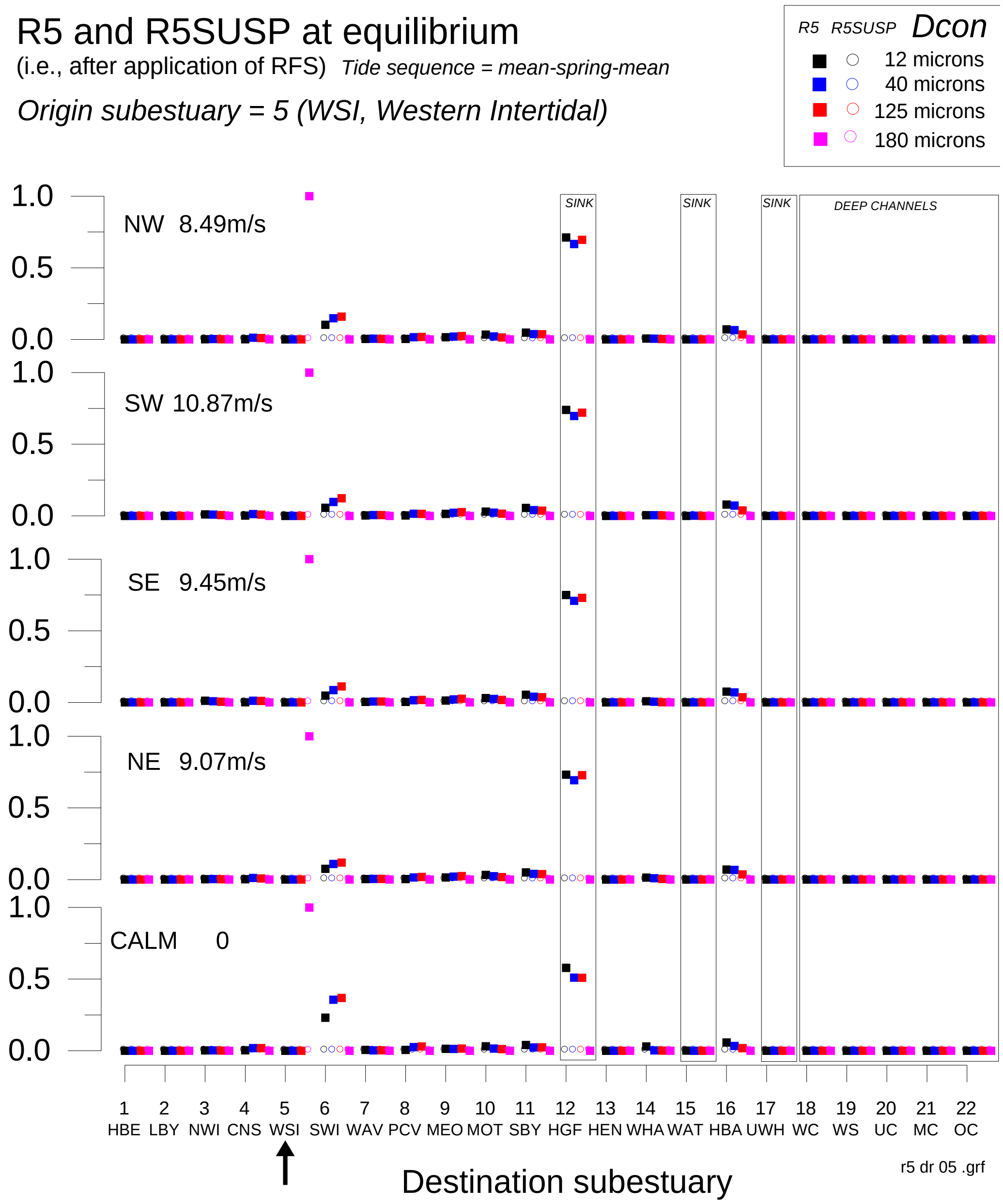
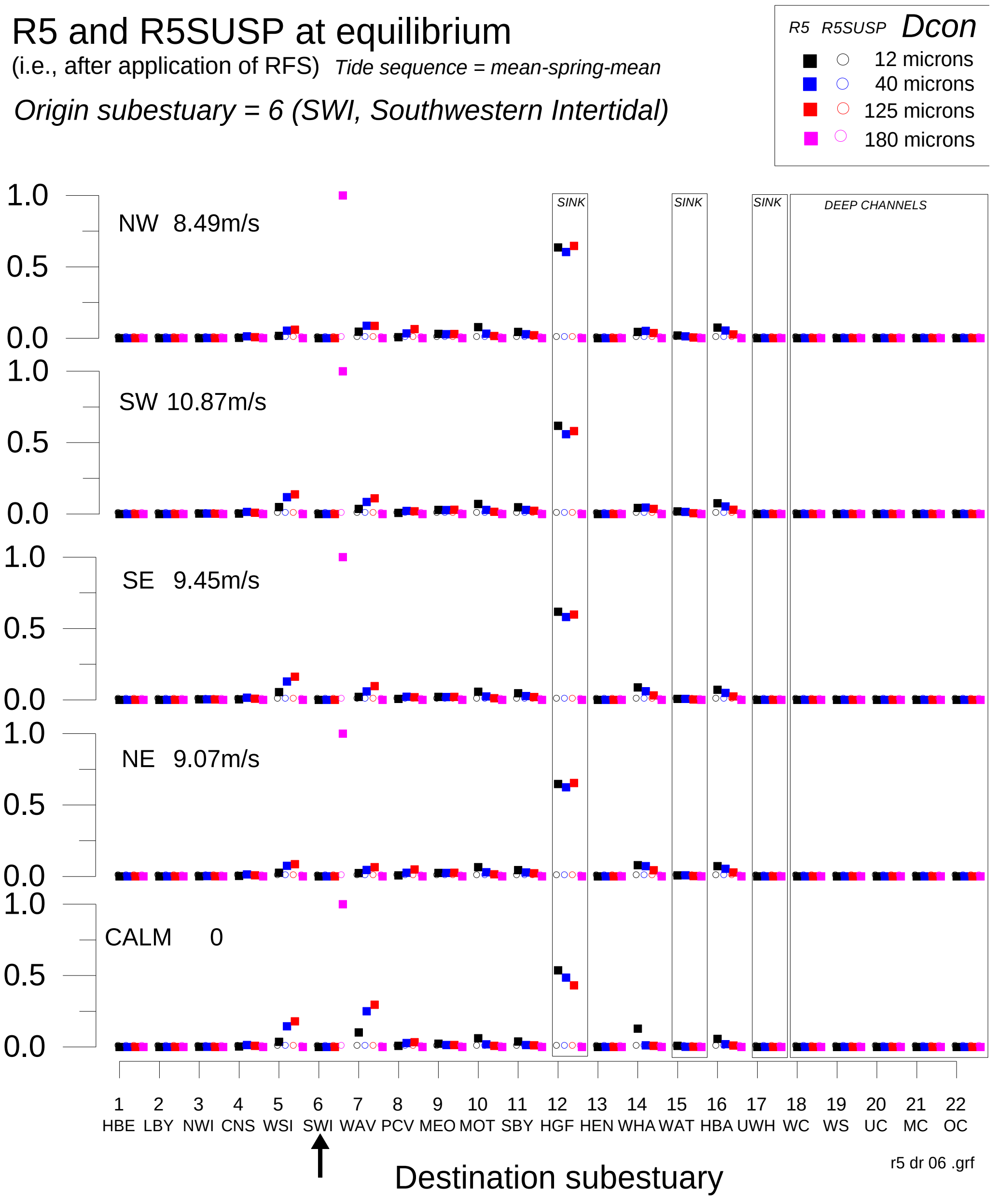

R5 and R5SUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = mean-spring-mean
Origin subestuary = 4 (CNS, Central Subtidal)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
1.0
0.5
0.0
SINK
SINK
SINK
DEEP CHANNELS
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r5 dr 04 .grf

Figure 153



R5 and R5SUSP at equilibrium
(i.e., after application of RFS) Tide sequence = mean-spring-mean
Origin subestuary = 5 (WSI, Western Intertidal)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
SINK
SINK
SINK
DEEP CHANNELS
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
1.0
0.5
0.0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22
HBE LBY NWI CNS WSI SWI WAV PCV MEO MOT SBY HGF HEN WHA WAT HBA UWH WC WS UC MC OC
Destination subestuary
r5 dr 05 .grf

Figure 154



R5 and R5SUSP at equilibrium
(i.e., after application of RFS) Tide sequence = mean-spring-mean
Origin subestuary = 6 (SWI, Southwestern Intertidal)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
1.0
0.5
0.0
SINK
SINK
SINK
DEEP CHANNELS
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22
HBE LBY NWI CNS WSI SWI WAV PCV MEO MOT SBY HGF HEN WHA WAT HBA UWH WC WS UC MC OC
Destination subestuary
r5 dr 06 .grf

**Figure 155**

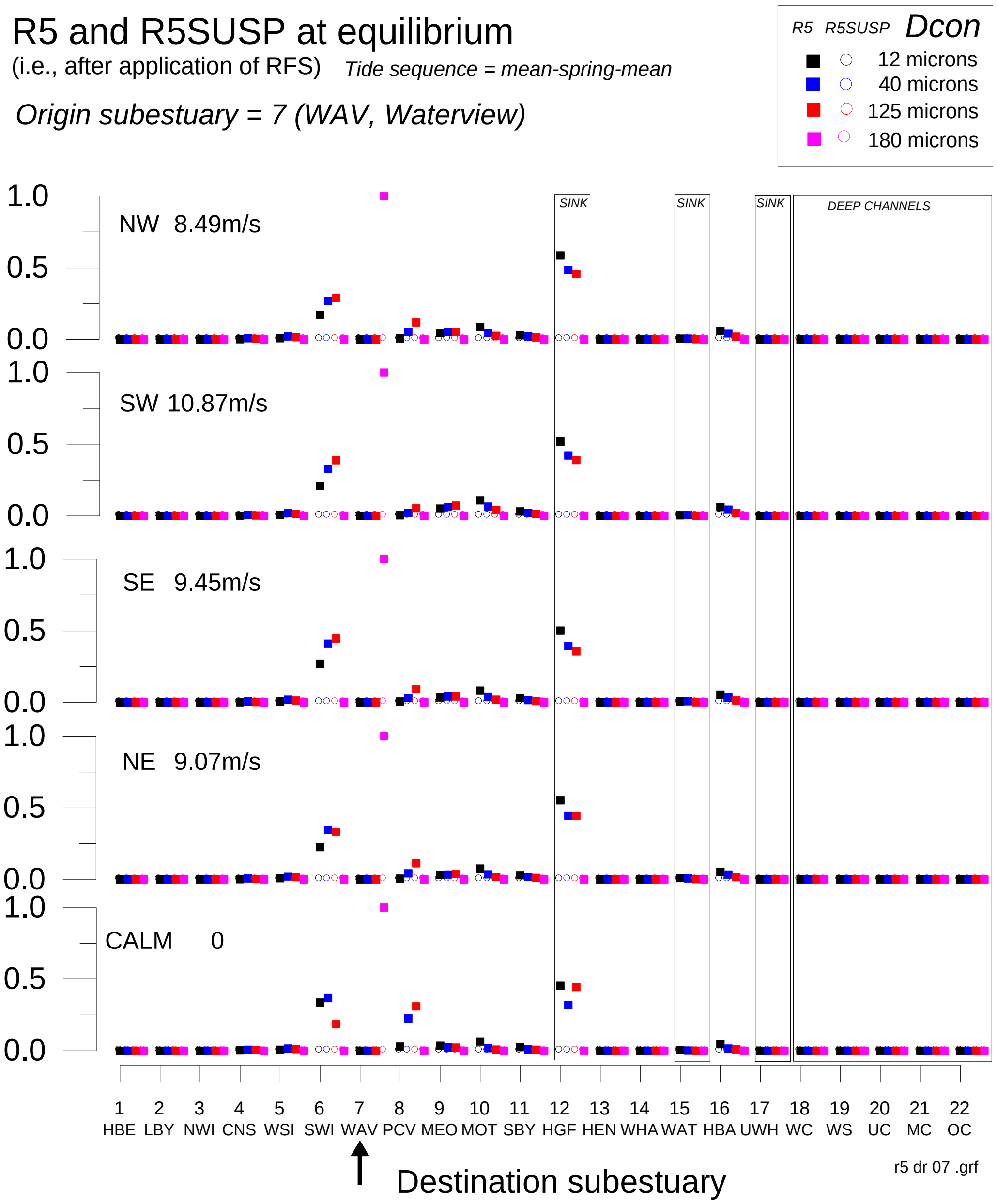

R5 and R5SUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = mean-spring-mean
Origin subestuary = 7 (WAV, Waterview)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
1.0
0.5
0.0
SINK
SINK
SINK
DEEP CHANNELS
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22
HBE LBY NWI CNS WSI SWI WAV PCV MEO MOT SBY HGF HEN WHA WAT HBA UWH WC WS UC MC OC
Destination subestuary
r5 dr 07 .grf

Figure 156

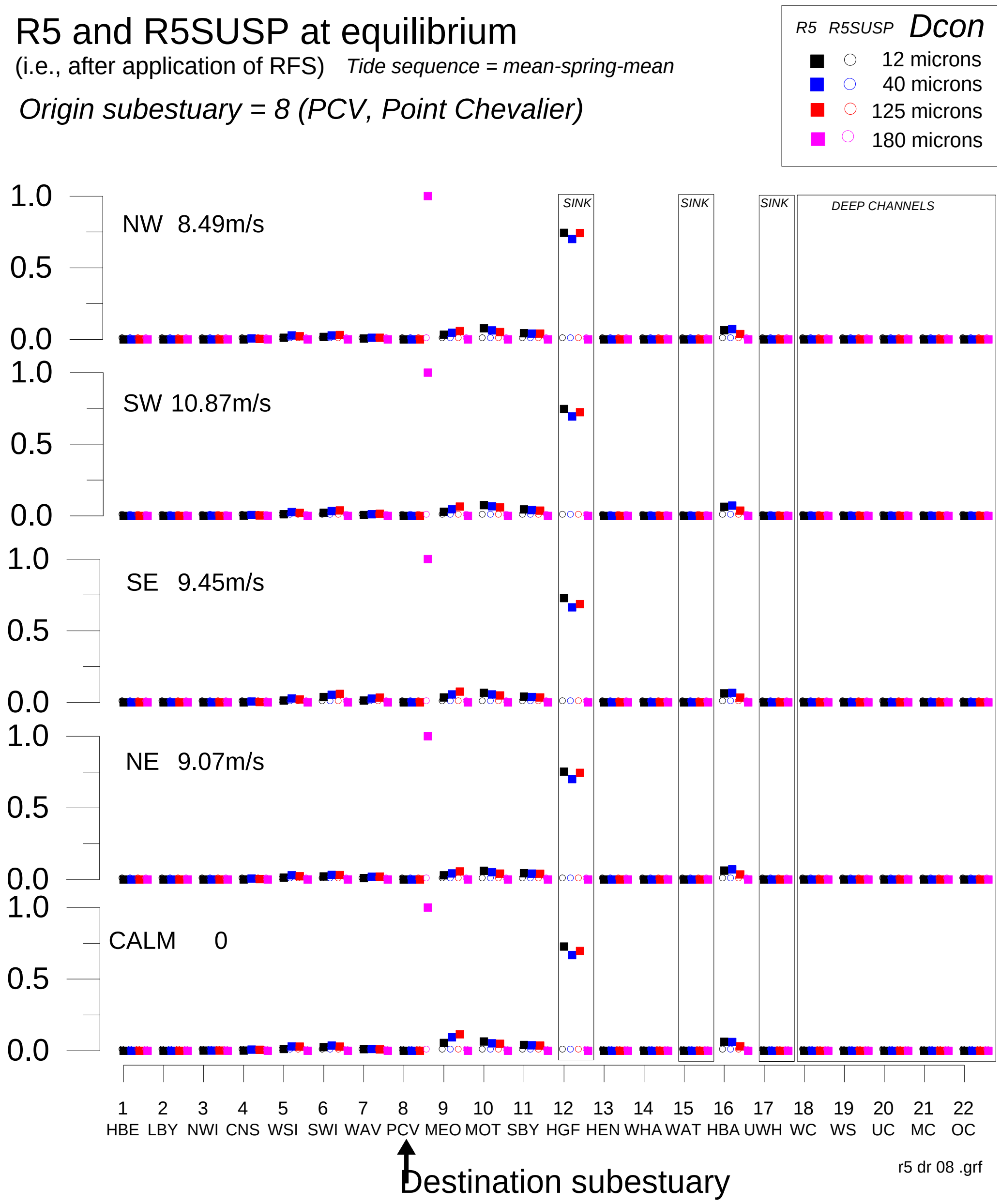

R5 and R5SUSP at equilibrium
(i.e., after application of RFS) Tide sequence = mean-spring-mean
Origin subestuary = 8 (PCV, Point Chevalier)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
1.0
0.5
0.0
SINK
SINK
SINK
DEEP CHANNELS
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22
HBE LBY NWI CNS WSI SWI WAV PCV MEO MOT SBY HGF HEN WHA WAT HBA UWH WC WS UC MC OC
Destination subestuary
r5 dr 08 .grf

Figure 157

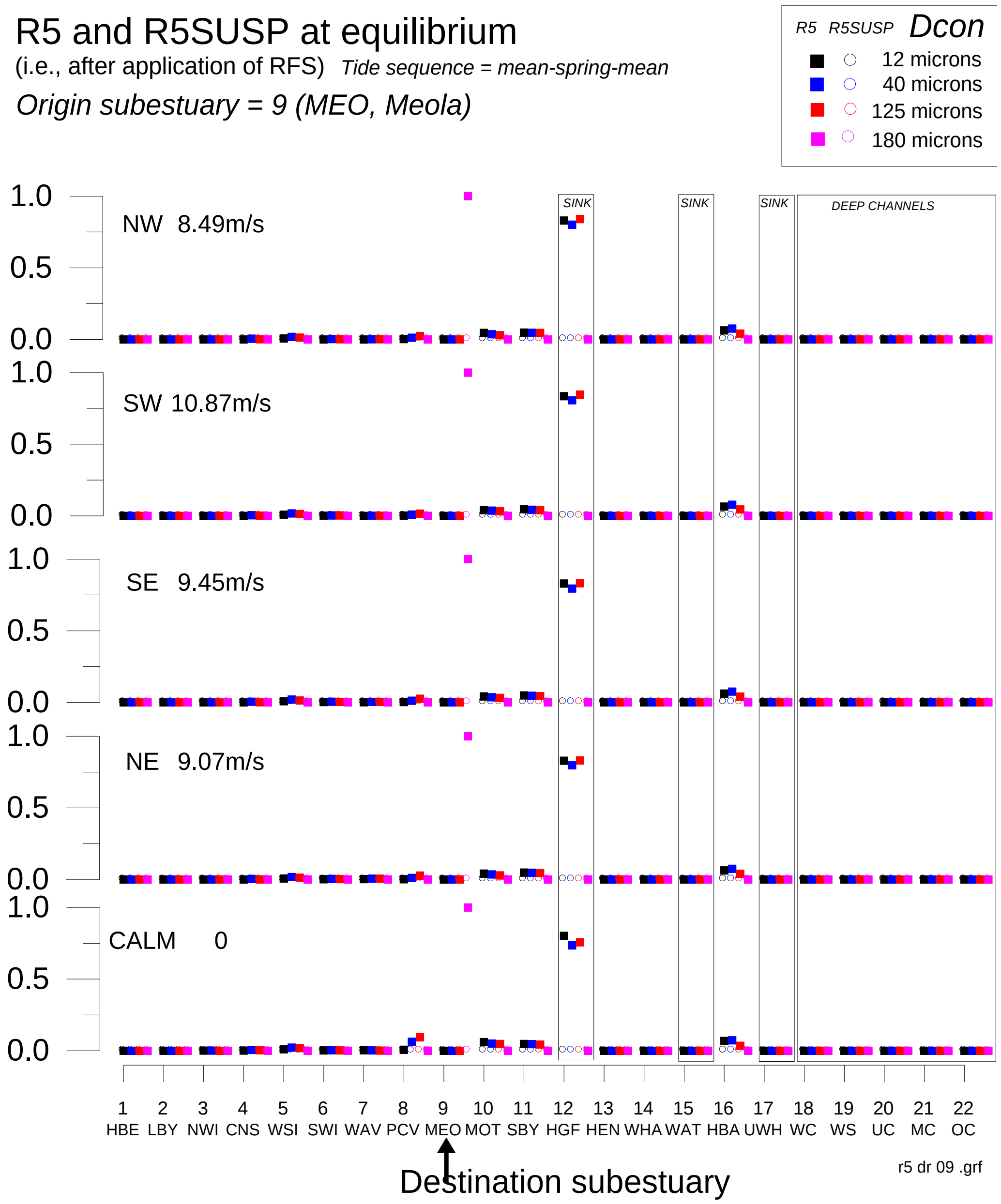

R5 and R5SUSP at equilibrium
(i.e., after application of RFS) Tide sequence = mean-spring-mean
Origin subestuary = 9 (MEO, Meola)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
SINK
SINK
SINK
DEEP CHANNELS
1.0
0.5
0.0
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r5 dr 09 .grf

Figure 158

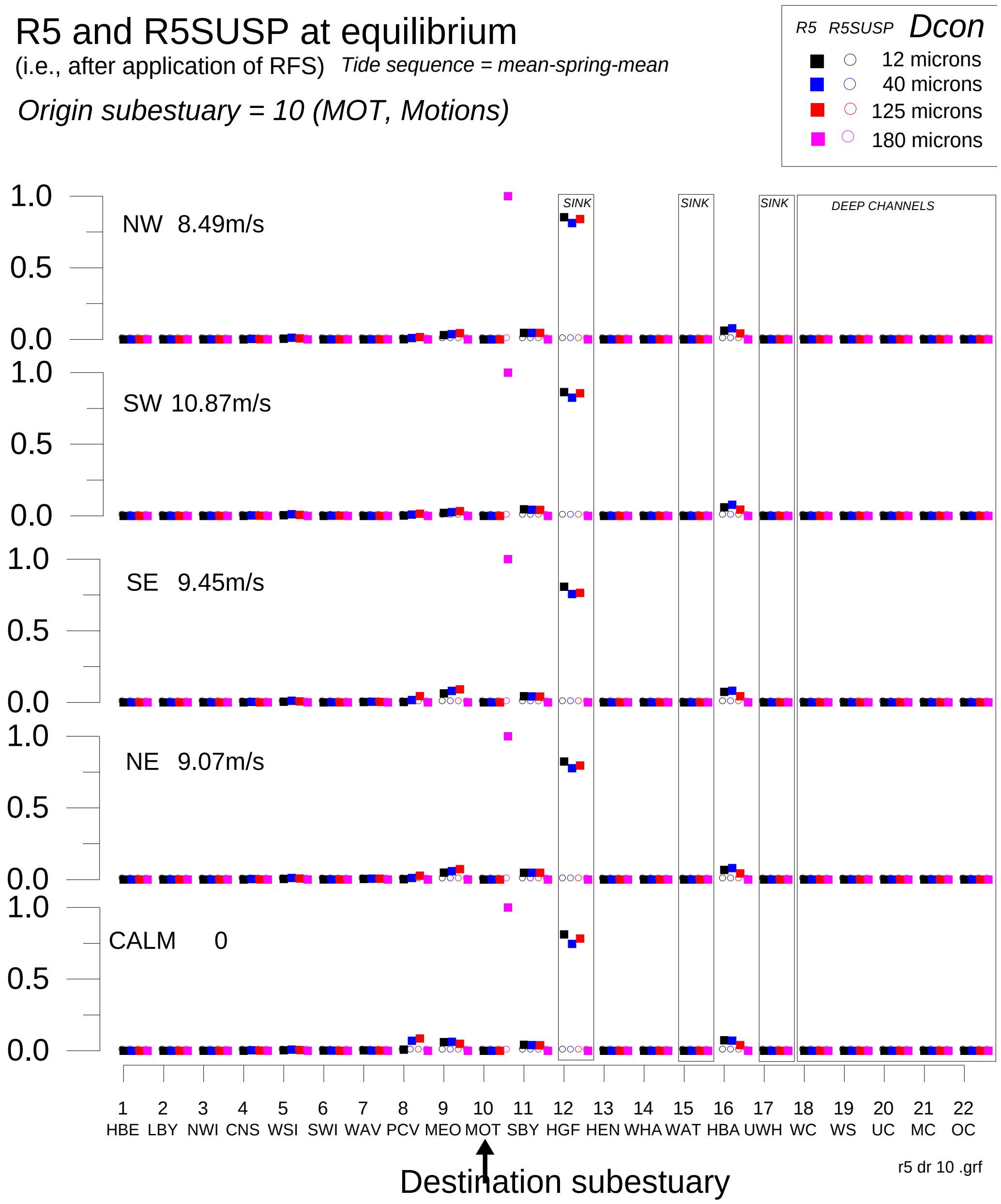
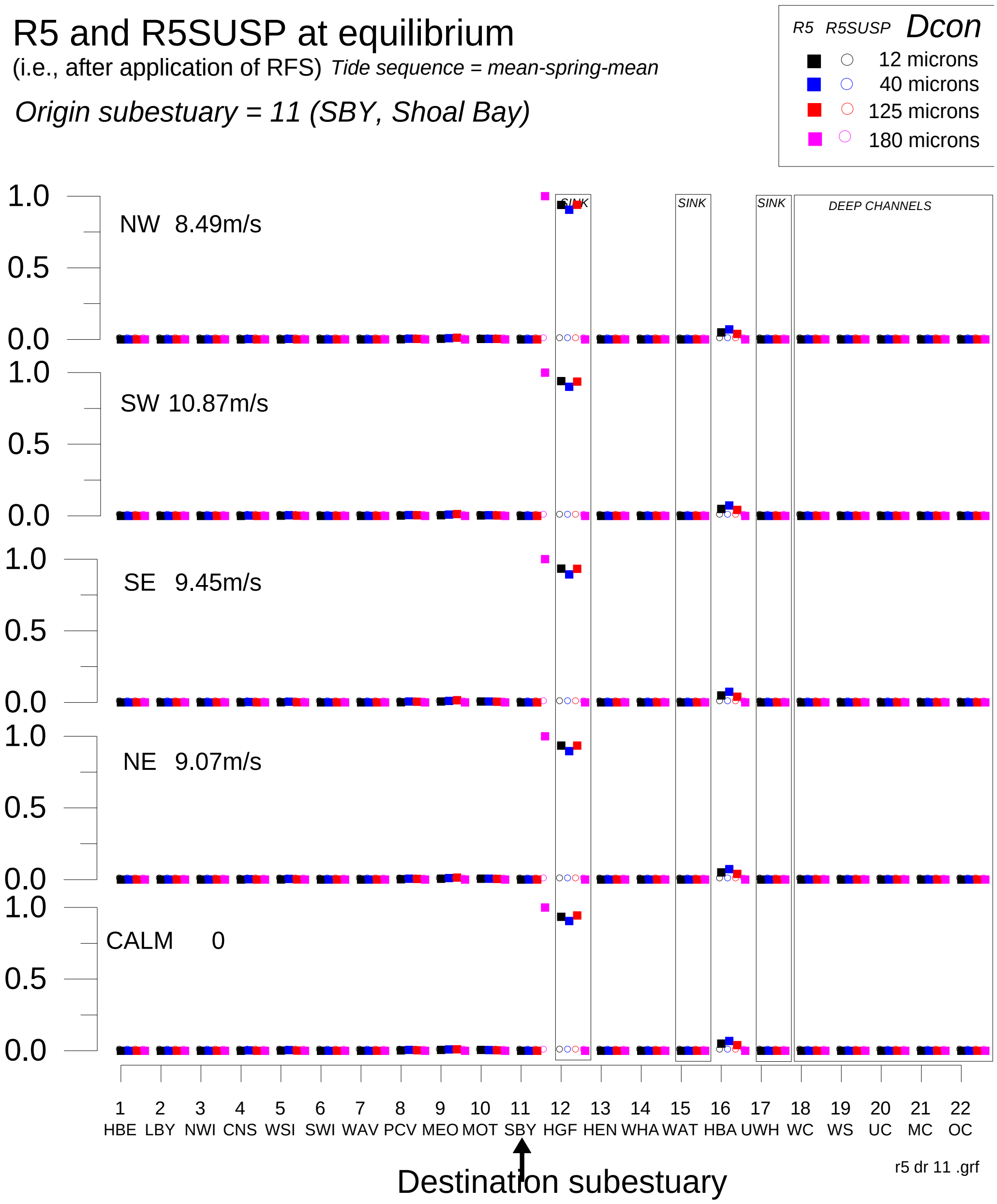

R5 and R5SUSP at equilibrium
(i.e., after application of RFS) Tide sequence = mean-spring-mean
Origin subestuary = 10 (MOT, Motions)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
1.0
0.5
0.0
SINK
SINK
SINK
DEEP CHANNELS
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r5 dr 10 .grf

Figure 159



R5 and R5SUSP at equilibrium
(i.e., after application of RFS) *Tide sequence = mean-spring-mean*
*Origin subestuary = 11 (SBY, Shoal Bay)*
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
1.0
0.5
0.0
SINK
SINK
SINK
DEEP CHANNELS
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r5 dr 11 .grf

**Figure 160**

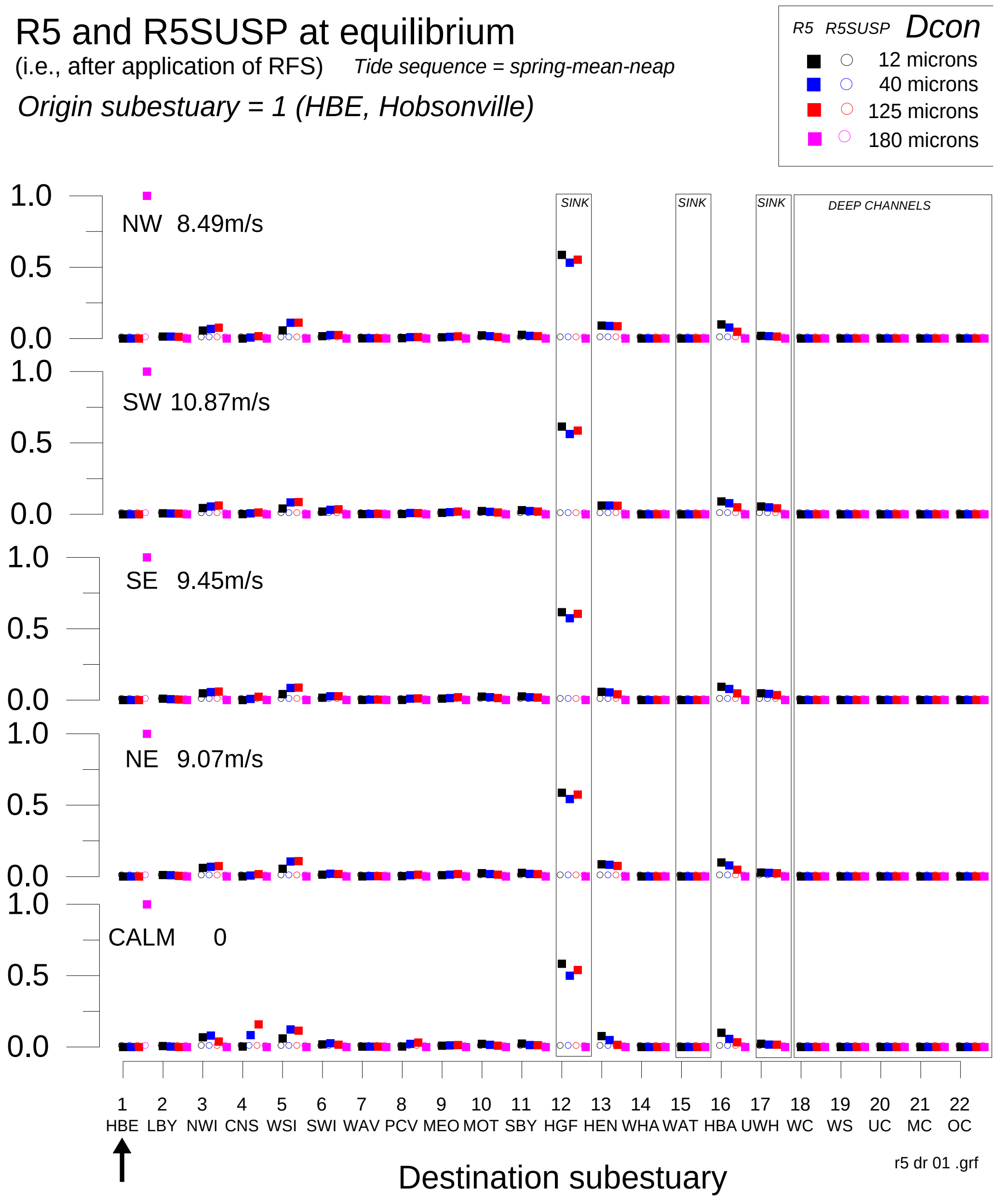

R5 and R5SUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = spring-mean-neap
Origin subestuary = 1 (HBE, Hobsonville)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
1.0
0.5
0.0
SINK
SINK
SINK
DEEP CHANNELS
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r5 dr 01 .grf

Figure 161

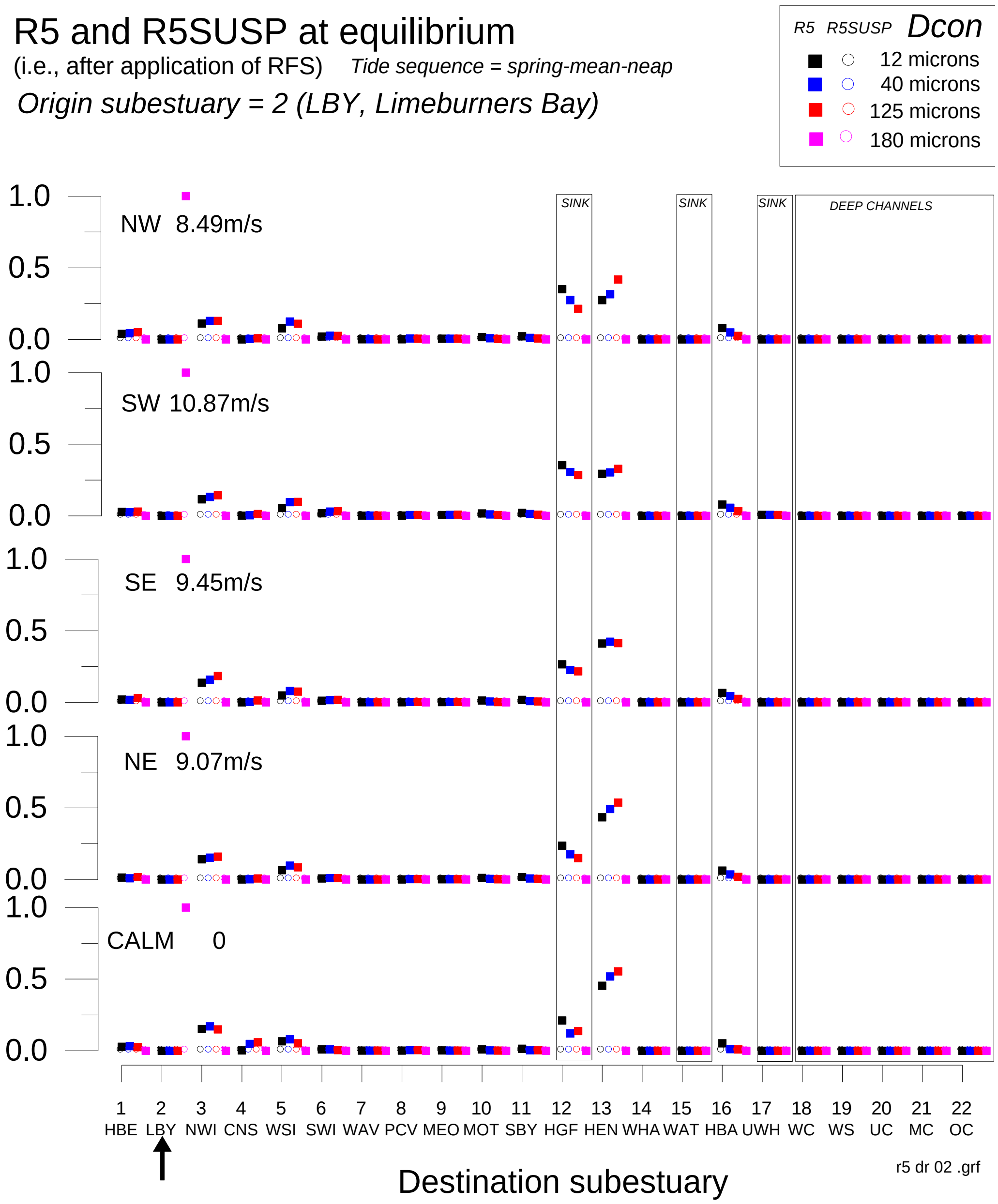

R5 and R5SUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = spring-mean-neap
Origin subestuary = 2 (LBY, Limeburners Bay)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
1.0
0.5
0.0
SINK
SINK
SINK
DEEP CHANNELS
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r5 dr 02 .grf

**Figure 162**

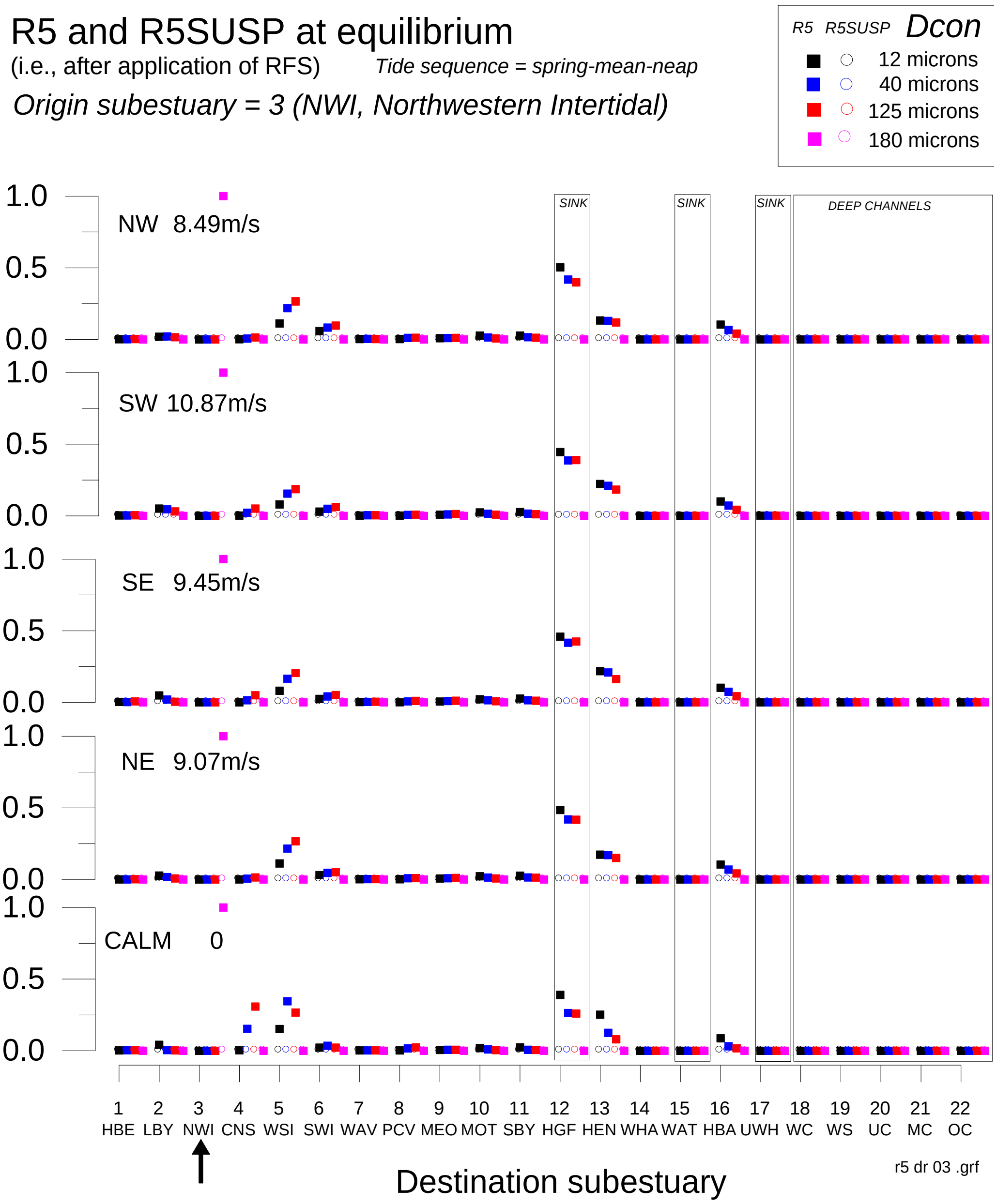
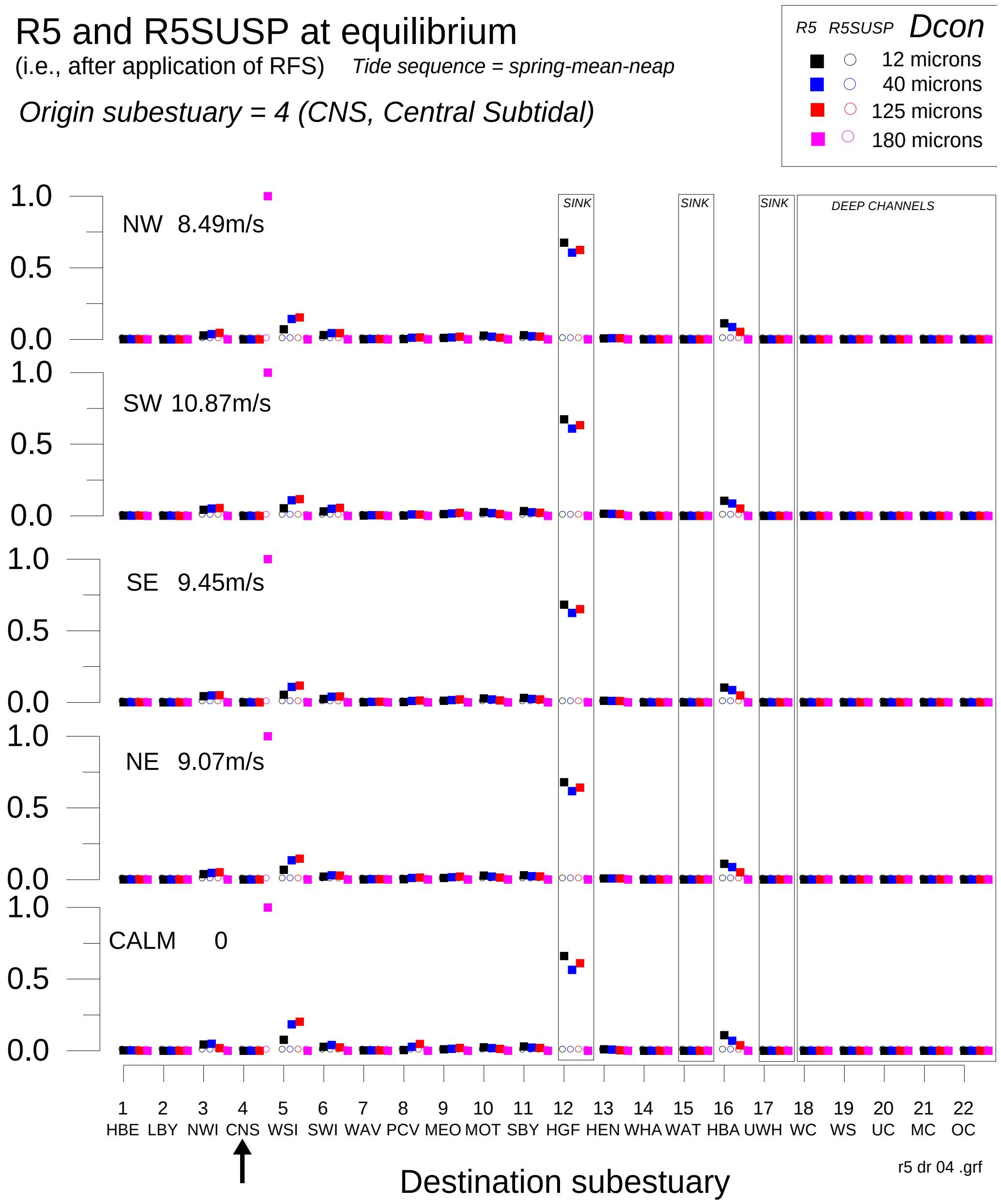
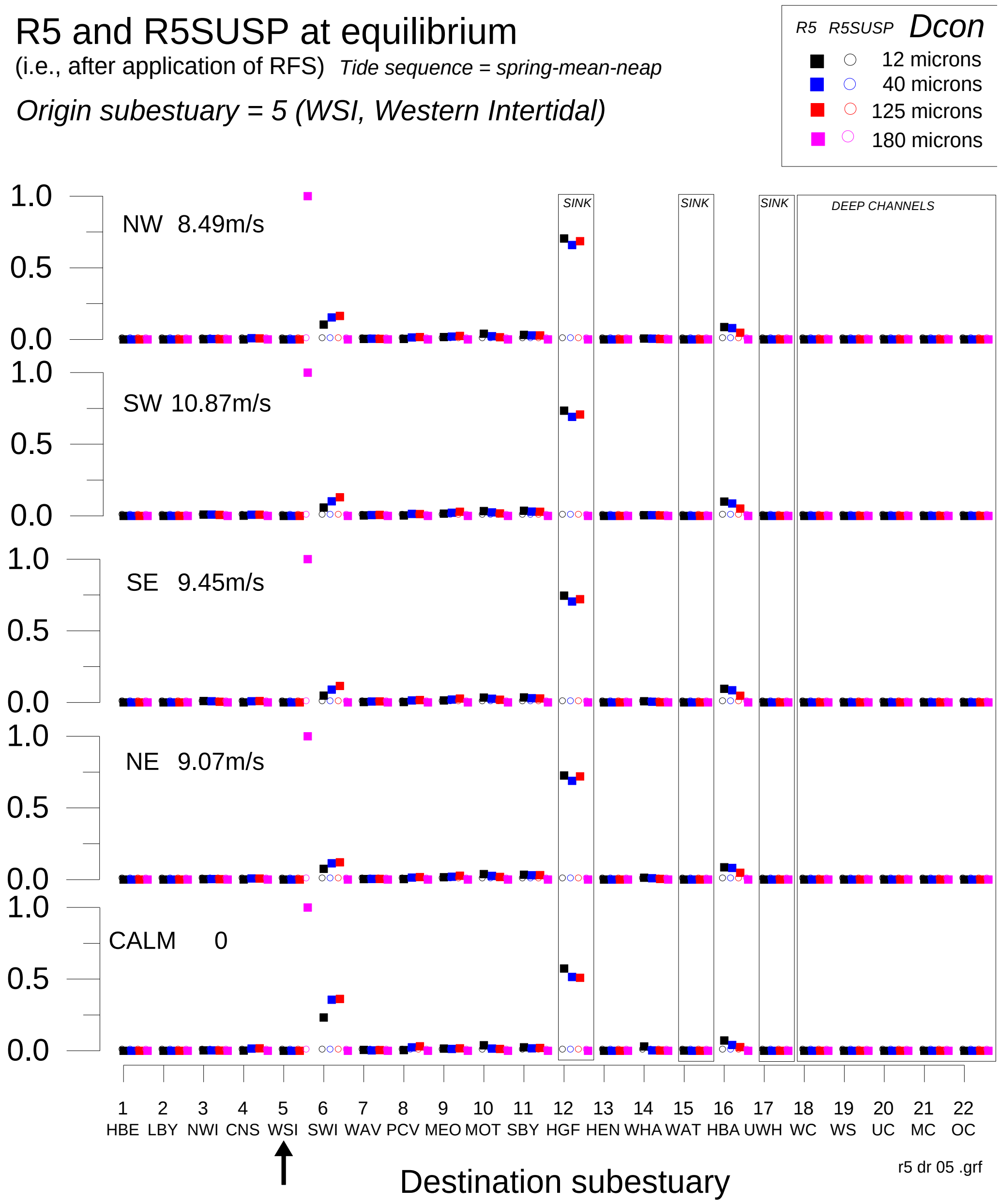

R5 and R5SUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = spring-mean-neap
Origin subestuary = 3 (NWI, Northwestern Intertidal)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
SINK
SINK
SINK
DEEP CHANNELS
1.0
0.5
0.0
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r5 dr 03 .grf

Figure 163



R5 and R5SUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = spring-mean-neap
Origin subestuary = 4 (CNS, Central Subtidal)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
SINK
SINK
SINK
DEEP CHANNELS
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r5 dr 04 .grf

Figure 164



R5 and R5SUSP at equilibrium
(i.e., after application of RFS) Tide sequence = spring-mean-neap
Origin subestuary = 5 (WSI, Western Intertidal)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
1.0
0.5
0.0
SINK
SINK
SINK
DEEP CHANNELS
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22
HBE LBY NWI CNS WSI SWI WAV PCV MEO MOT SBY HGF HEN WHA WAT HBA UWH WC WS UC MC OC
Destination subestuary
r5 dr 05 .grf

Figure 165

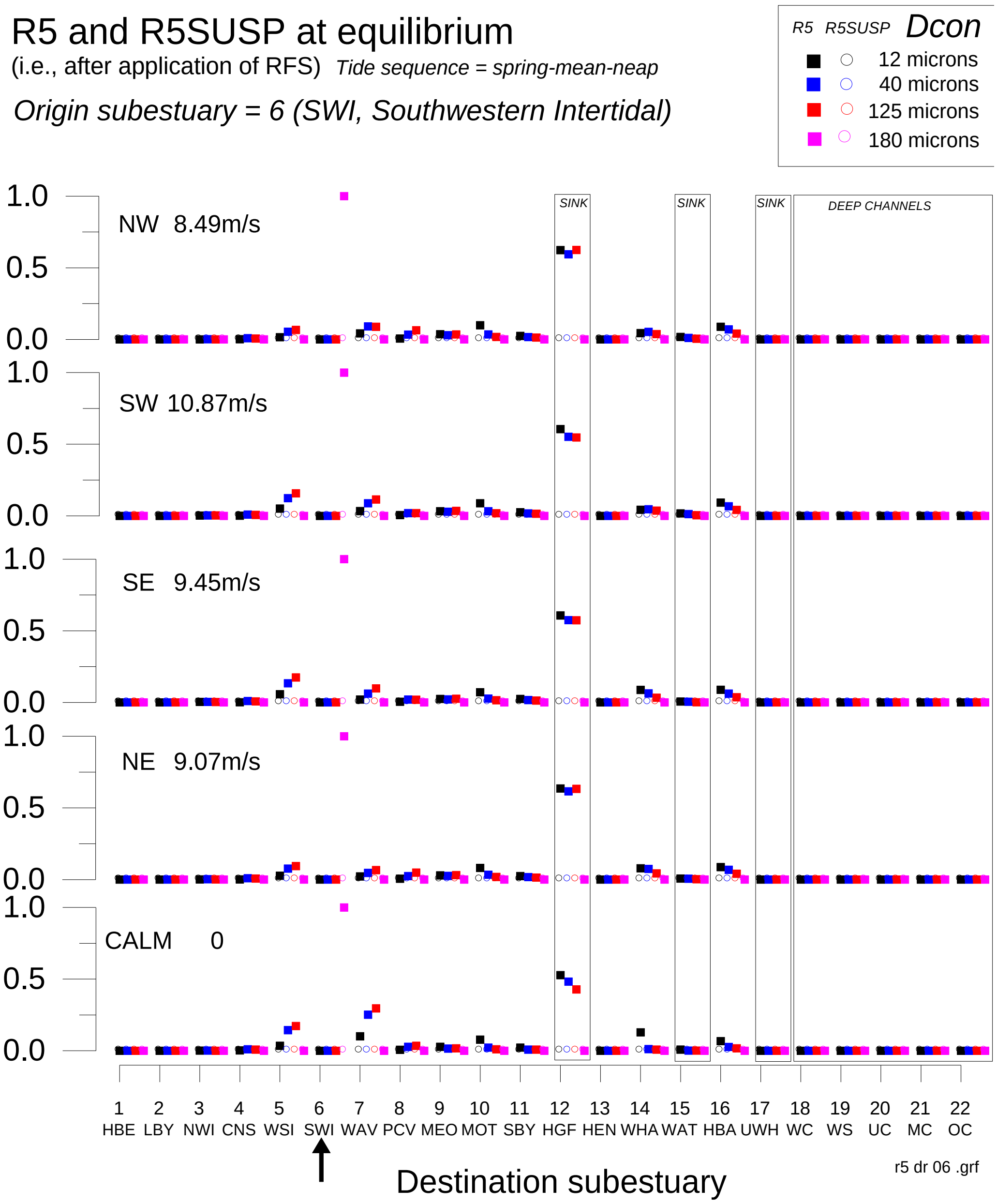

R5 and R5SUSP at equilibrium
(i.e., after application of RFS) Tide sequence = spring-mean-neap
Origin subestuary = 6 (SWI, Southwestern Intertidal)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
1.0
0.5
0.0
SINK
DEEP CHANNELS
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22
HBE LBY NWI CNS WSI SWI WAV PCV MEO MOT SBY HGF HEN WHA WAT HBA UWH WC WS UC MC OC
Destination subestuary
r5 dr 06 .grf

Figure 166

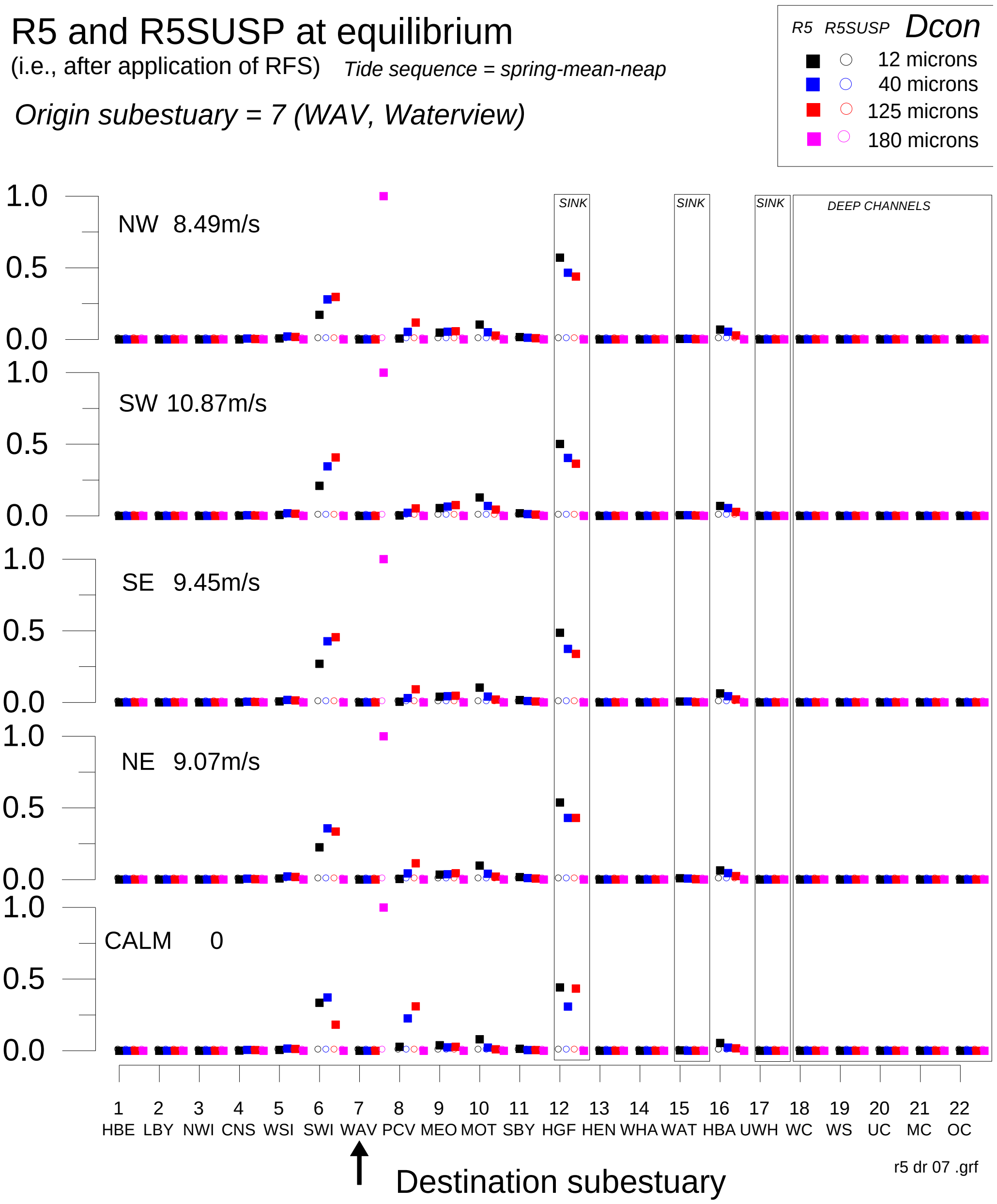

R5 and R5SUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = spring-mean-neap
Origin subestuary = 7 (WAV, Waterview)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
1.0
0.5
0.0
SINK
SINK
SINK
DEEP CHANNELS
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r5 dr 07 .grf

Figure 167

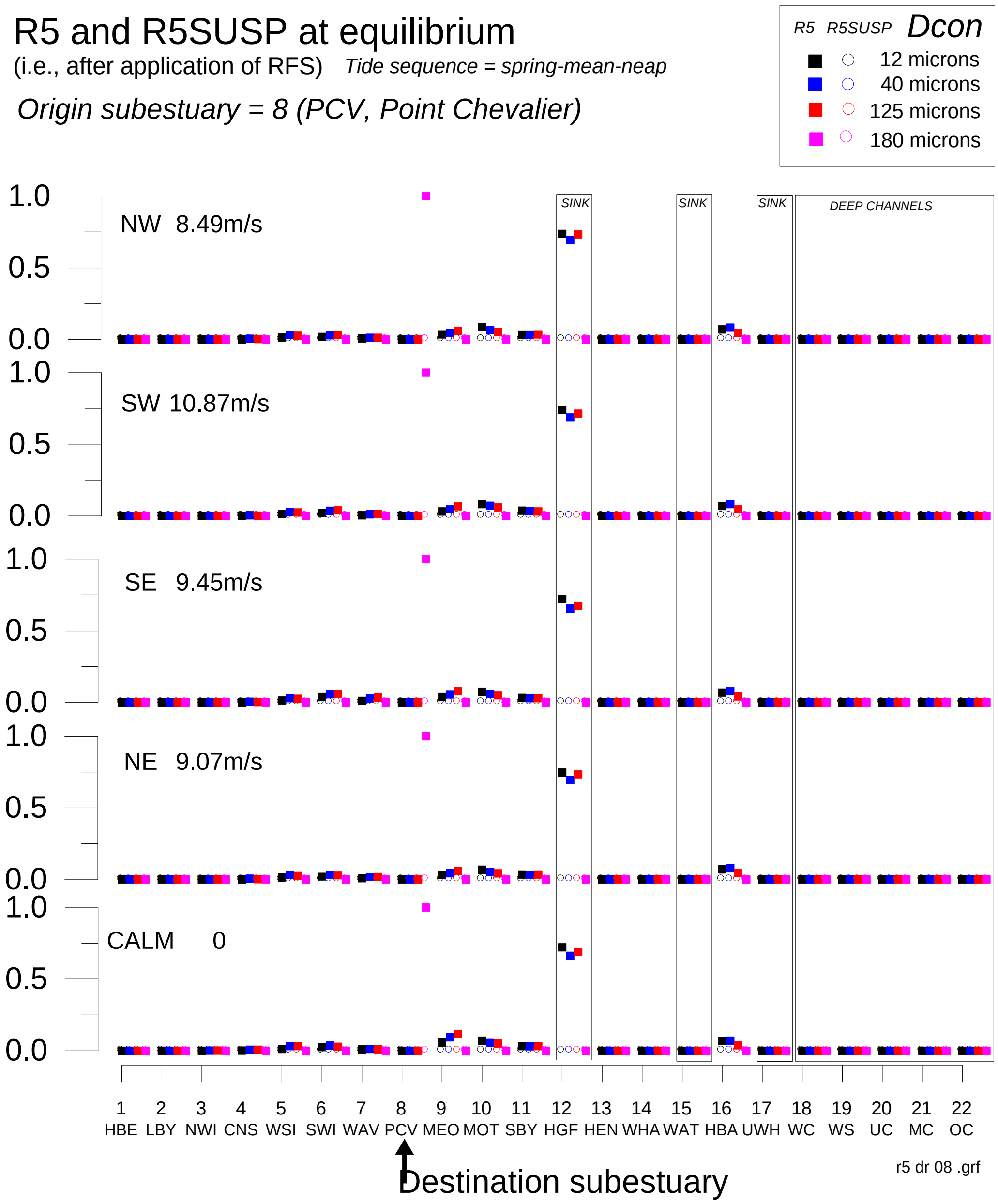
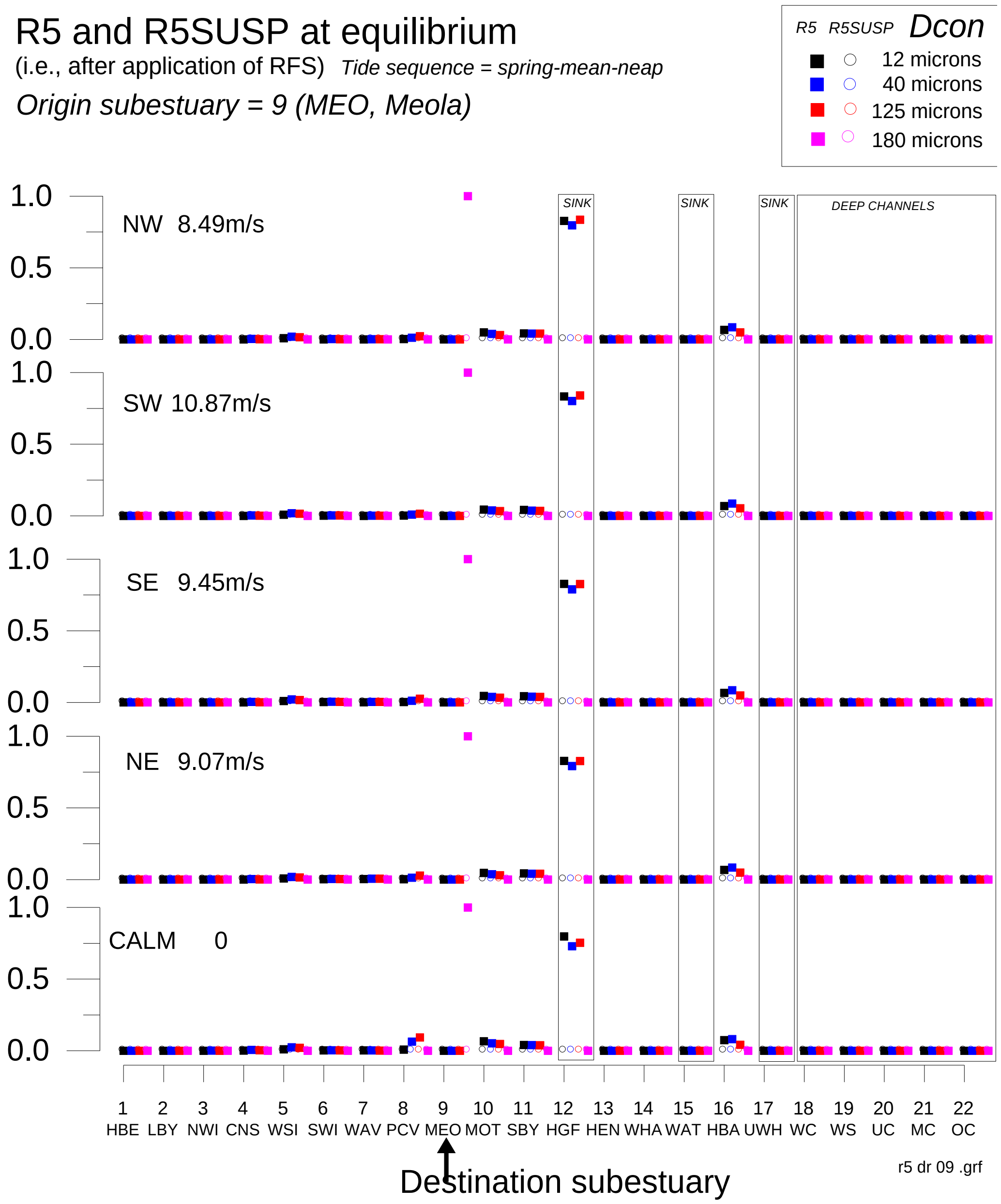
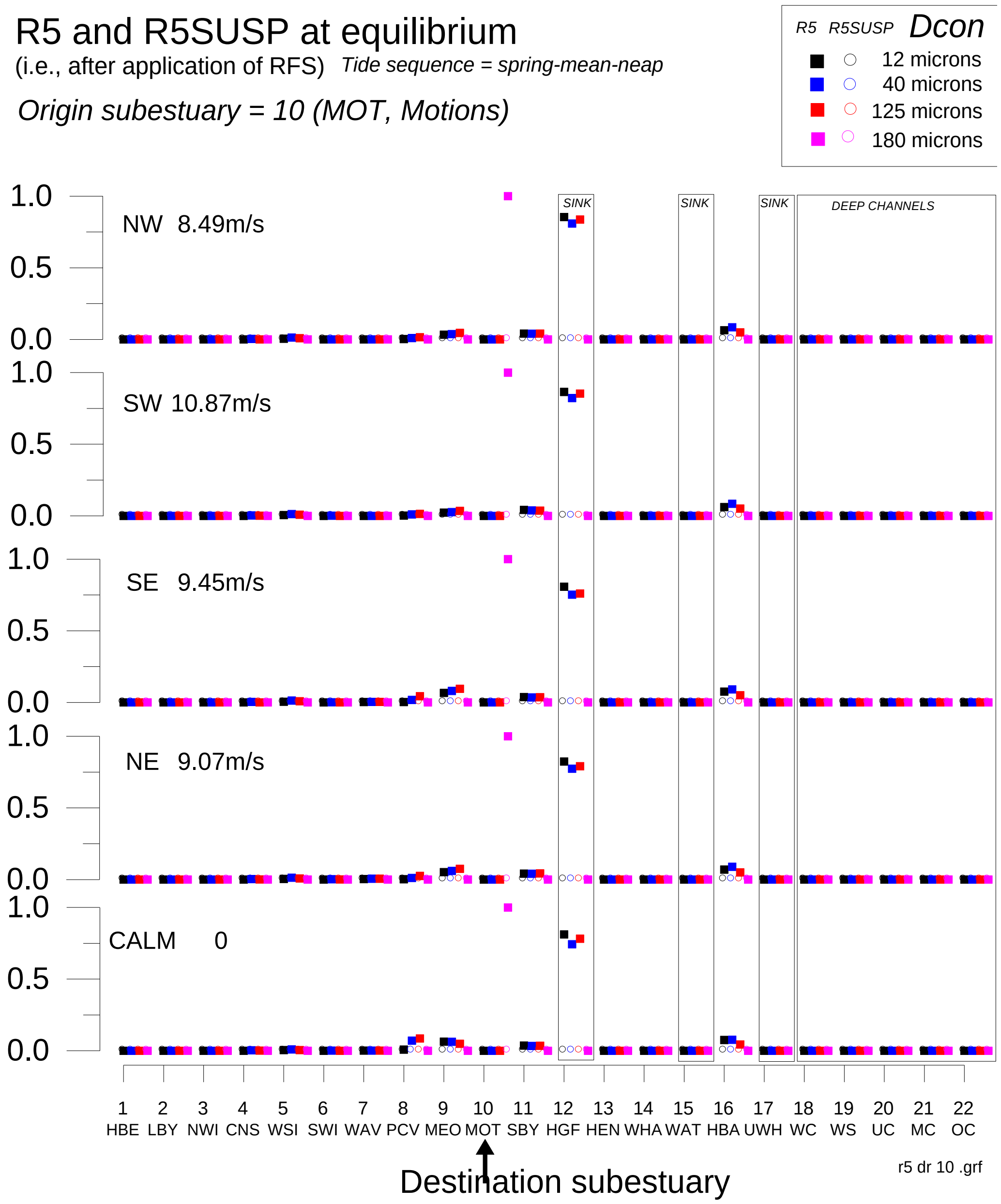

R5 and R5SUSP at equilibrium
(i.e., after application of RFS) Tide sequence = spring-mean-neap
Origin subestuary = 8 (PCV, Point Chevalier)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
SINK
SINK
SINK
DEEP CHANNELS
1.0
0.5
0.0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22
HBE LBY NWI CNS WSI SWI WAV PCV MEO MOT SBY HGF HEN WHA WAT HBA UWH WC WS UC MC OC
Destination subestuary
r5 dr 08 .grf

Figure 168



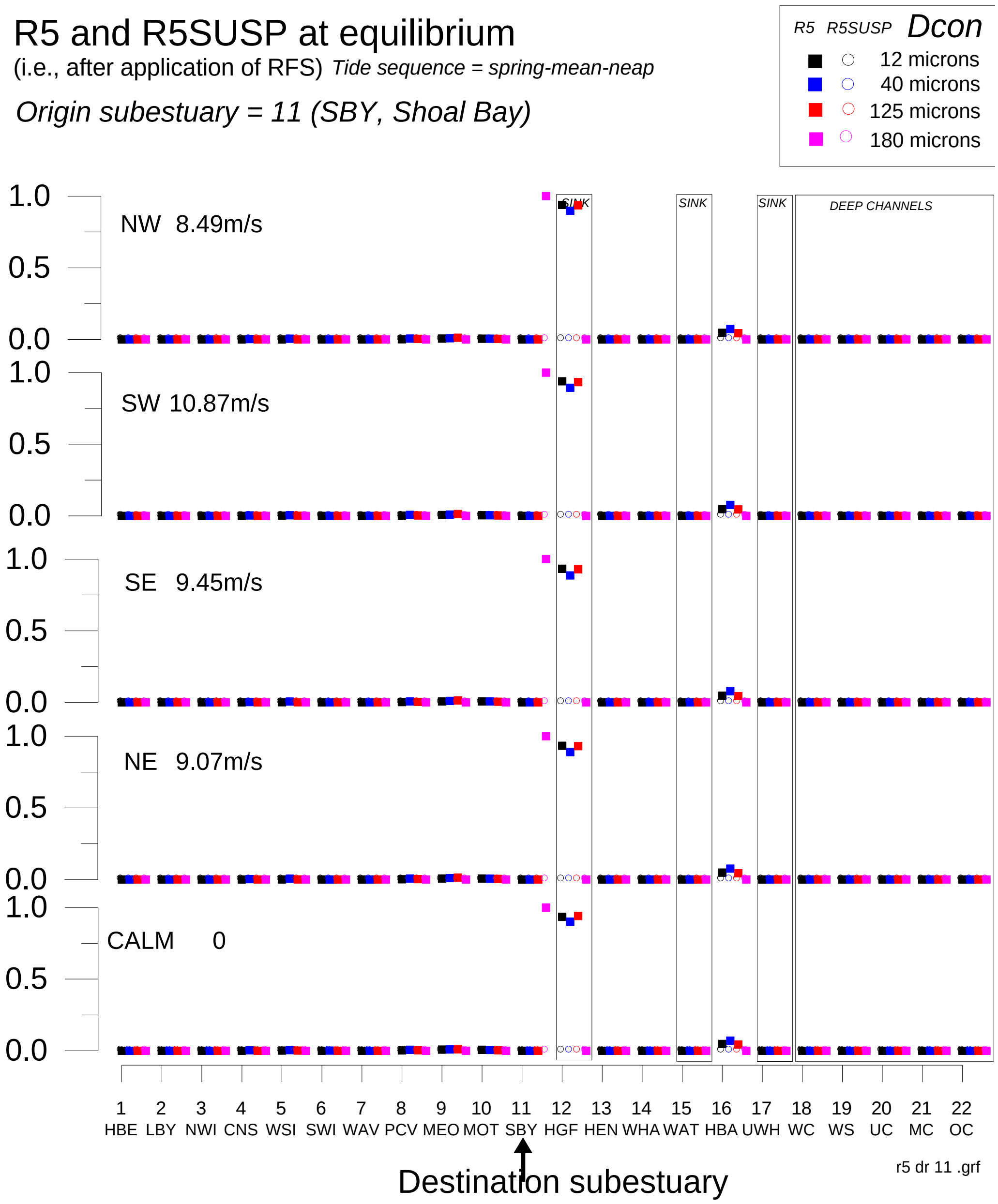
R5 and R5SUSP at equilibrium
(i.e., after application of RFS) Tide sequence = spring-mean-neap
Origin subestuary = 9 (MEO, Meola)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
1.0
0.5
0.0
SINK
SINK
SINK
DEEP CHANNELS
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22
HBE LBY NWI CNS WSI SWI WAV PCV MEO MOT SBY HGF HEN WHA WAT HBA UWH WC WS UC MC OC
Destination subestuary
r5 dr 09 .grf

**Figure 169**



R5 and R5SUSP at equilibrium
(i.e., after application of RFS) Tide sequence = spring-mean-neap
Origin subestuary = 10 (MOT, Motions)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
SINK
SINK
SINK
DEEP CHANNELS
1.0
0.5
0.0
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r5 dr 10 .grf

Figure 170


R5 and R5SUSP at equilibrium
(i.e., after application of RFS) Tide sequence = spring-mean-neap
Origin subestuary = 11 (SBY, Shoal Bay)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
1.0
0.5
0.0
SINK
SINK
SINK
DEEP CHANNELS
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22
HBE LBY NWI CNS WSI SWI WAV PCV MEO MOT SBY HGF HEN WHA WAT HBA UWH WC WS UC MC OC
Destination subestuary
r5 dr 11 .grf

## 17.4 Tide sequence mean–neap–mean

Figure 171

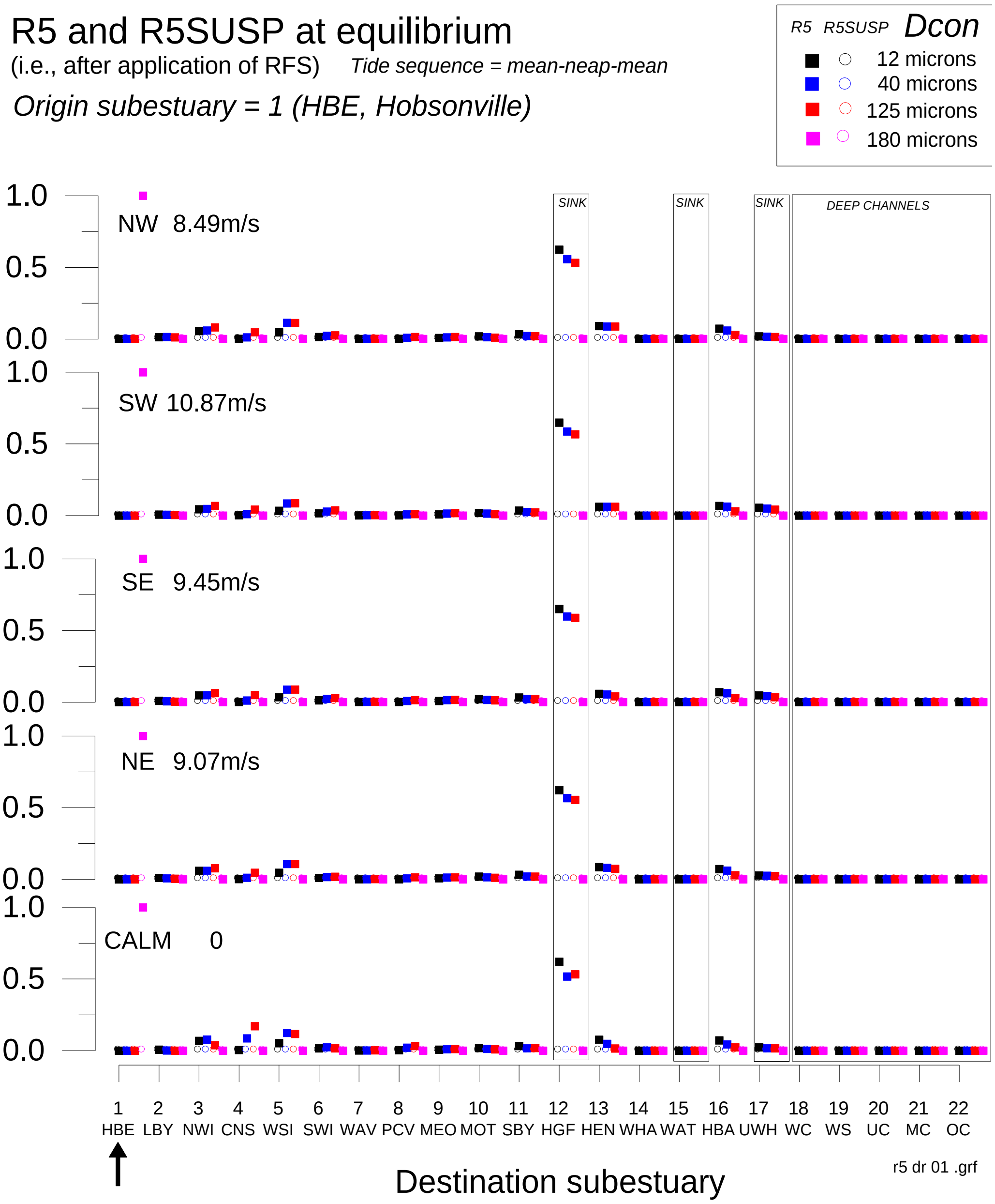


Figure 172

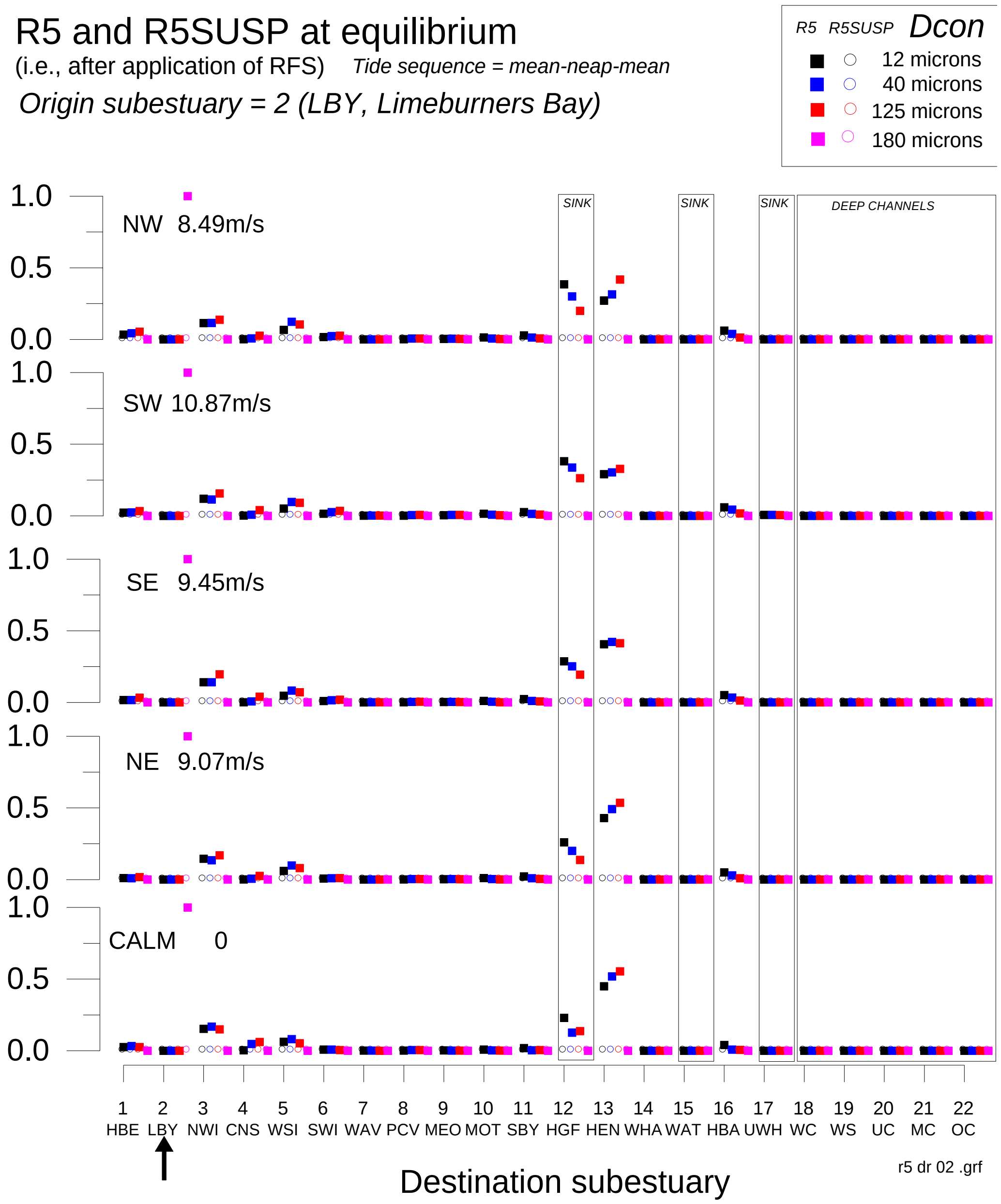

R5 and R5SUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = mean-neap-mean
Origin subestuary = 2 (LBY, Limeburners Bay)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
1.0
0.5
0.0
SINK
SINK
SINK
DEEP CHANNELS
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r5 dr 02 .grf

Figure 173

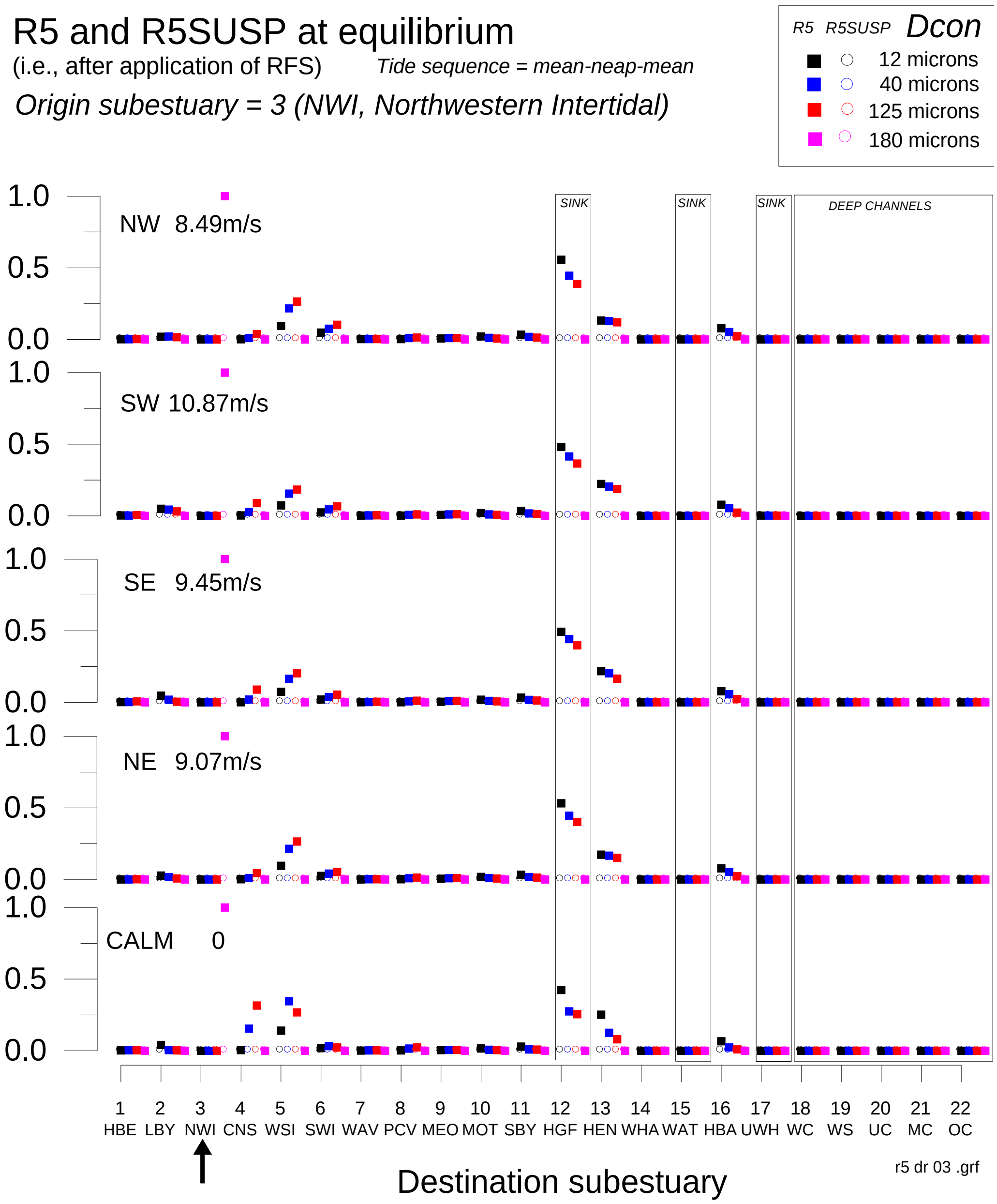

R5 and R5SUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = mean-neap-mean
Origin subestuary = 3 (NWI, Northwestern Intertidal)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
SINK
SINK
SINK
DEEP CHANNELS
1.0
0.5
0.0
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r5 dr 03 .grf

Figure 174

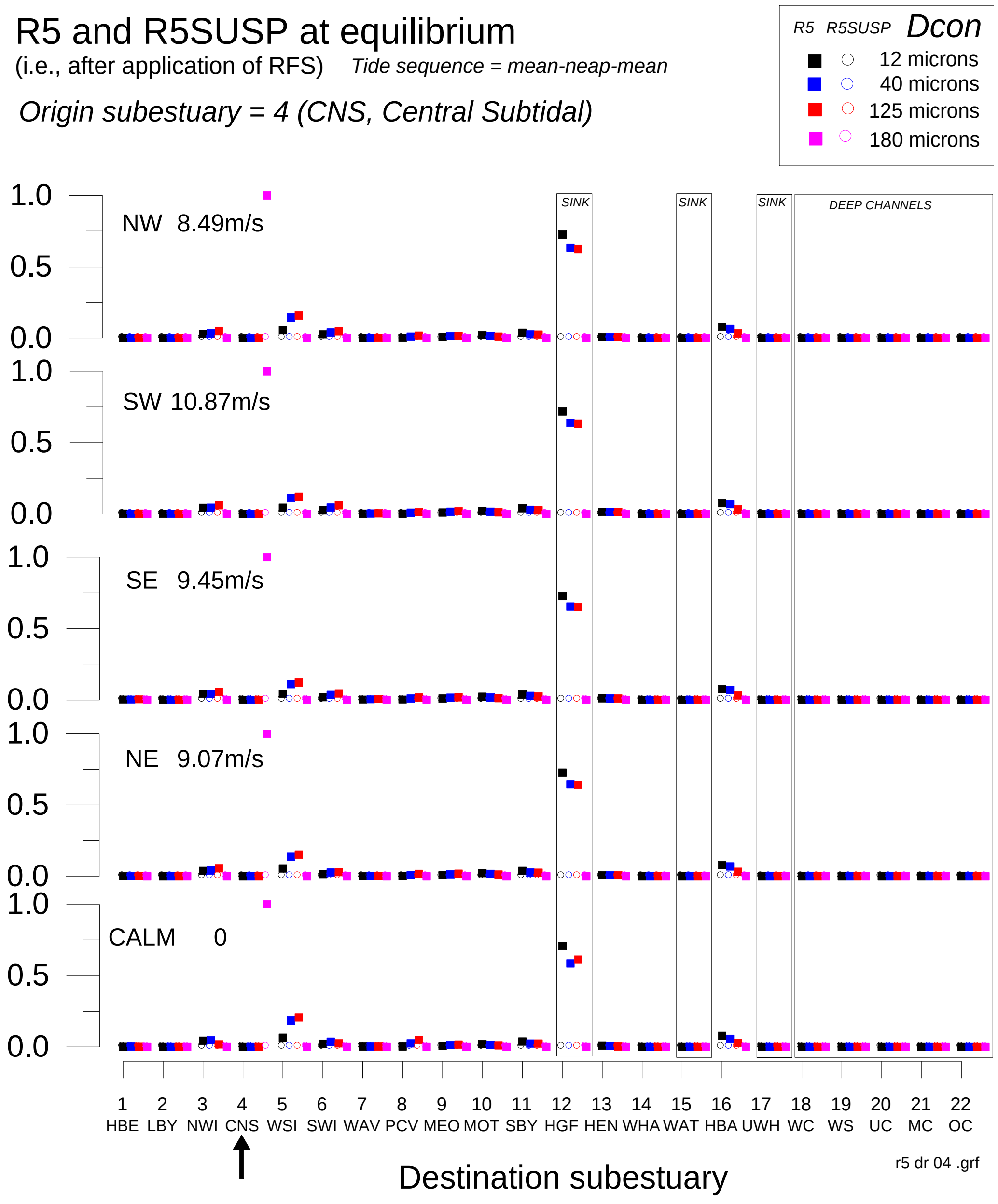
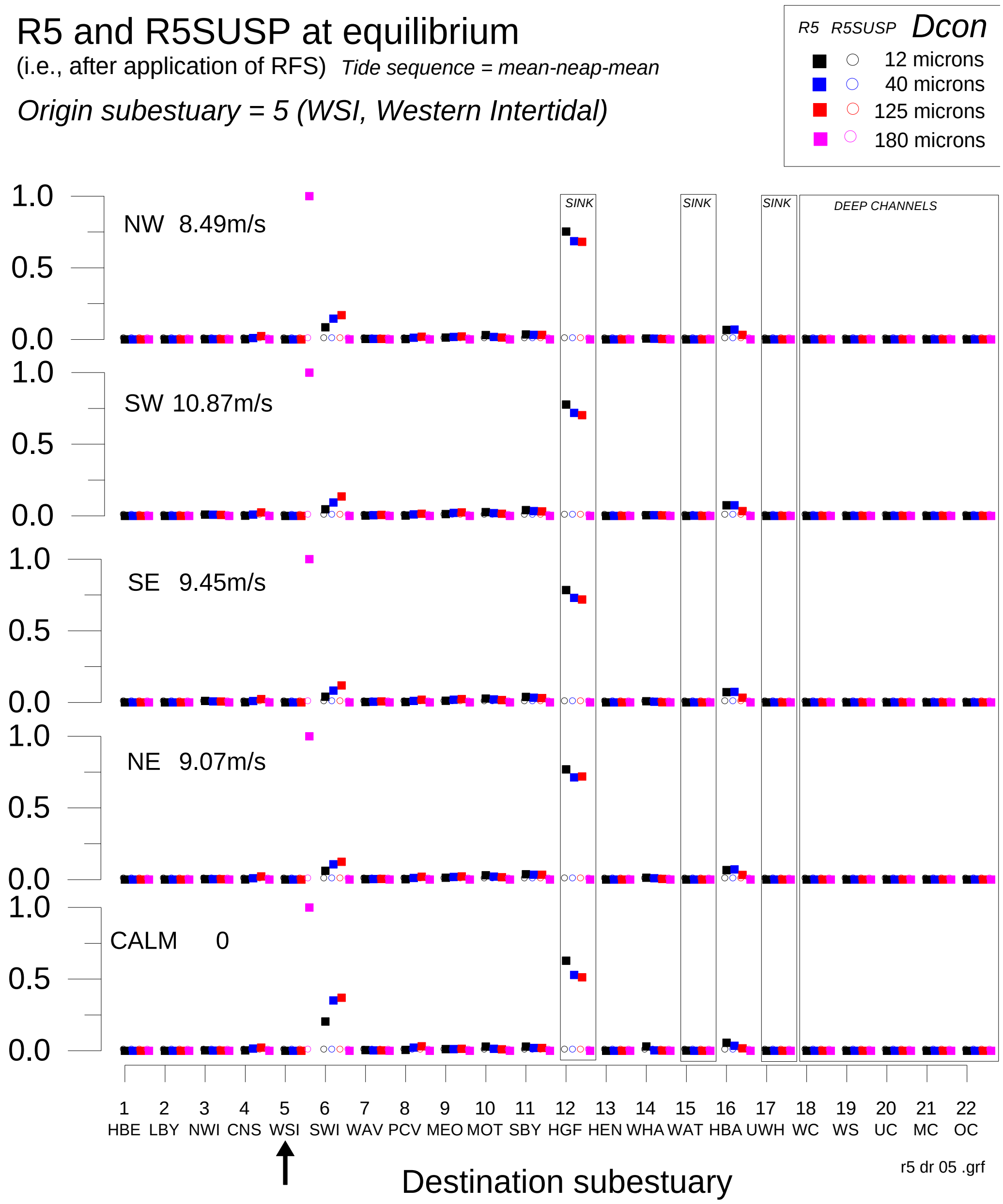

R5 and R5SUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = mean-neap-mean
Origin subestuary = 4 (CNS, Central Subtidal)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
1.0
0.5
0.0
SINK
SINK
SINK
DEEP CHANNELS
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22
HBE LBY NWI CNS WSI SWI WAV PCV MEO MOT SBY HGF HEN WHA WAT HBA UWH WC WS UC MC OC
Destination subestuary
r5 dr 04 .grf

Figure 175



R5 and R5SUSP at equilibrium
(i.e., after application of RFS) Tide sequence = mean-neap-mean
Origin subestuary = 5 (WSI, Western Intertidal)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
1.0
0.5
0.0
SINK
SINK
SINK
DEEP CHANNELS
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r5 dr 05 .grf

Figure 176

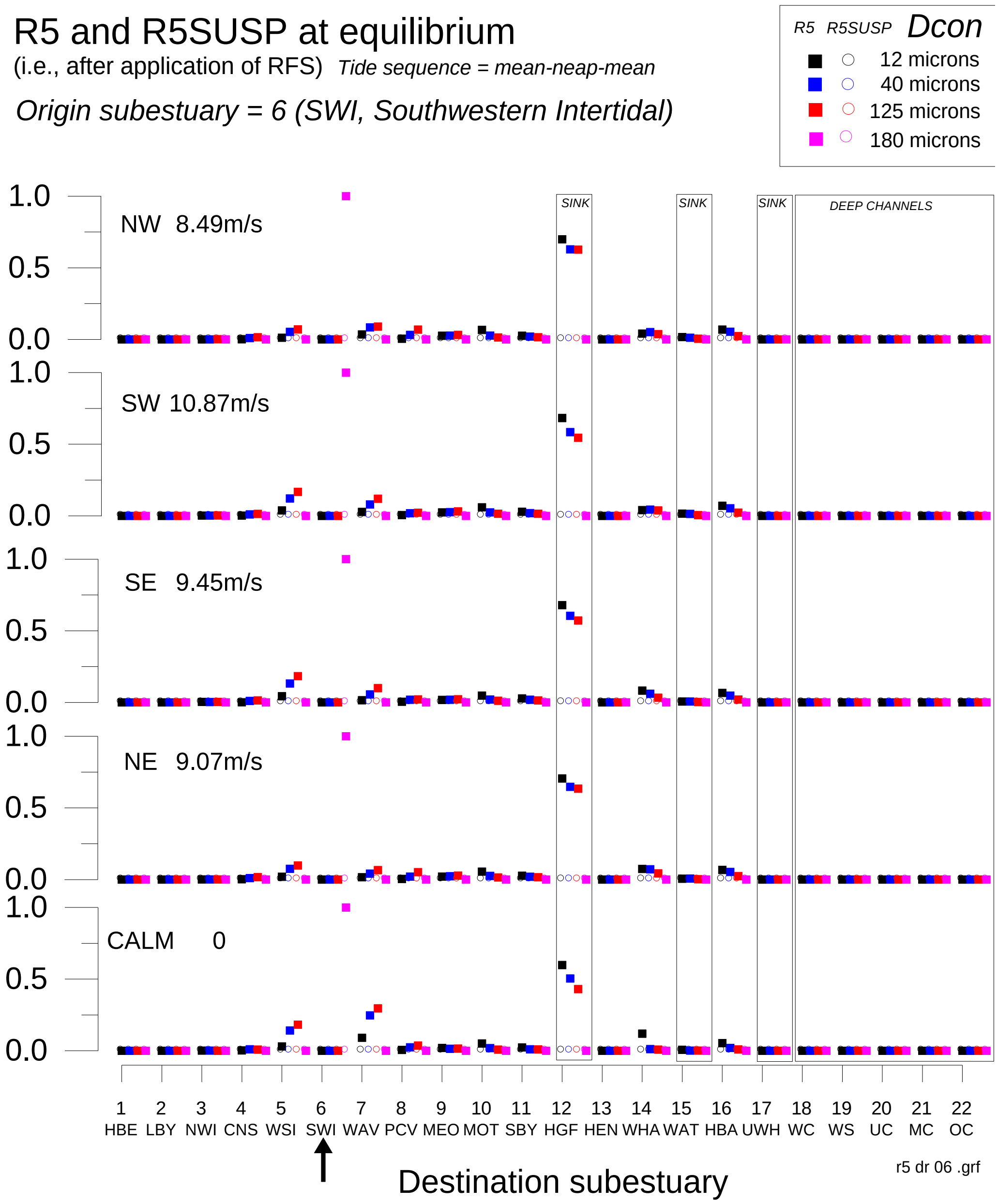
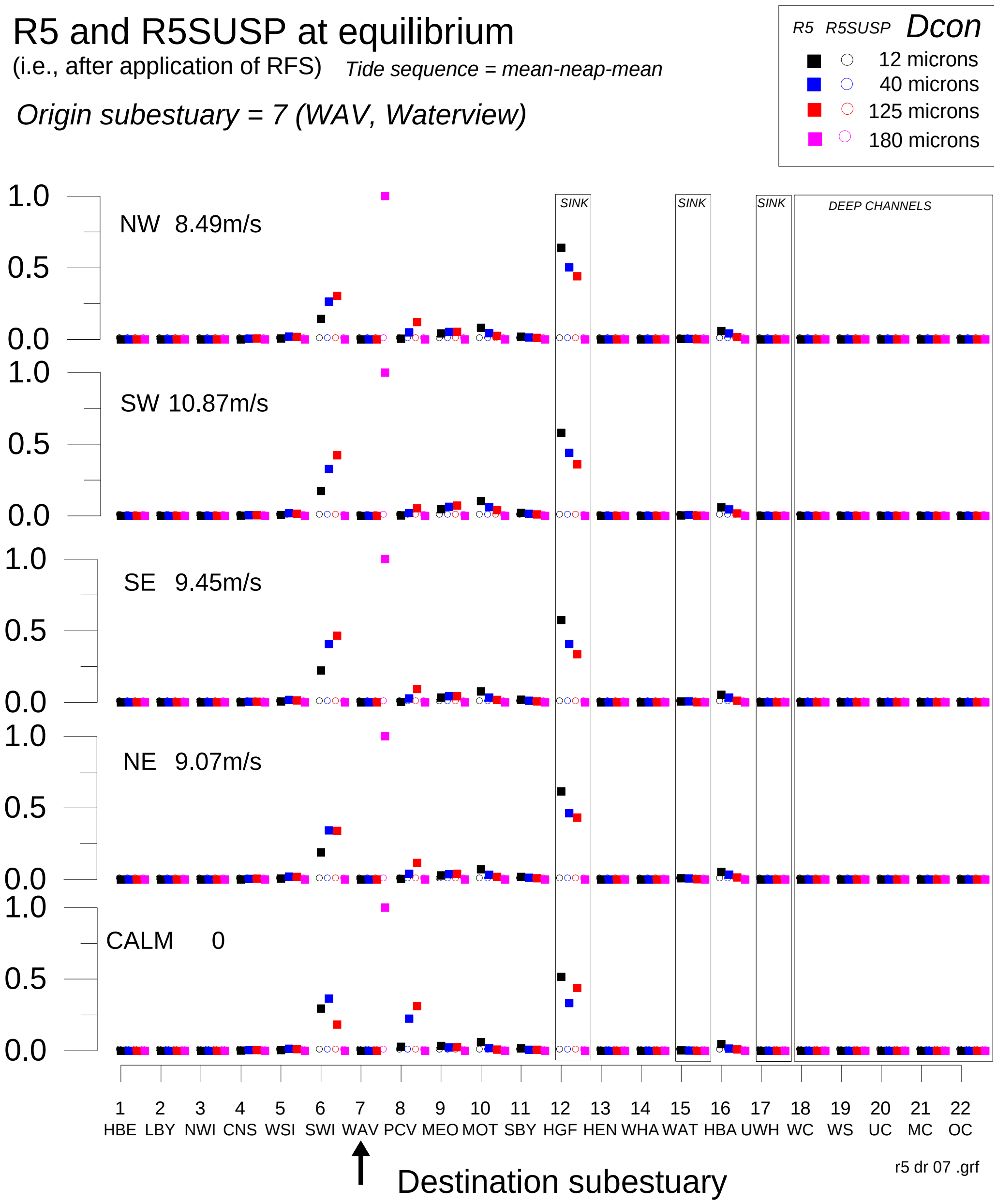

R5 and R5SUSP at equilibrium
(i.e., after application of RFS) Tide sequence = mean-neap-mean
Origin subestuary = 6 (SWI, Southwestern Intertidal)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
1.0
0.5
0.0
SINK
SINK
SINK
DEEP CHANNELS
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r5 dr 06 .grf

Figure 177



R5 and R5SUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = mean-neap-mean
Origin subestuary = 7 (WAV, Waterview)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
1.0
0.5
0.0
SINK
SINK
SINK
DEEP CHANNELS
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22
HBE LBY NWI CNS WSI SWI WAV PCV MEO MOT SBY HGF HEN WHA WAT HBA UWH WC WS UC MC OC
Destination subestuary
r5 dr 07 .grf

Figure 178

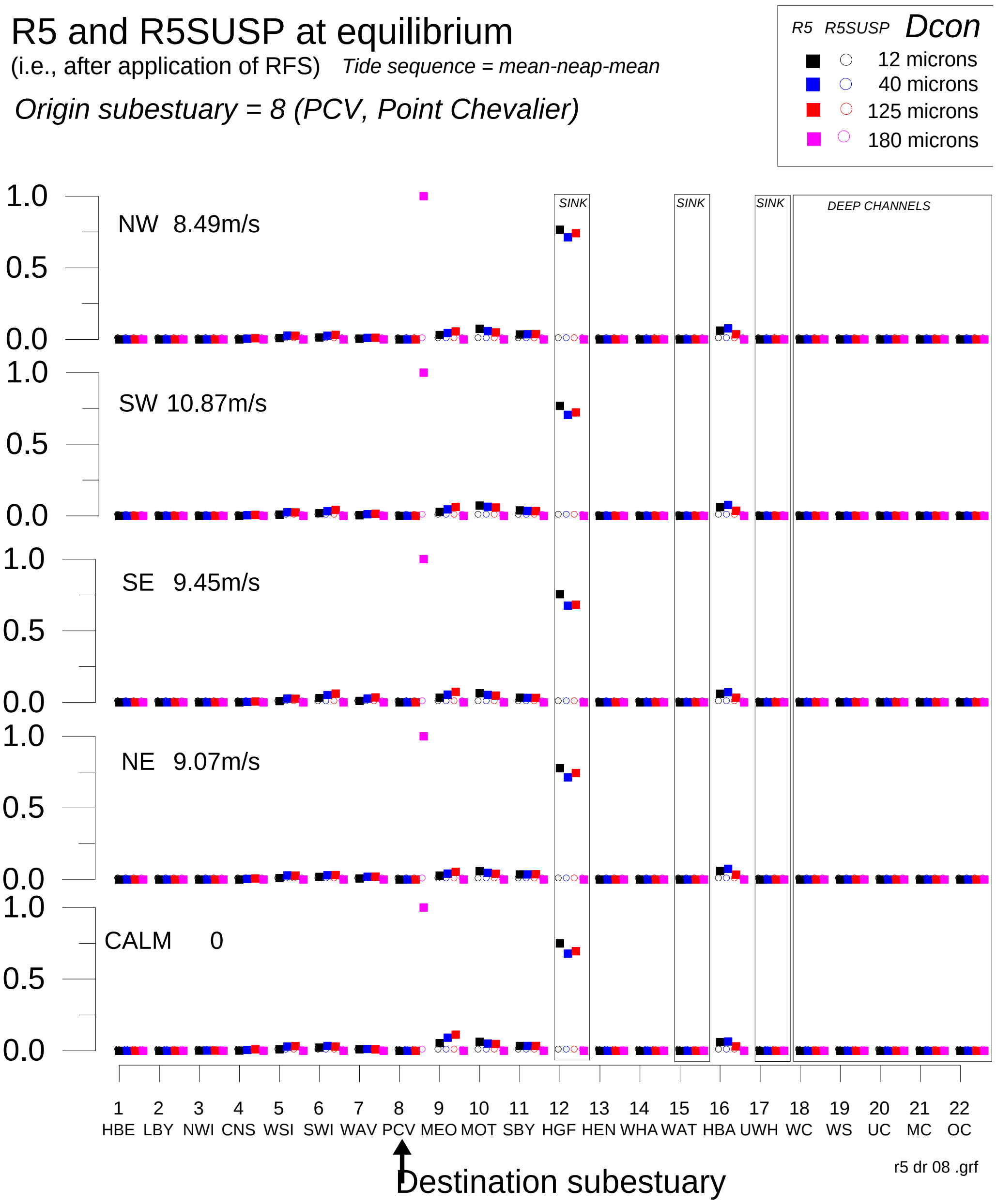

R5 and R5SUSP at equilibrium
(i.e., after application of RFS) Tide sequence = mean-neap-mean
Origin subestuary = 8 (PCV, Point Chevalier)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
SINK
DEEP CHANNELS
1.0
0.5
0.0
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r5 dr 08 .grf

Figure 179

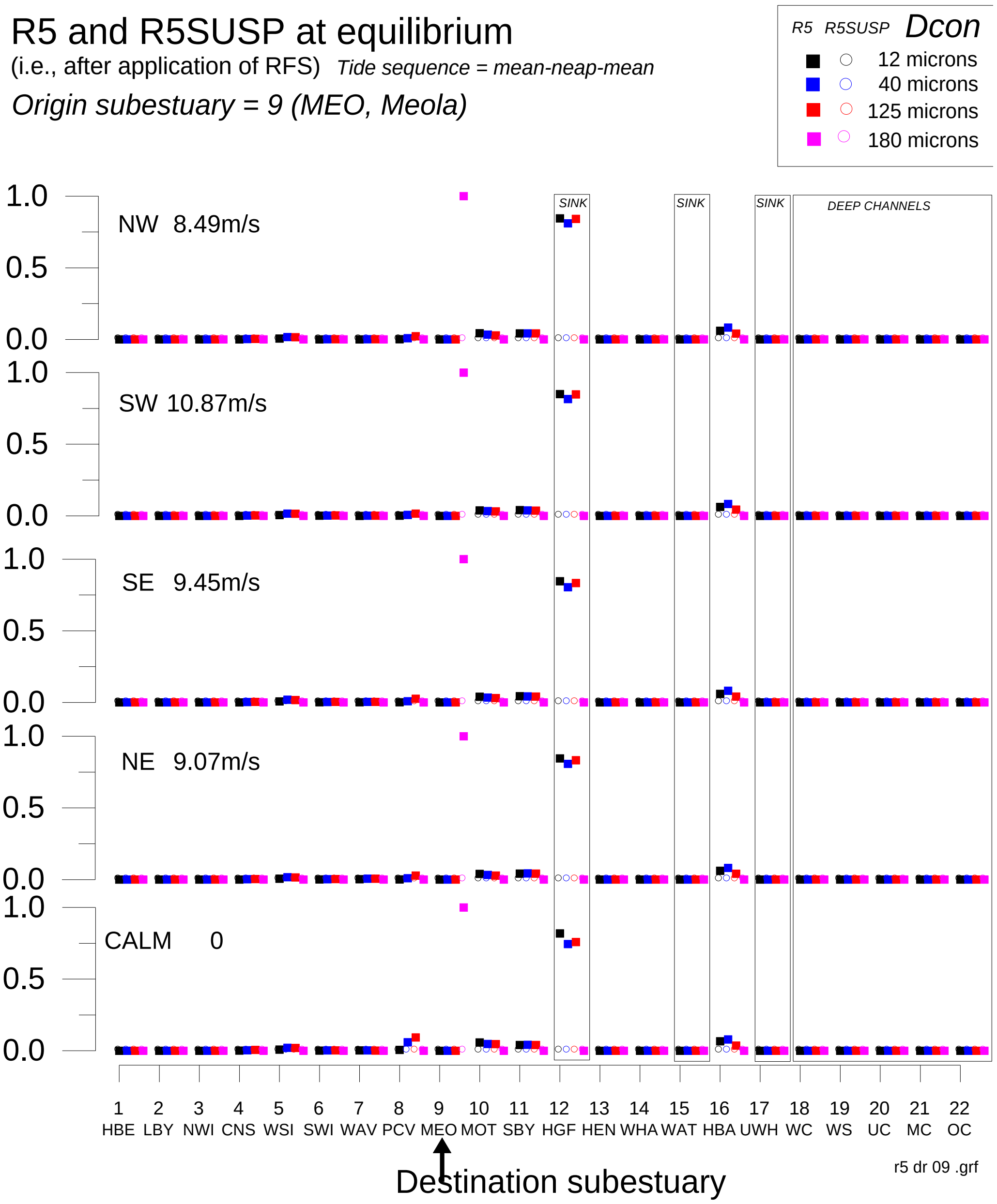
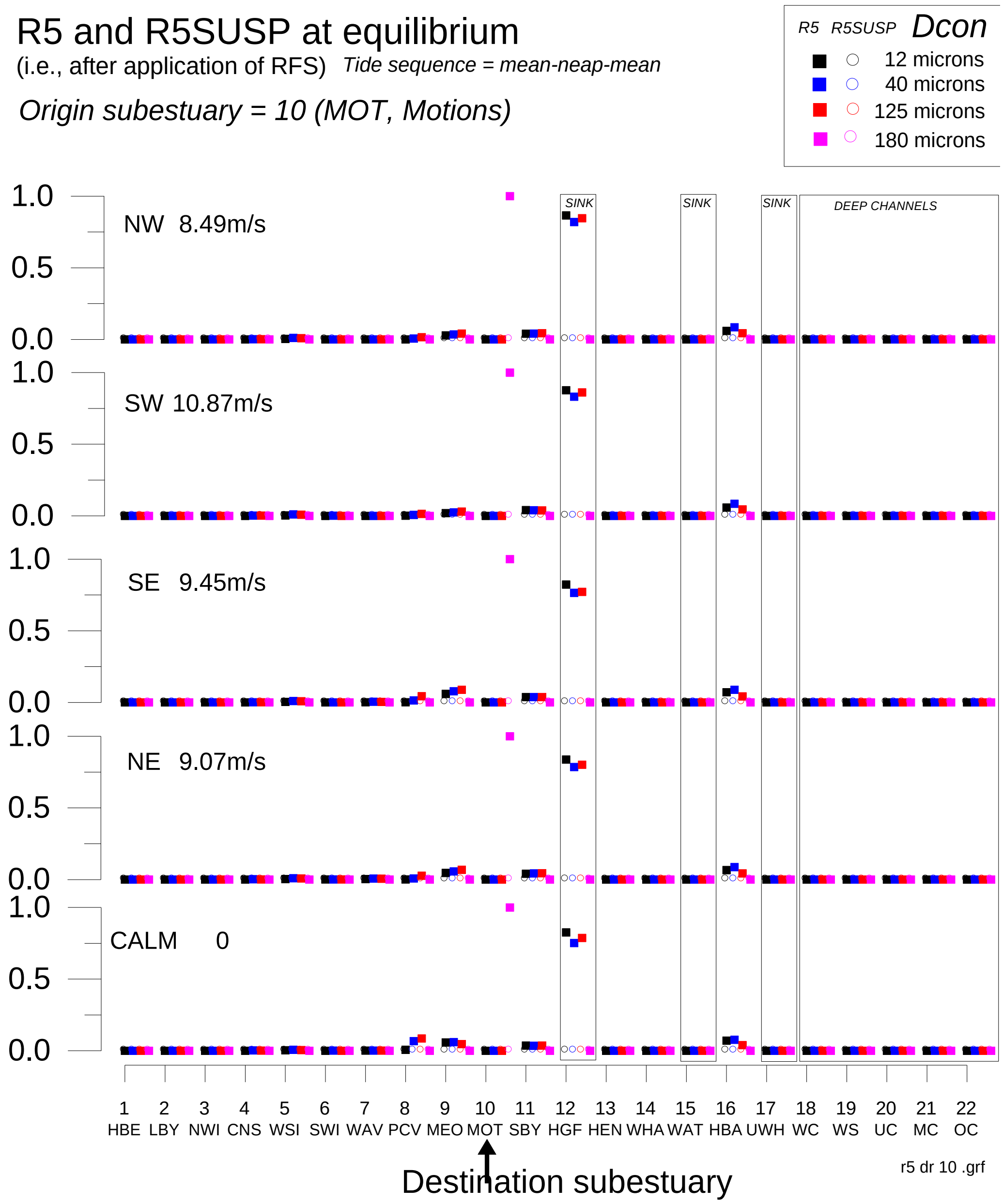
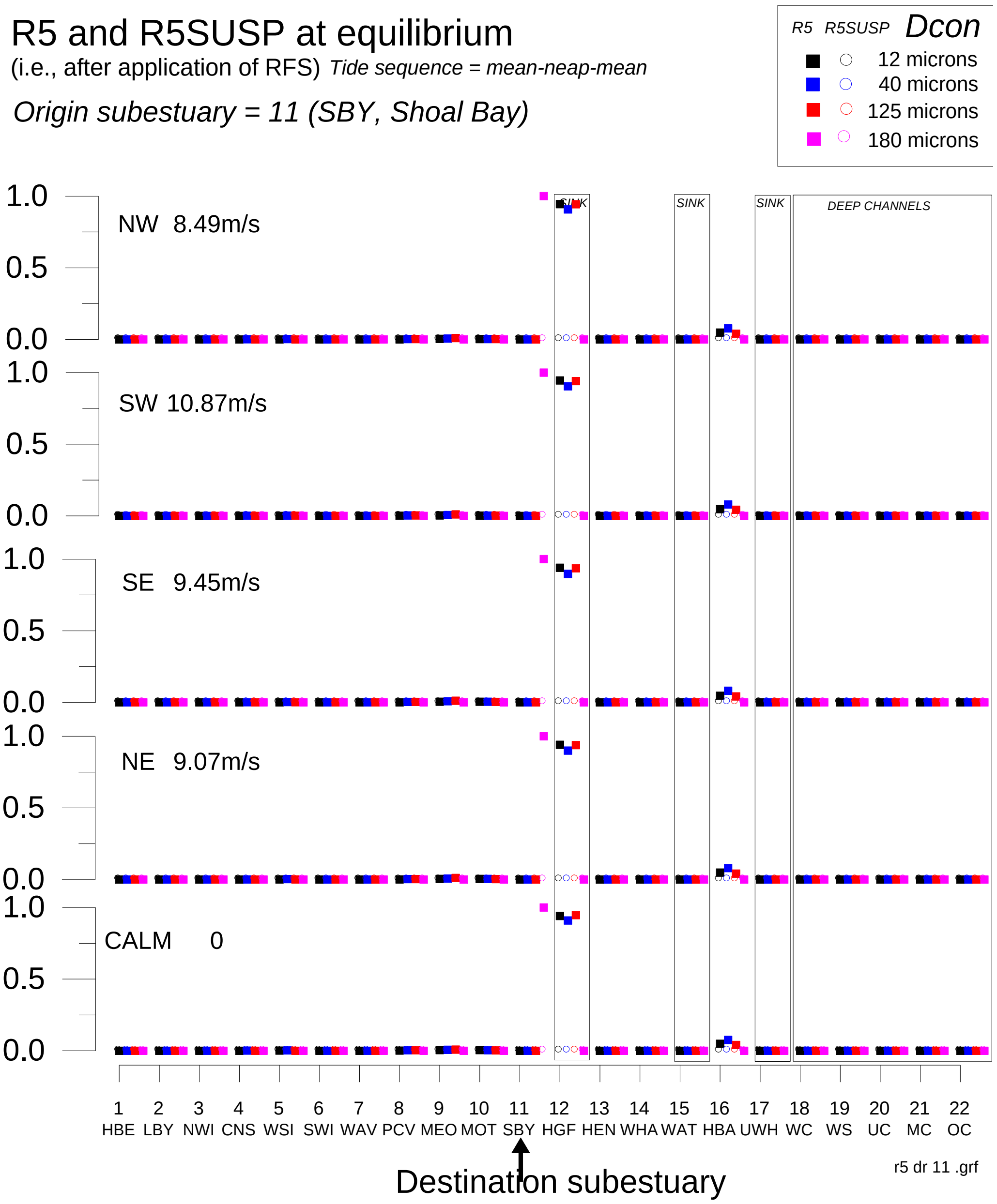

R5 and R5SUSP at equilibrium
(i.e., after application of RFS) Tide sequence = mean-neap-mean
Origin subestuary = 9 (MEO, Meola)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
1.0
0.5
0.0
SINK
SINK
SINK
DEEP CHANNELS
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r5 dr 09 .grf

Figure 180



R5 and R5SUSP at equilibrium
(i.e., after application of RFS) Tide sequence = mean-neap-mean
Origin subestuary = 10 (MOT, Motions)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
SINK
DEEP CHANNELS
1.0
0.5
0.0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22
HBE LBY NWI CNS WSI SWI WAV PCV MEO MOT SBY HGF HEN WHA WAT HBA UWH WC WS UC MC OC
Destination subestuary
r5 dr 10 .grf

Figure 181


R5 and R5SUSP at equilibrium
(i.e., after application of RFS) Tide sequence = mean-neap-mean
Origin subestuary = 11 (SBY, Shoal Bay)
R5 R5SUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
SINK
SINK
SINK
DEEP CHANNELS
1.0
0.5
0.0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22
HBE LBY NWI CNS WSI SWI WAV PCV MEO MOT SBY HGF HEN WHA WAT HBA UWH WC WS UC MC OC
Destination subestuary
r5 dr 11 .grf

# 18 Appendix 9: R (Equilibrium)

## 18.1 Tide sequence neap-mean-spring

**Figure 182**

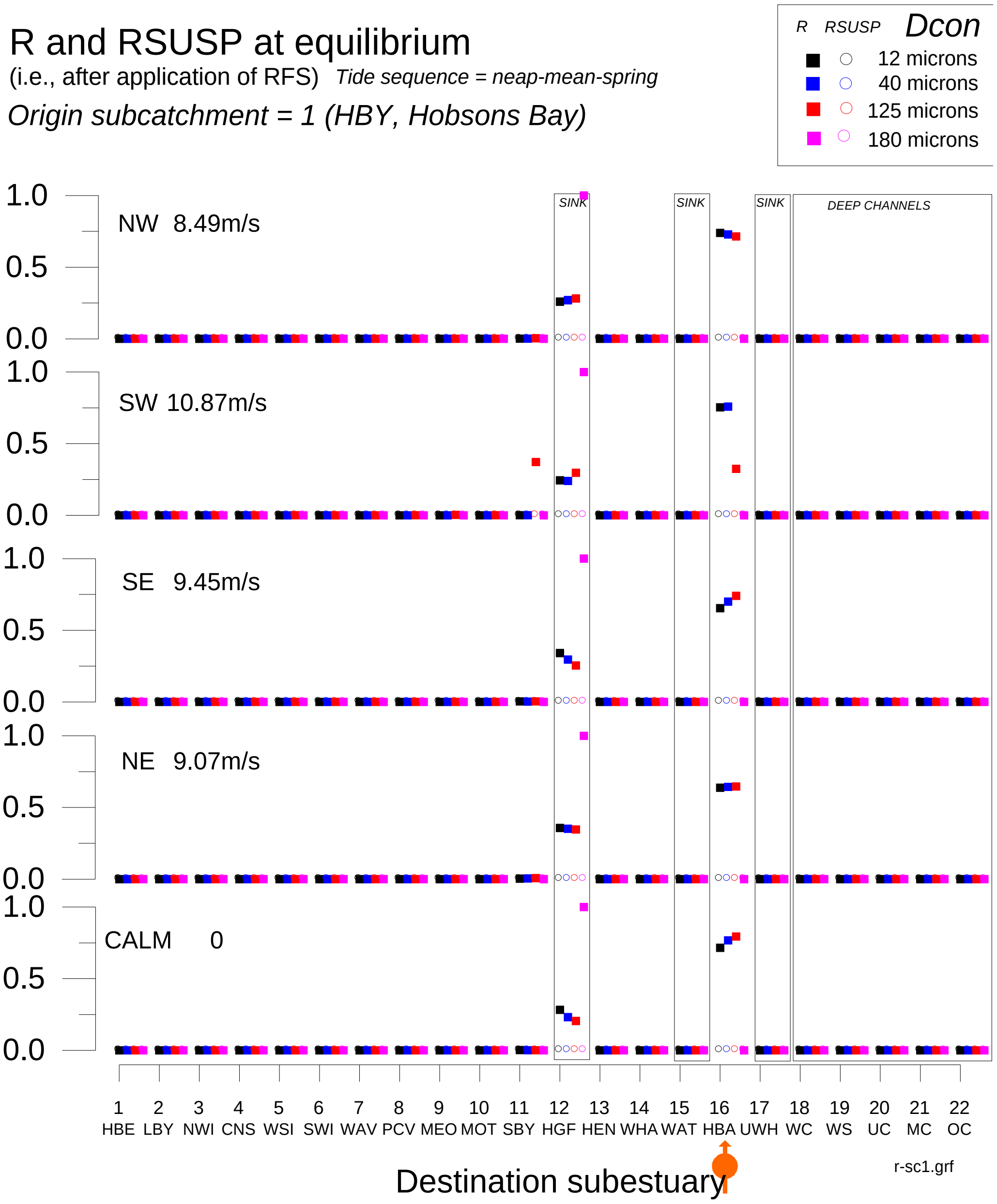


Figure 183

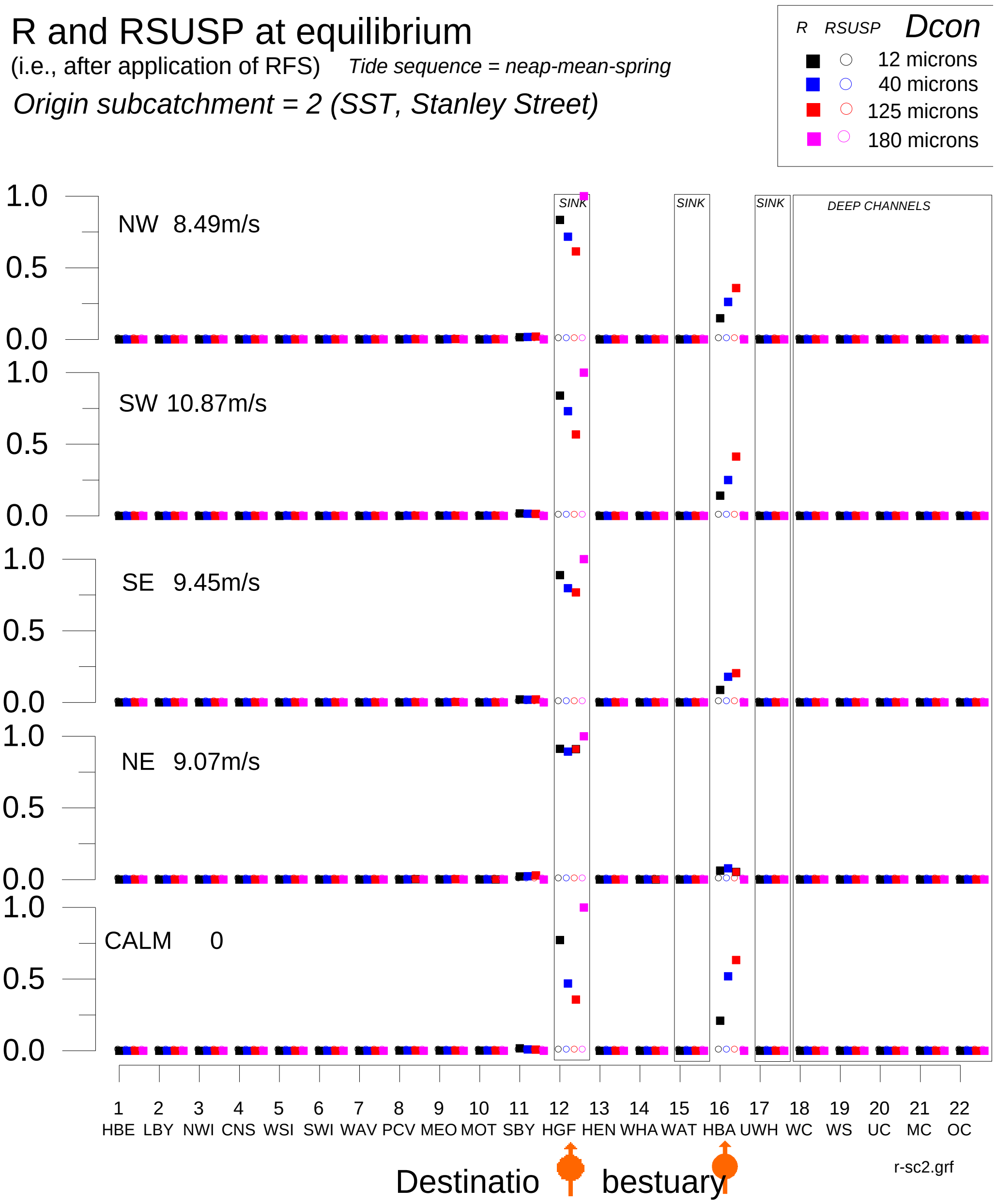

R and RSUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = neap-mean-spring
Origin subcatchment = 2 (SST, Stanley Street)
R RSUSP Dcon
12 microns
40 microns
125 microns
180 microns
SINK
SINK
SINK
DEEP CHANNELS
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
1.0
0.5
0.0
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destinatio bestuary
r-sc2.grf

Figure 184

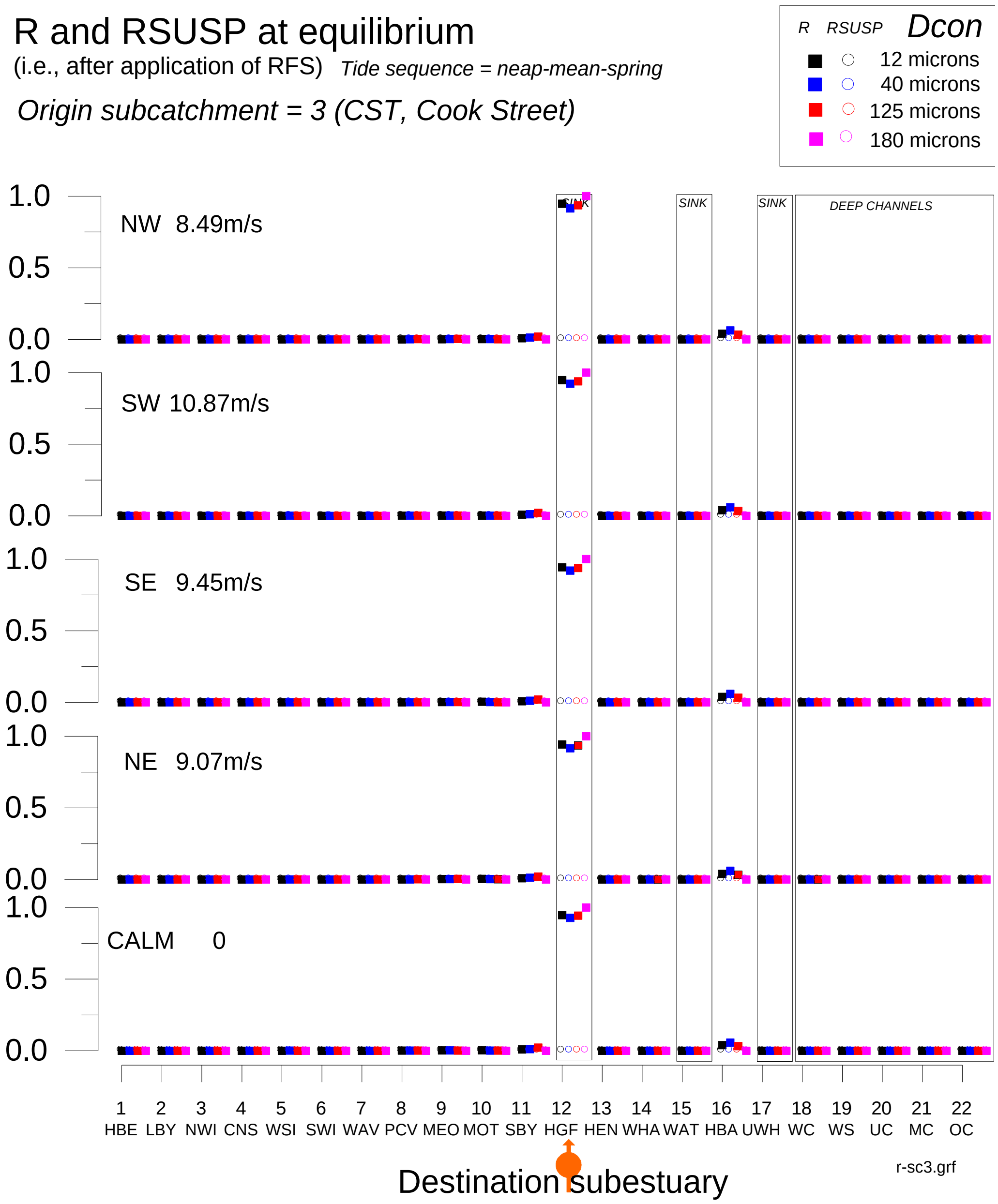

R and RSUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = neap-mean-spring
Origin subcatchment = 3 (CST, Cook Street)
R RSUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
1.0
0.5
0.0
SINK
SINK
SINK
DEEP CHANNELS
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r-sc3.grf

Figure 185

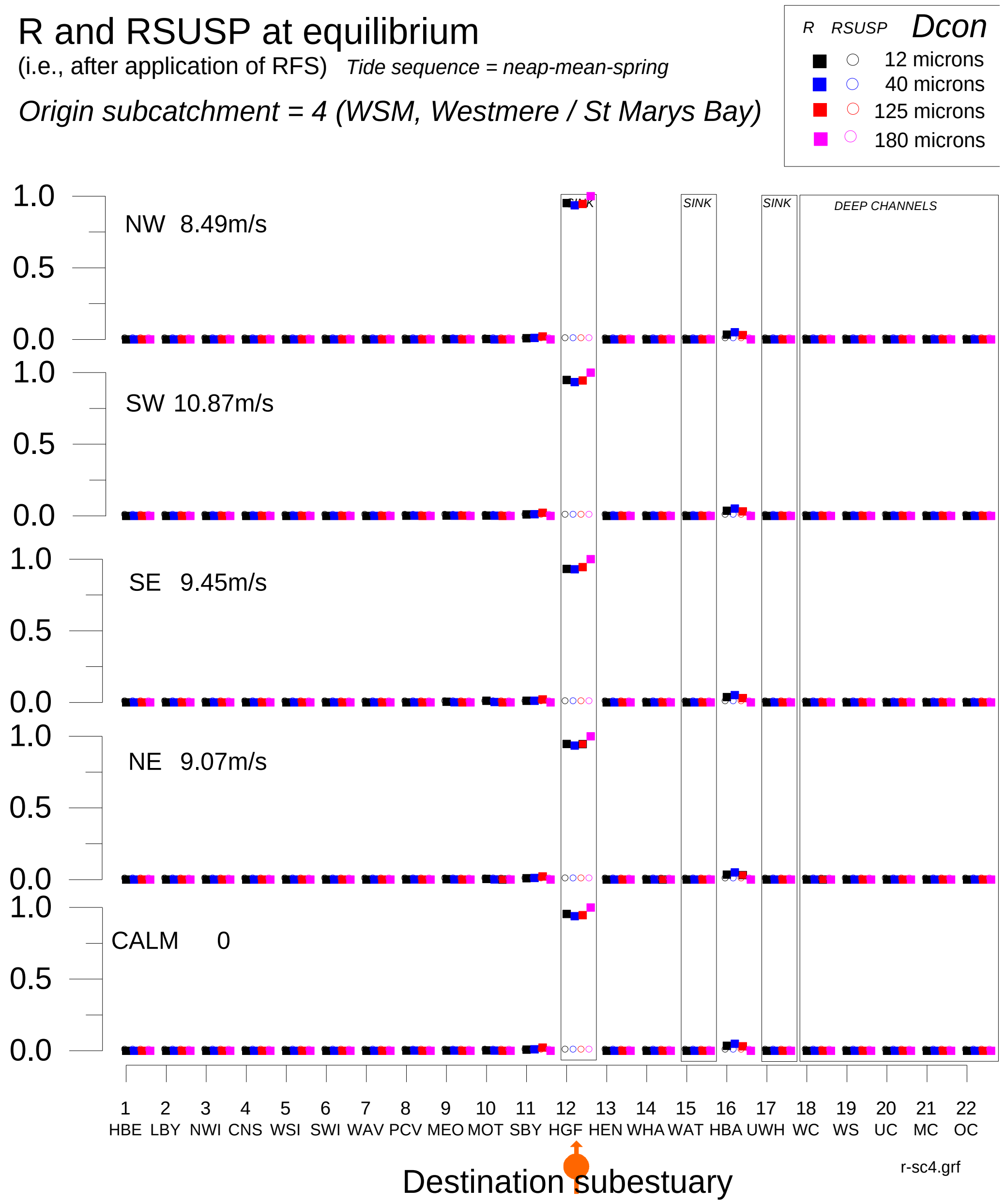
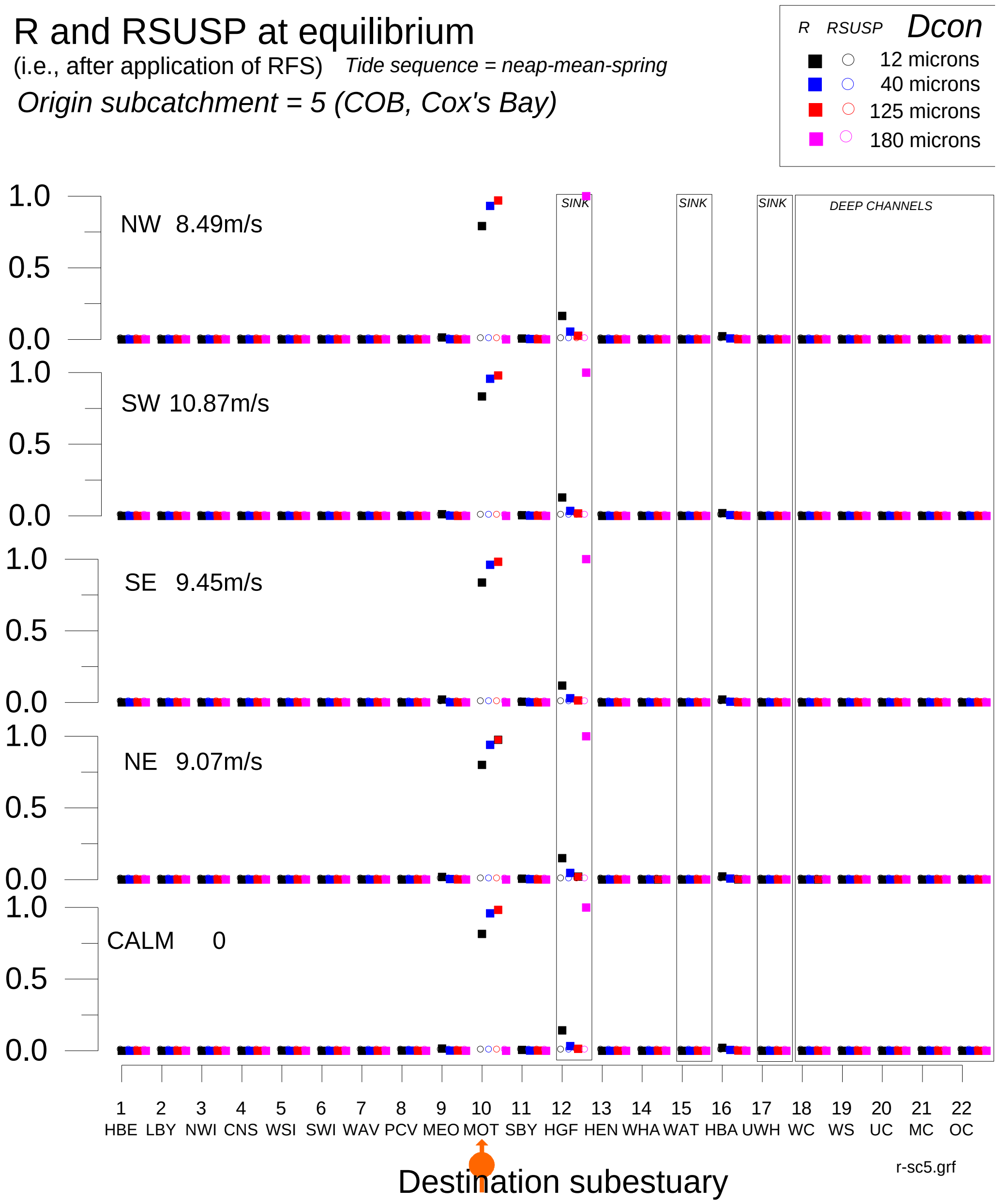

R and RSUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = neap-mean-spring
Origin subcatchment = 4 (WSM, Westmere / St Marys Bay)
R RSUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
1.0
0.5
0.0
SINK
SINK
SINK
DEEP CHANNELS
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22
HBE LBY NWI CNS WSI SWI WAV PCV MEO MOT SBY HGF HEN WHA WAT HBA UWH WC WS UC MC OC
Destination subestuary
r-sc4.grf

Figure 186



R and RSUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = neap-mean-spring
Origin subcatchment = 5 (COB, Cox's Bay)
R
RSUSP
Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
1.0
0.5
0.0
SINK
DEEP CHANNELS
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r-sc5.grf

Figure 187

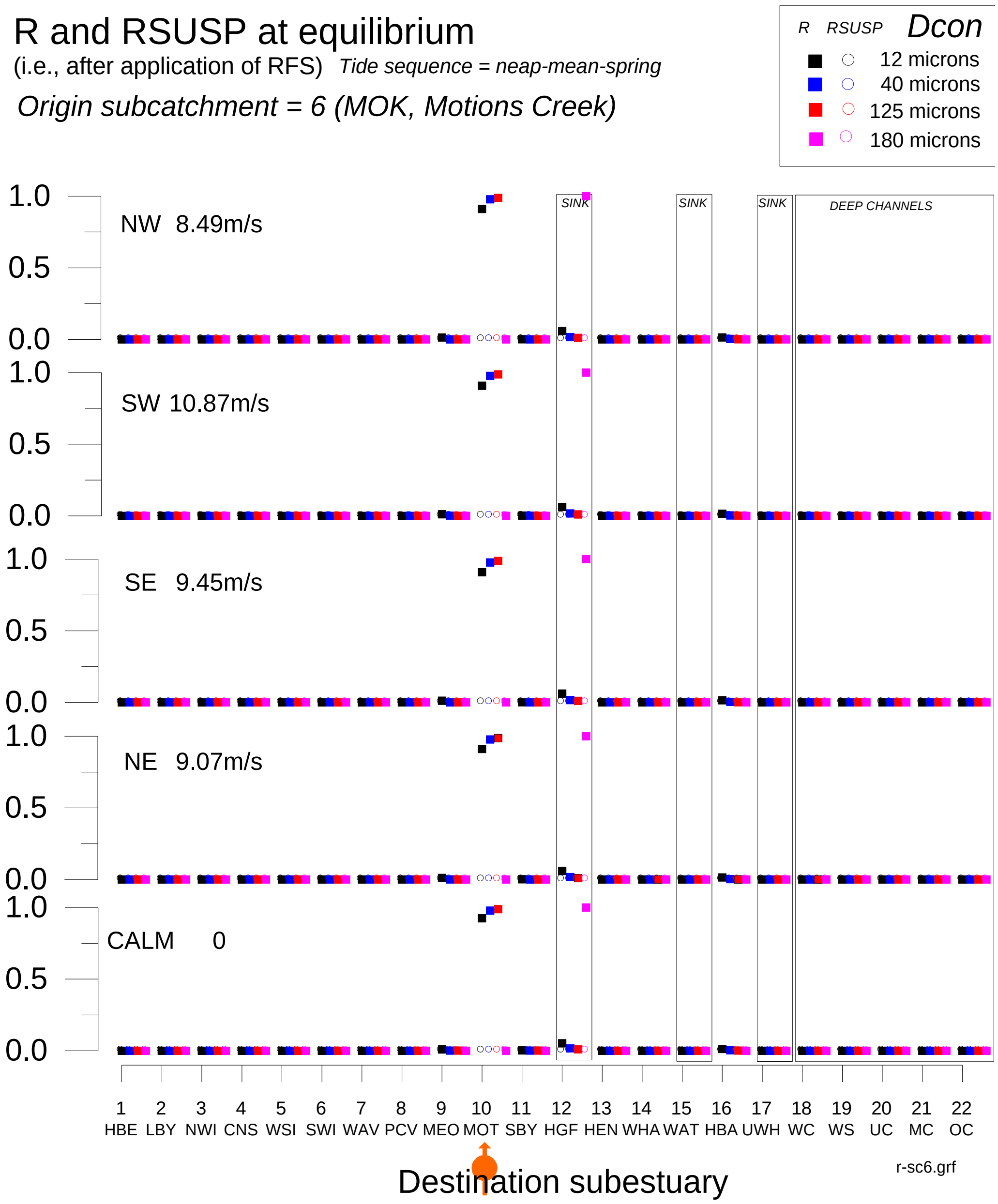
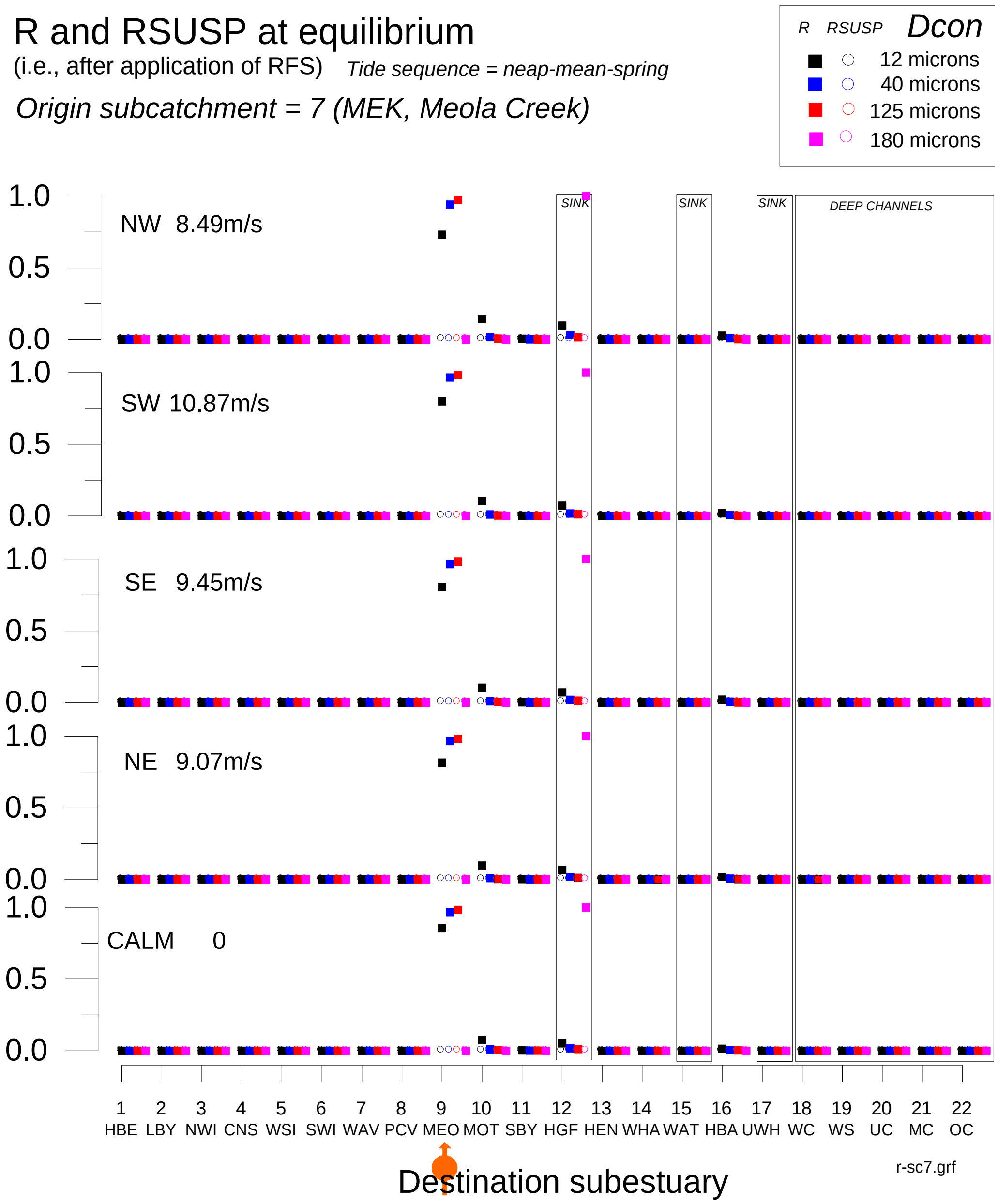

R and RSUSP at equilibrium
(i.e., after application of RFS) Tide sequence = neap-mean-spring
Origin subcatchment = 6 (MOK, Motions Creek)
R RSUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
1.0
0.5
0.0
SINK
SINK
SINK
DEEP CHANNELS
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22
HBE LBY NWI CNS WSI SWI WAV PCV MEO MOT SBY HGF HEN WHA WAT HBA UWH WC WS UC MC OC
Destination subestuary
r-sc6.grf

**Figure 188**



R and RSUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = neap-mean-spring
Origin subcatchment = 7 (MEK, Meola Creek)
R RSUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
1.0
0.5
0.0
SINK
SINK
SINK
DEEP CHANNELS
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22
HBE LBY NWI CNS WSI SWI WAV PCV MEO MOT SBY HGF HEN WHA WAT HBA UWH WC WS UC MC OC
Destination subestuary
r-sc7.grf

Figure 189

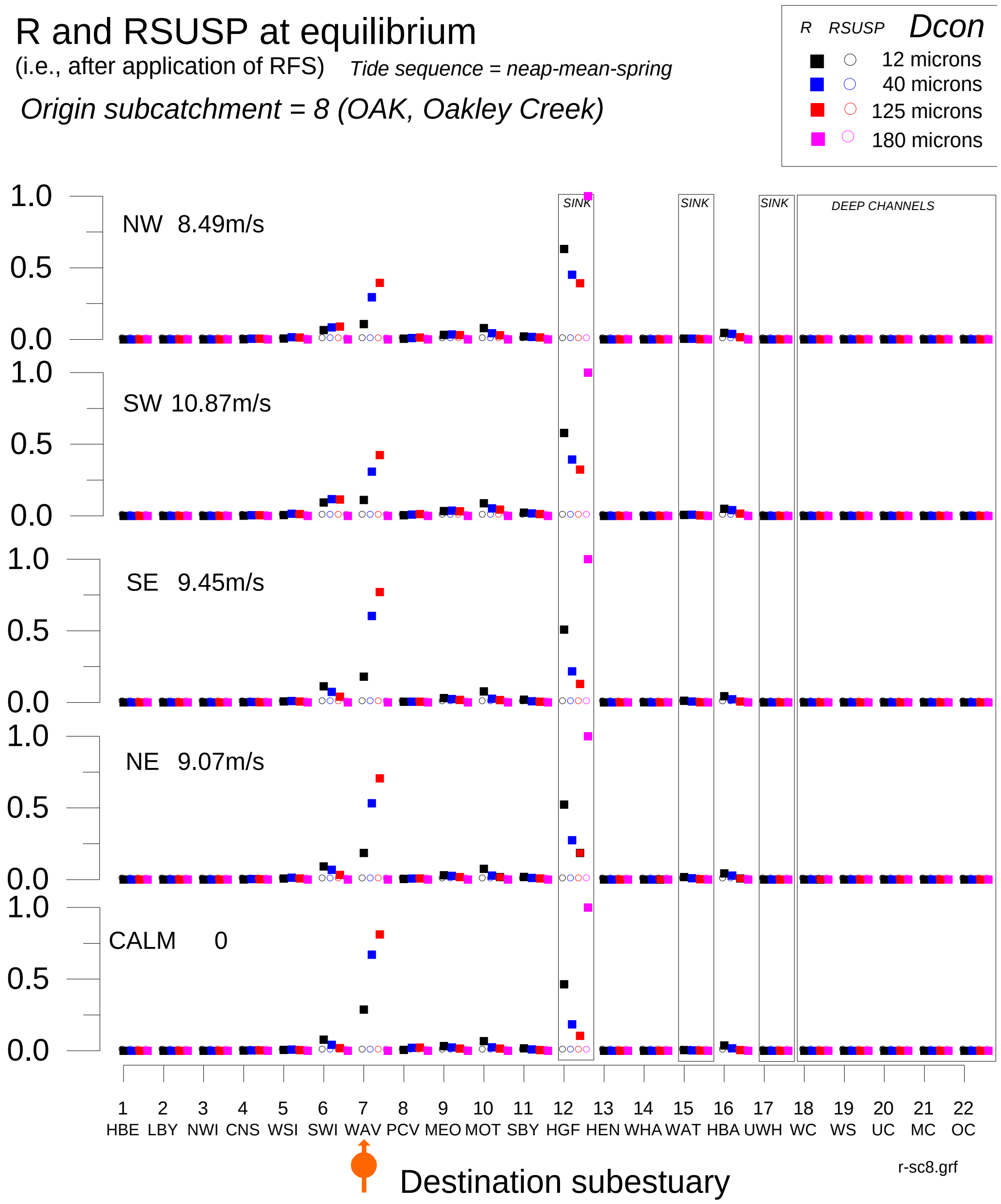
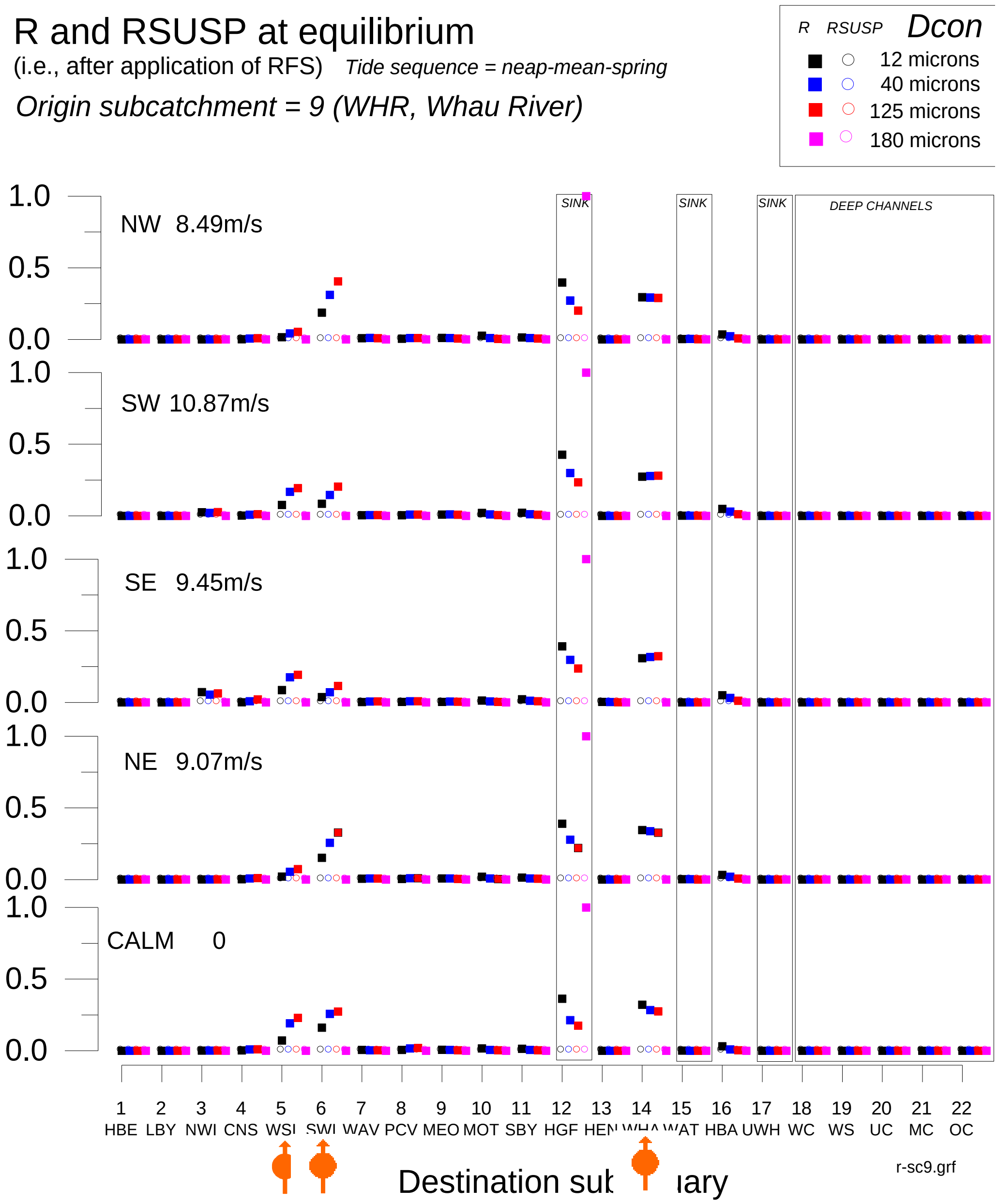

R and RSUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = neap-mean-spring
Origin subcatchment = 8 (OAK, Oakley Creek)
R RSUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
SINK
SINK
SINK
DEEP CHANNELS
1.0
0.5
0.0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22
HBE LBY NWI CNS WSI SWI WAV PCV MEO MOT SBY HGF HEN WHA WAT HBA UWH WC WS UC MC OC
Destination subestuary
r-sc8.grf

Figure 190



R and RSUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = neap-mean-spring
Origin subcatchment = 9 (WHR, Whau River)
R RSUSP Dcon
12 microns
40 microns
125 microns
180 microns
SINK
SINK
SINK
DEEP CHANNELS
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
1.0
0.5
0.0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22
HBE LBY NWI CNS WSI SWI WAV PCV MEO MOT SBY HGF HEN WHA WAT HBA UWH WC WS UC MC OC
Destination subcatchment
r-sc9.grf

Figure 191

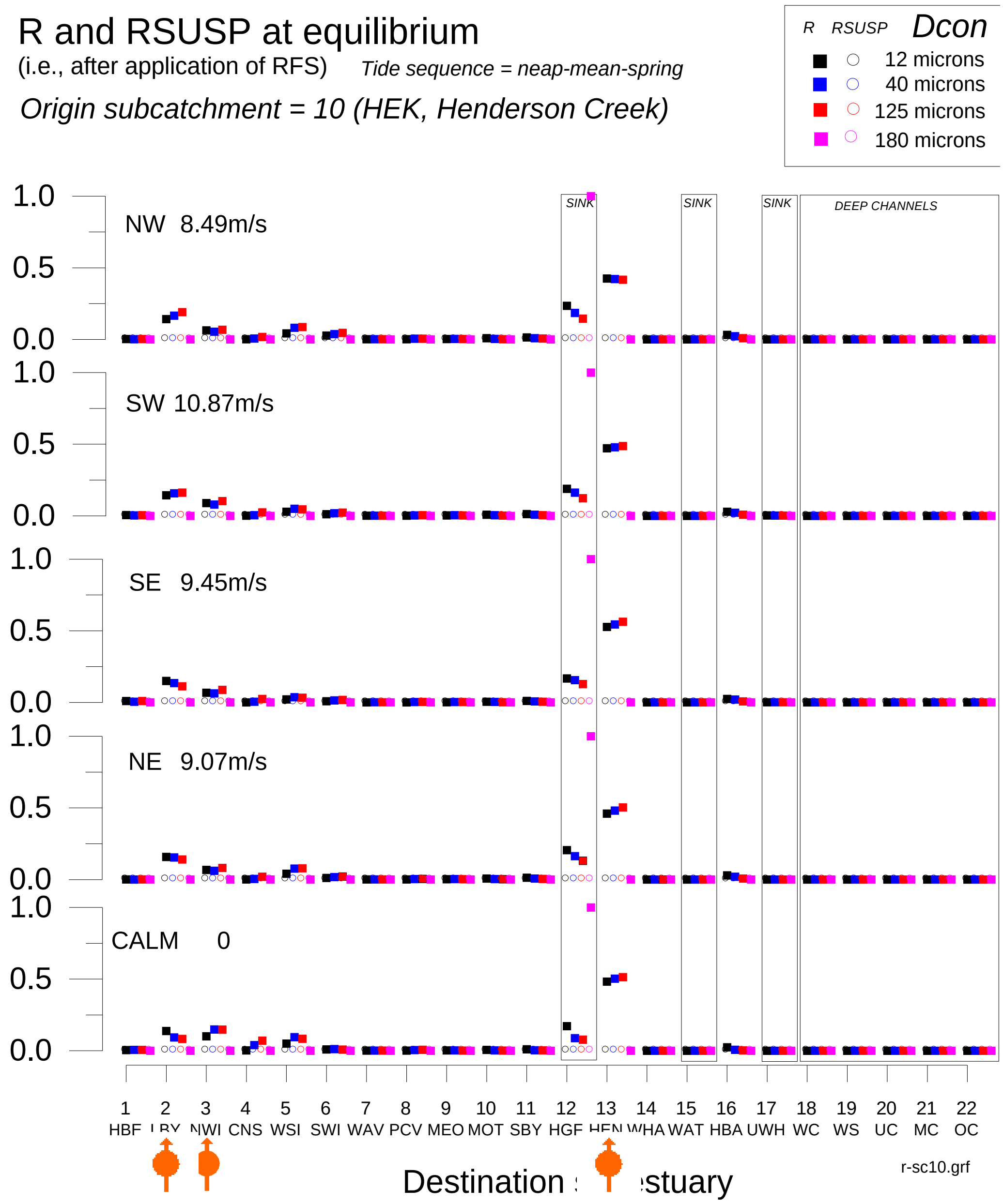

R and RSUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = neap-mean-spring
Origin subcatchment = 10 (HEK, Henderson Creek)
R RSUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
SINK
DEEP CHANNELS
1.0
0.5
0.0
1 HBF
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination estuary
r-sc10.grf

Figure 192

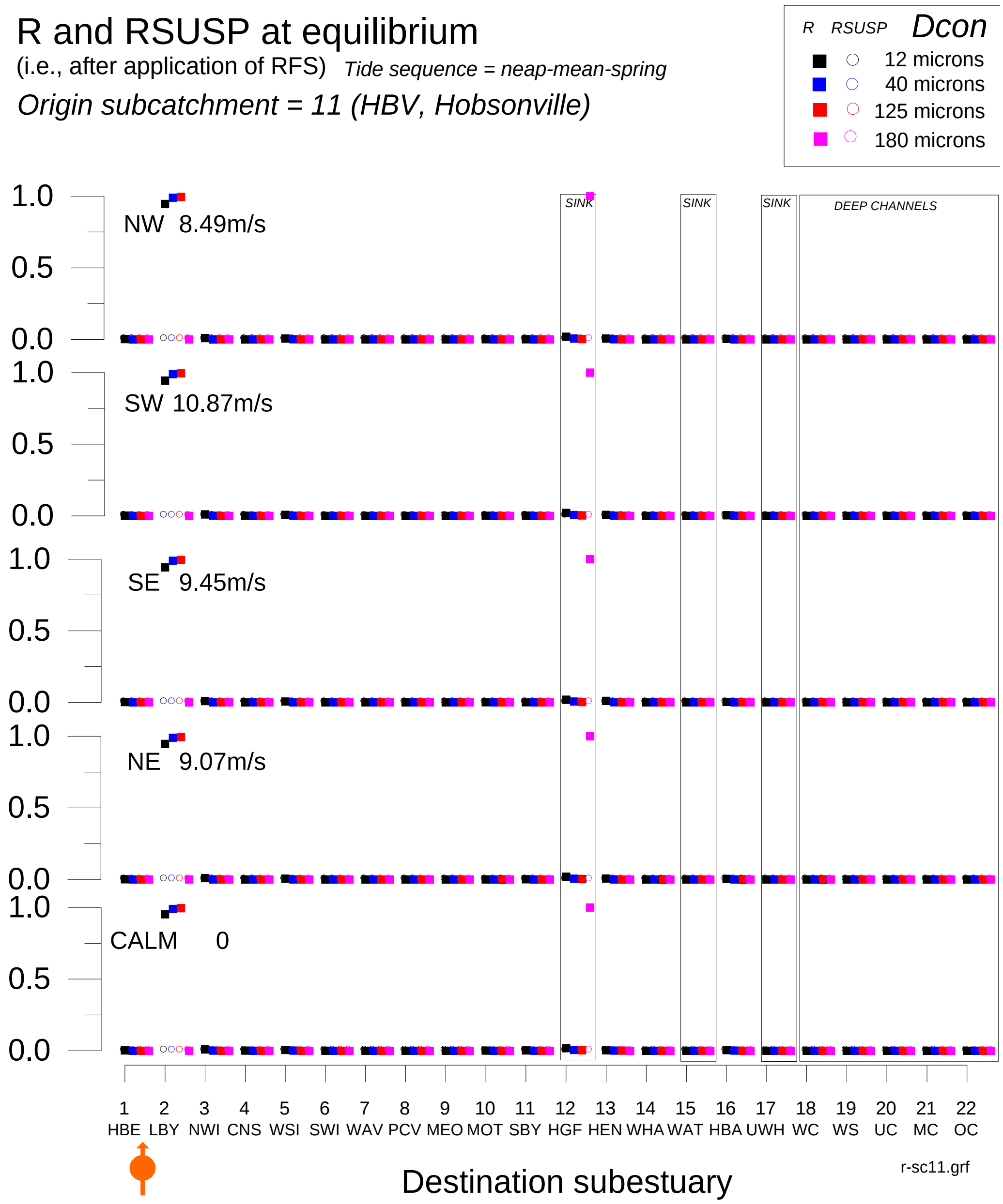
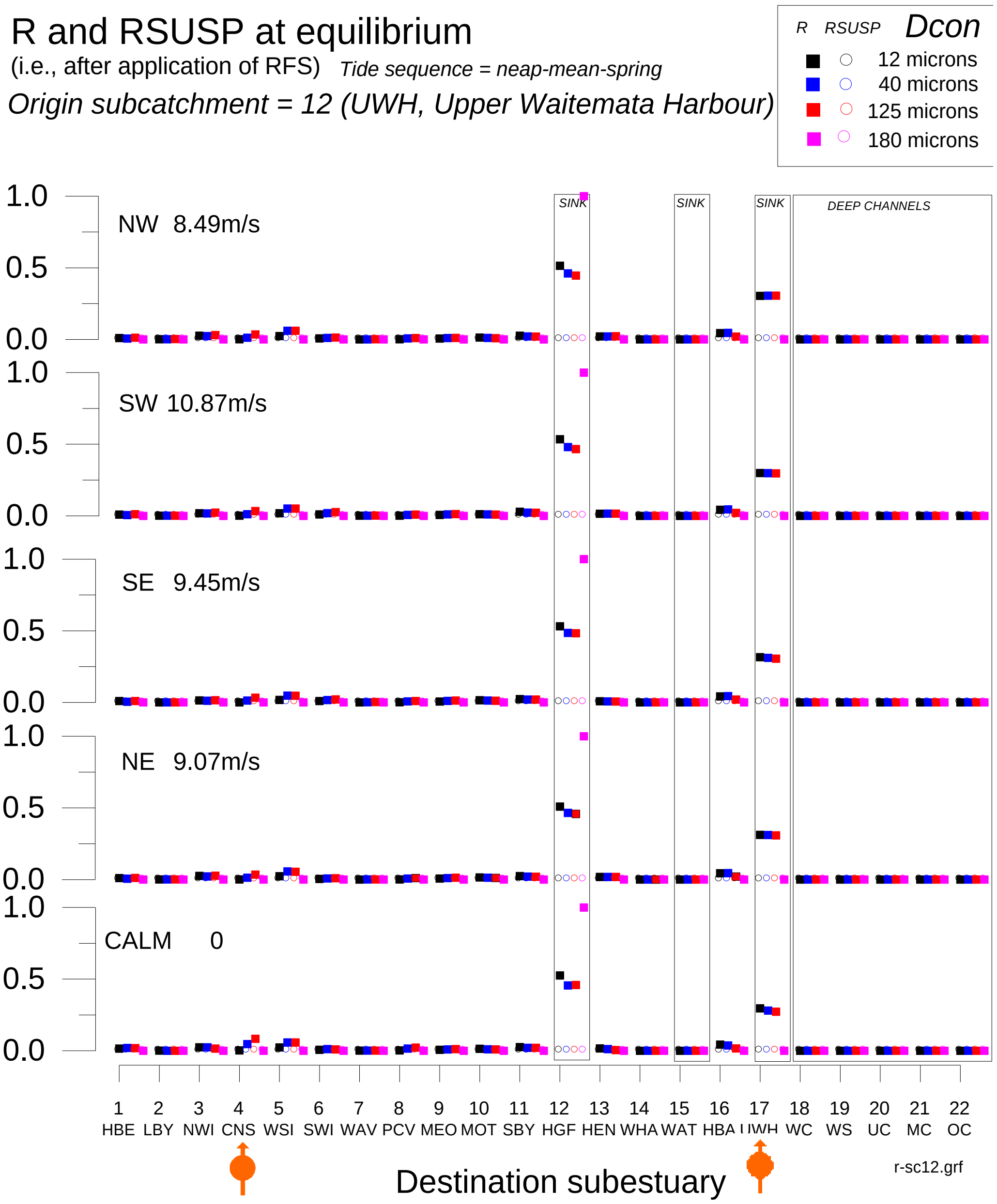

R and RSUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = neap-mean-spring
Origin subcatchment = 11 (HBV, Hobsonville)
R
RSUSP
Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
1.0
0.5
0.0
SINK
SINK
SINK
DEEP CHANNELS
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r-sc11.grf

Figure 193



R and RSUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = neap-mean-spring
Origin subcatchment = 12 (UWH, Upper Waitemata Harbour)
R
RSUSP
Dcon
12 microns
40 microns
125 microns
180 microns
SINK
SINK
SINK
DEEP CHANNELS
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
1.0
0.5
0.0
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r-sc12.grf

Figure 194

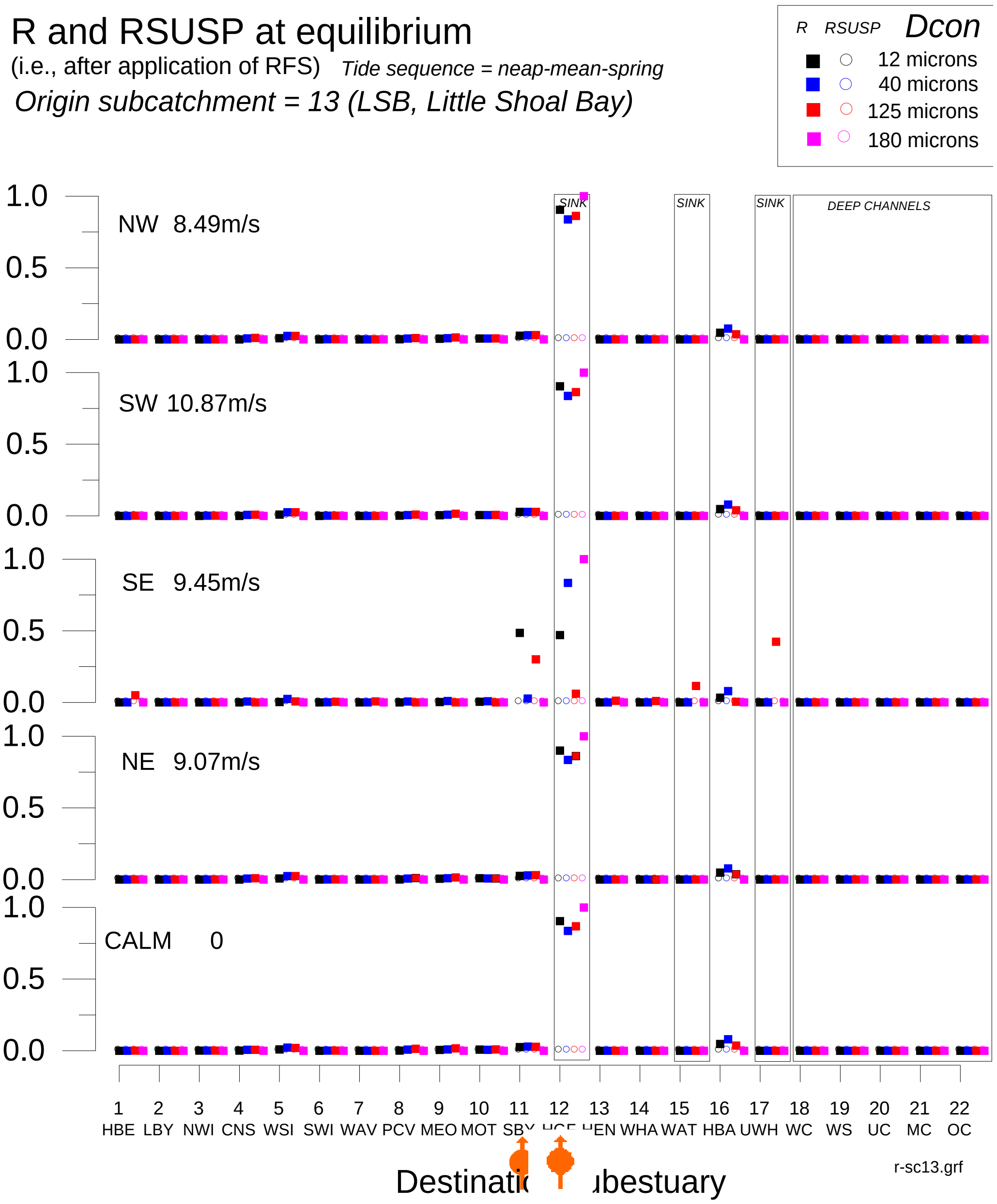

R and RSUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = neap-mean-spring
Origin subcatchment = 13 (LSB, Little Shoal Bay)
R RSUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
1.0
0.5
0.0
SINK
DEEP CHANNELS
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11
12
13
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
r-sc13.grf

**Figure 195**

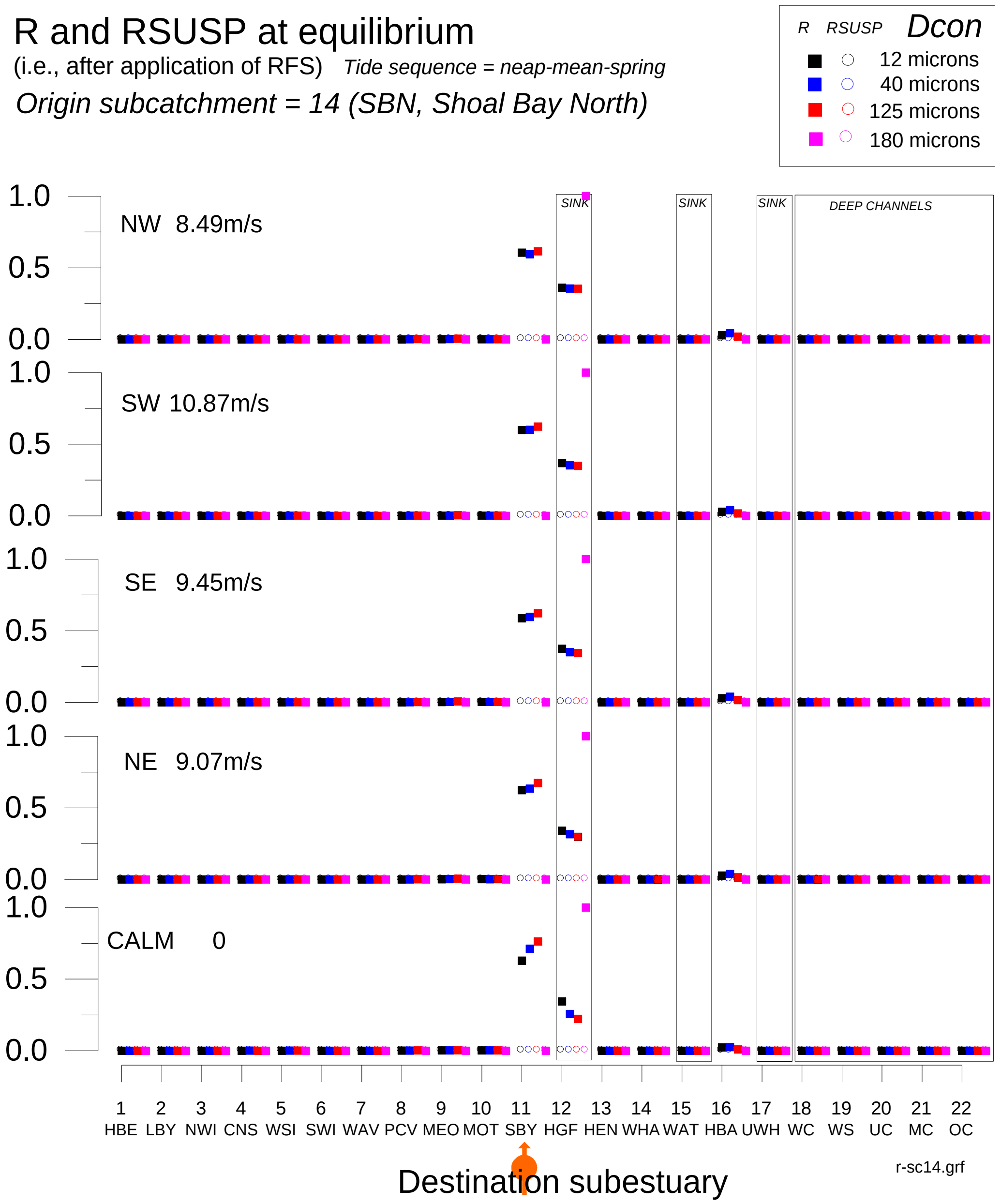
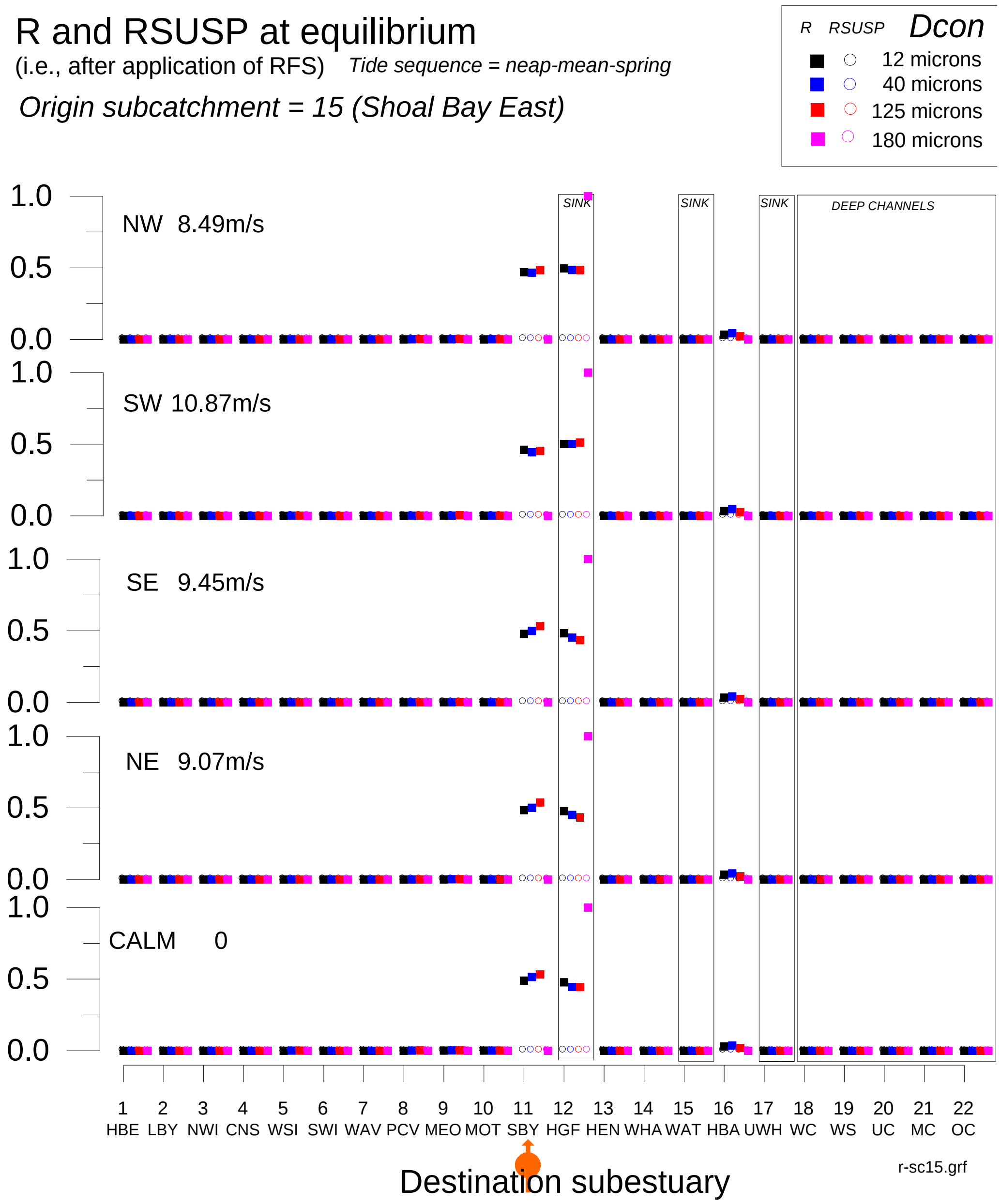

R and RSUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = neap-mean-spring
Origin subcatchment = 14 (SBN, Shoal Bay North)
R RSUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
SINK
SINK
SINK
DEEP CHANNELS
1.0
0.5
0.0
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r-sc14.grf

Figure 196


R and RSUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = neap-mean-spring
Origin subcatchment = 15 (Shoal Bay East)
R RSUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
SINK
SINK
SINK
DEEP CHANNELS
1.0
0.5
0.0
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r-sc15.grf

## 18.2 Tide sequence mean-spring-neap

**Figure 197**

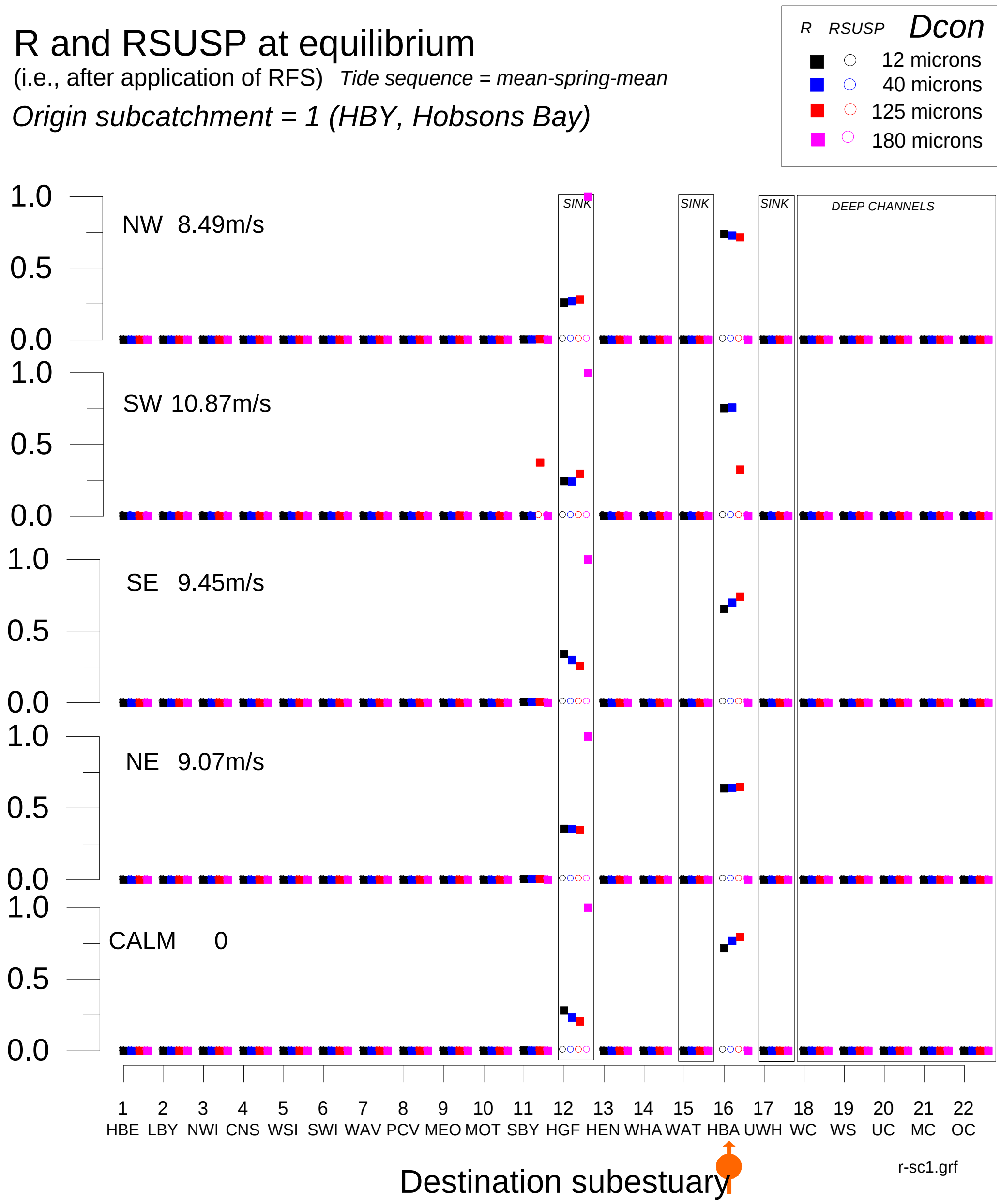


Figure 198

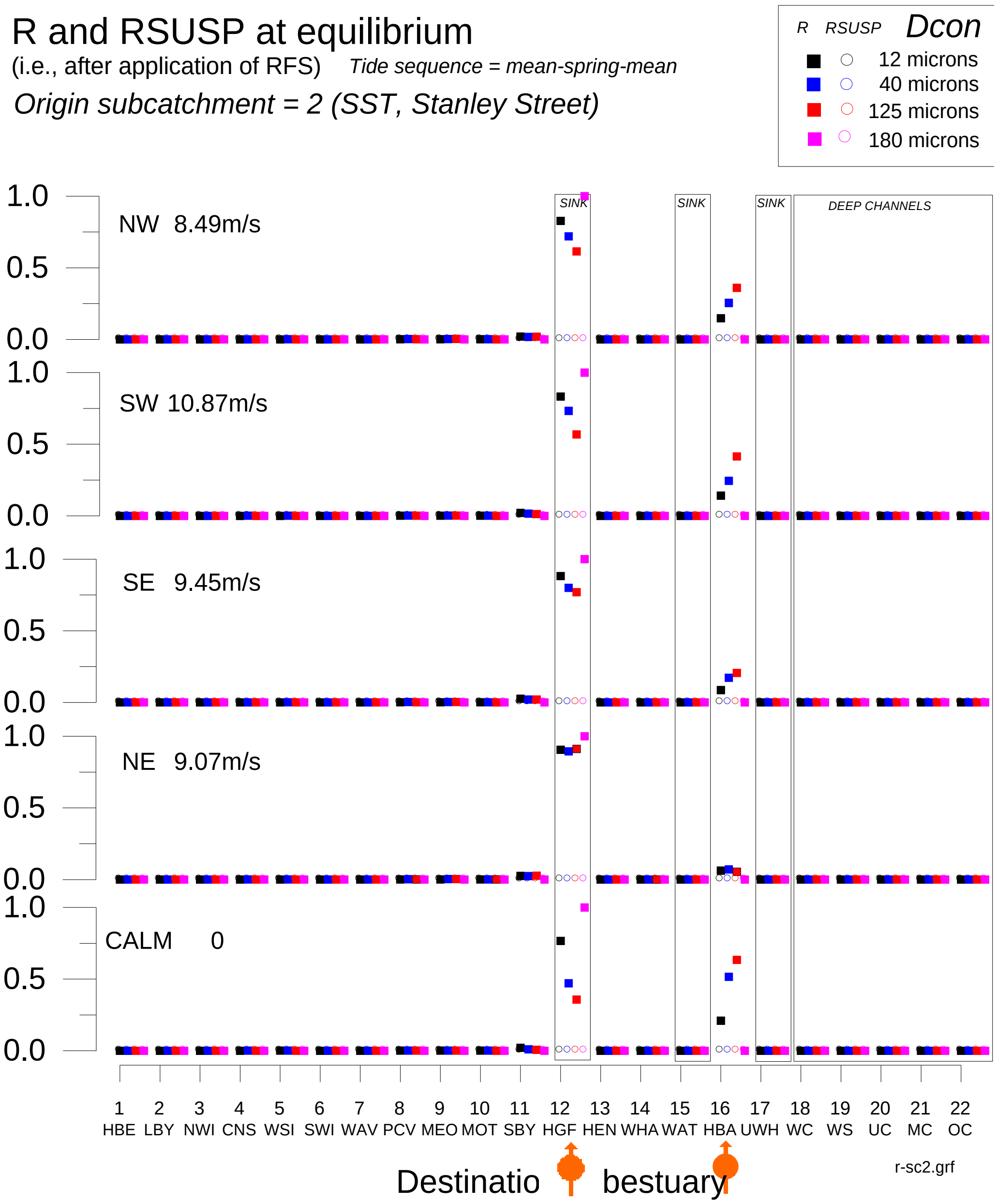

R and RSUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = mean-spring-mean
Origin subcatchment = 2 (SST, Stanley Street)
R
RSUSP
Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
1.0
0.5
0.0
SINK
SINK
SINK
DEEP CHANNELS
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22
HBE LBY NWI CNS WSI SWI WAV PCV MEO MOT SBY HGF HEN WHA WAT HBA UWH WC WS UC MC OC
Destinatio
bestuary
r-sc2.grf

**Figure 199**

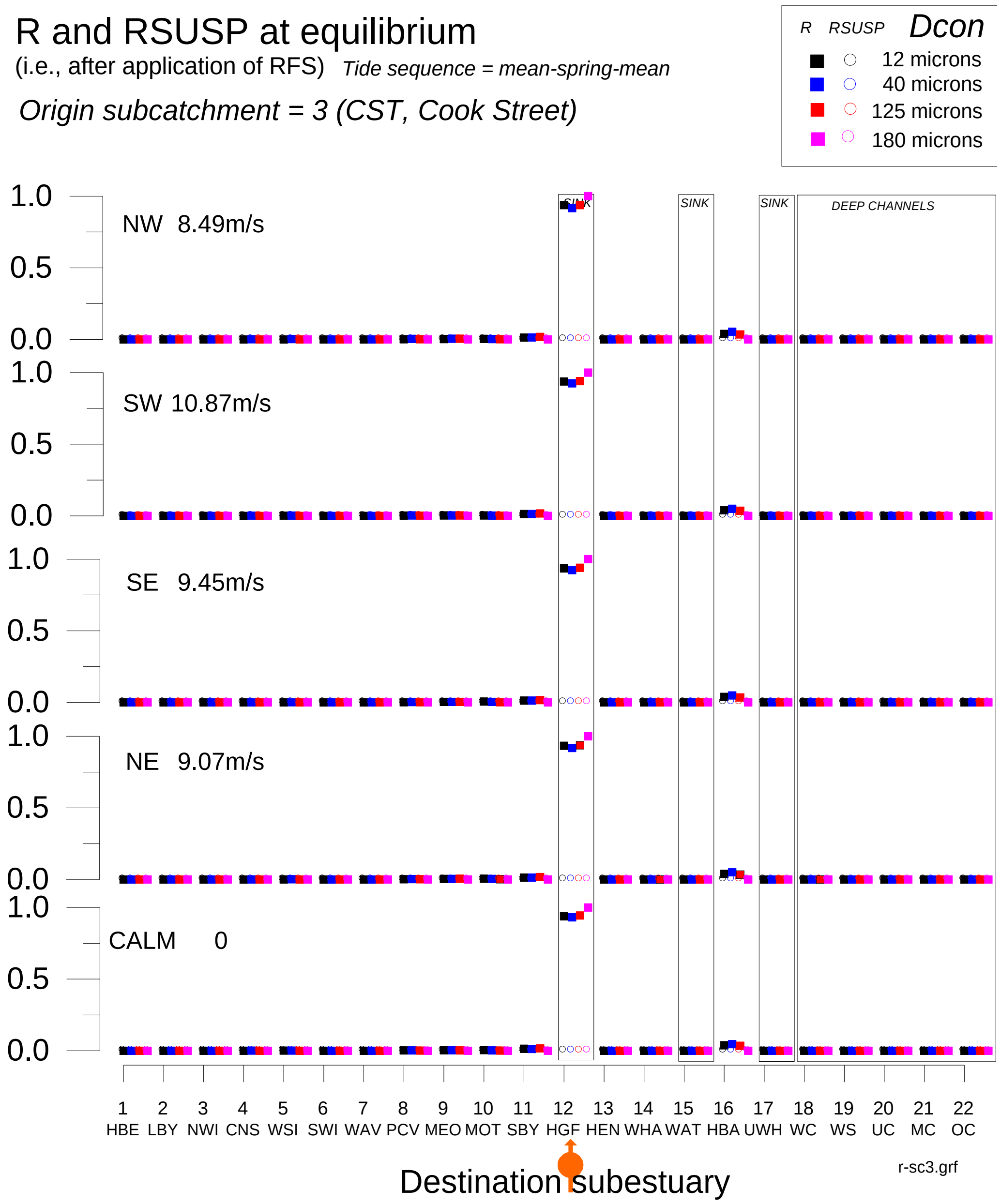

R and RSUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = mean-spring-mean
Origin subcatchment = 3 (CST, Cook Street)
R RSUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
SINK
SINK
SINK
DEEP CHANNELS
1.0
0.5
0.0
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r-sc3.grf

Figure 200

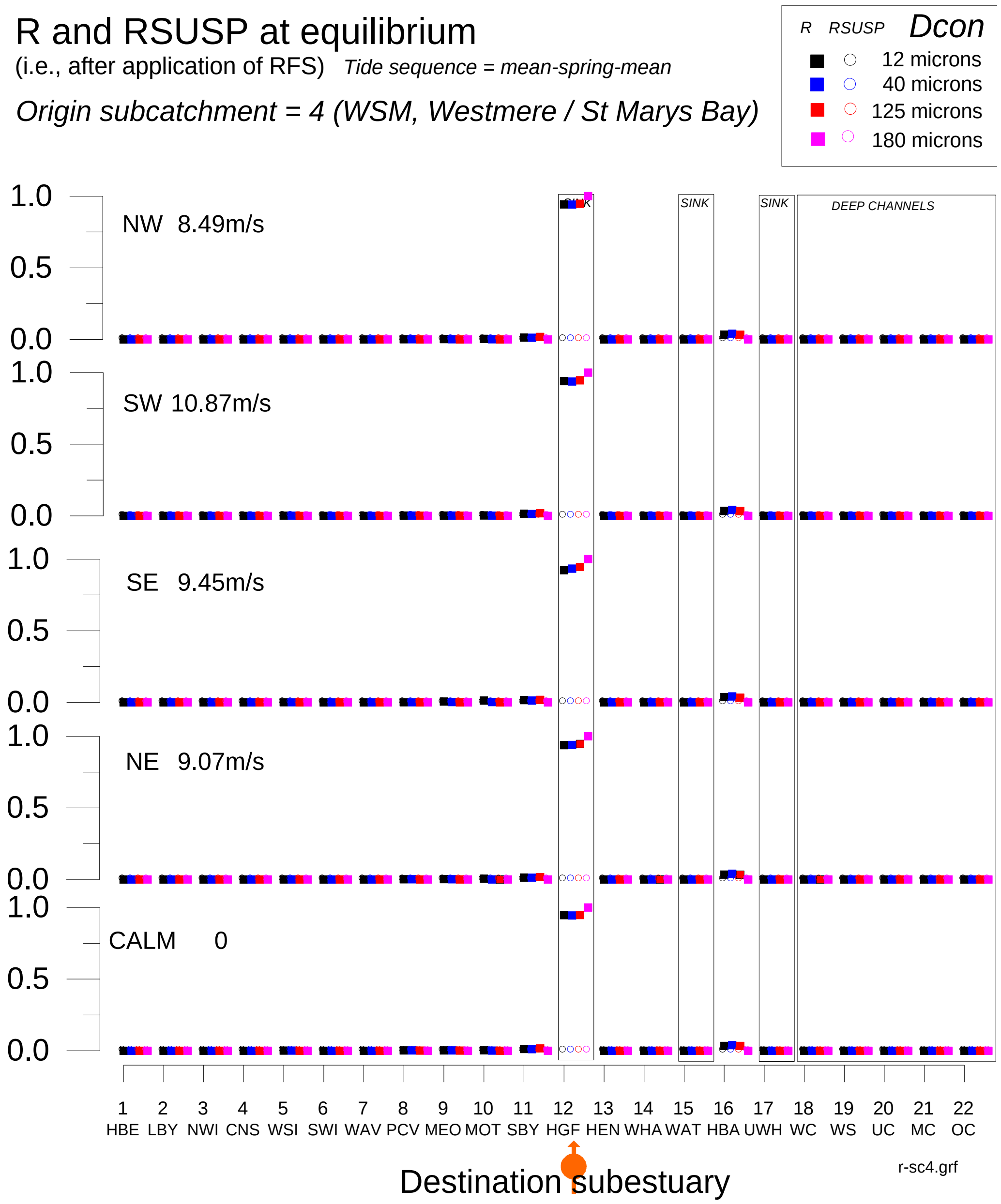
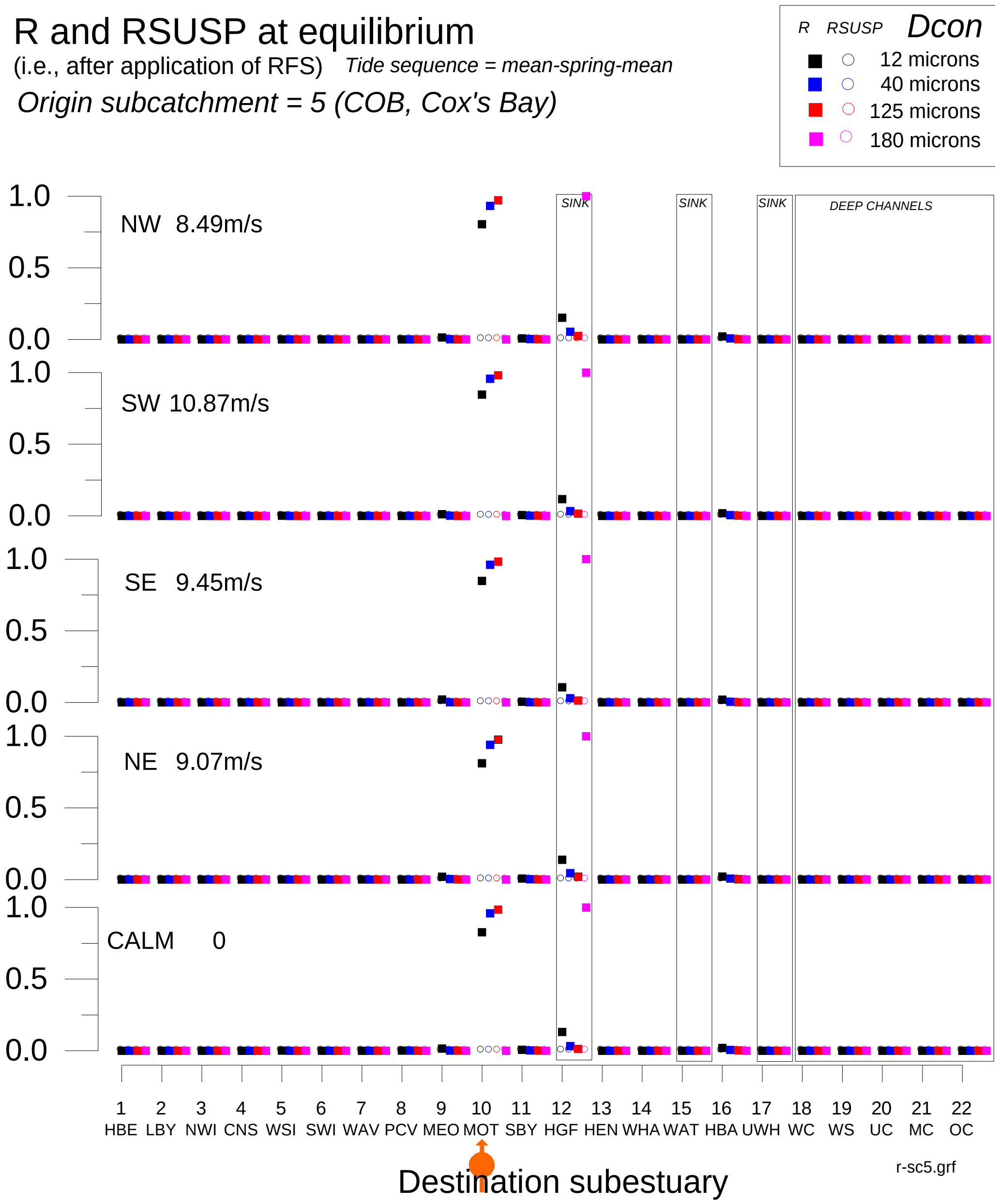

R and RSUSP at equilibrium
(i.e., after application of RFS) Tide sequence = mean-spring-mean
Origin subcatchment = 4 (WSM, Westmere / St Marys Bay)
R RSUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
SINK
SINK
DEEP CHANNELS
1.0
0.5
0.0
1 HBE 2 LBY 3 NWI 4 CNS 5 WSI 6 SWI 7 WAV 8 PCV 9 MEO 10 MOT 11 SBY 12 HGF 13 HEN 14 WHA 15 WAT 16 HBA 17 UWH 18 WC 19 WS 20 UC 21 MC 22 OC
Destination subestuary
r-sc4.grf

Figure 201



R and RSUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = mean-spring-mean
Origin subcatchment = 5 (COB, Cox's Bay)
R RSUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
1.0
0.5
0.0
SINK
SINK
SINK
DEEP CHANNELS
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r-sc5.grf

Figure 202

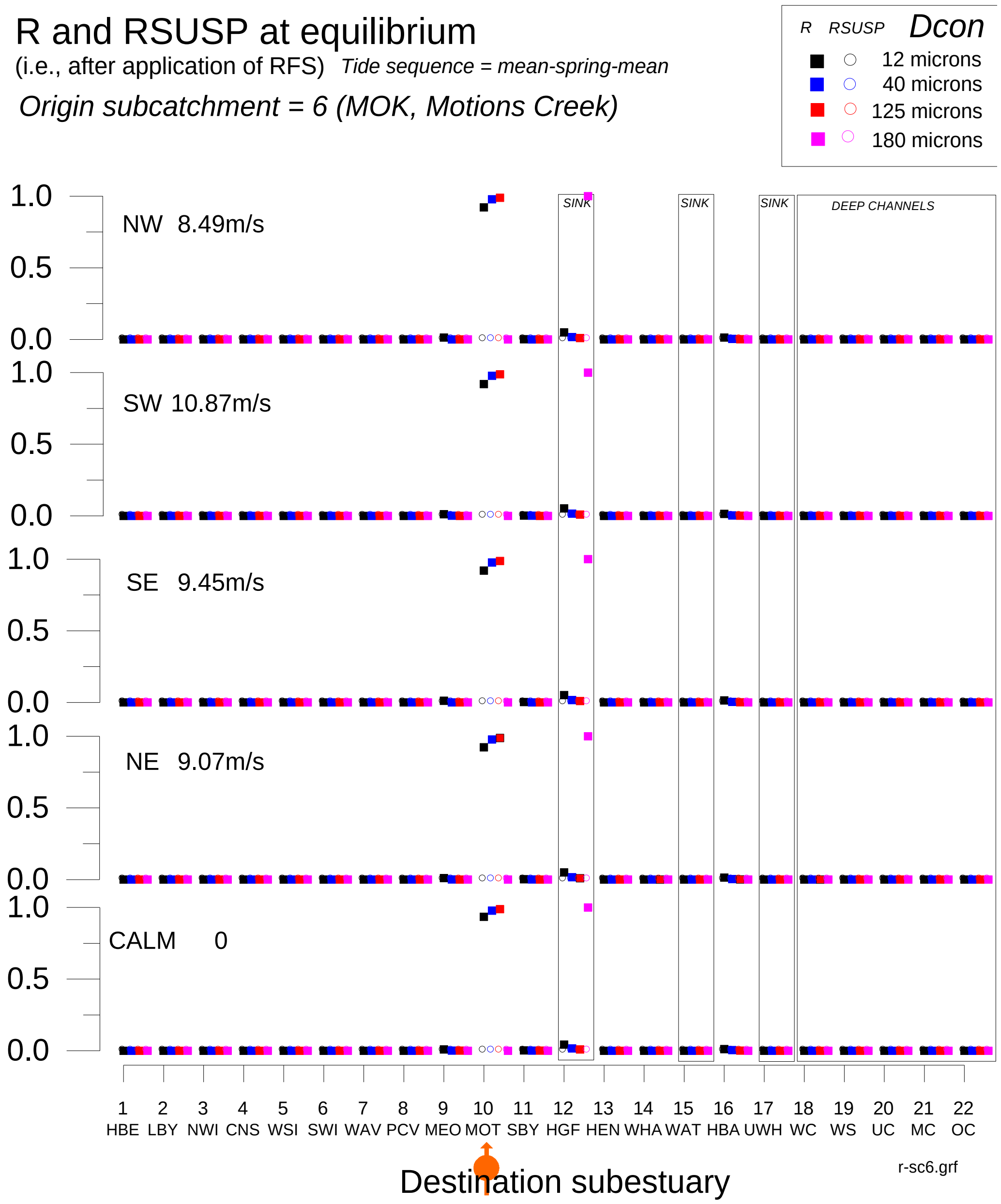
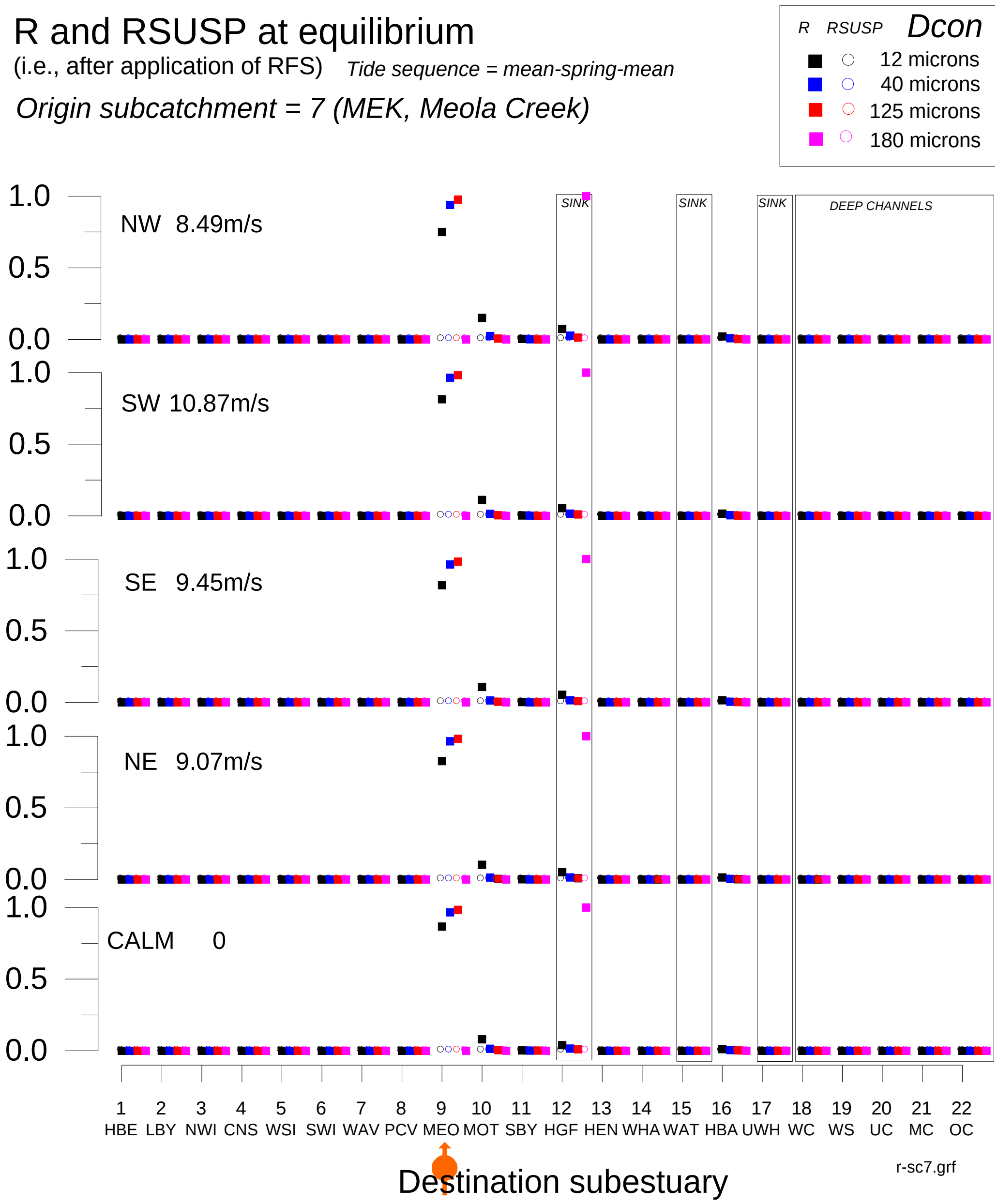

R and RSUSP at equilibrium
(i.e., after application of RFS) Tide sequence = mean-spring-mean
Origin subcatchment = 6 (MOK, Motions Creek)
R RSUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
1.0
0.5
0.0
SINK
SINK
SINK
DEEP CHANNELS
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r-sc6.grf

Figure 203



R and RSUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = mean-spring-mean
Origin subcatchment = 7 (MEK, Meola Creek)
R RSUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
SINK
SINK
SINK
DEEP CHANNELS
1.0
0.5
0.0
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r-sc7.grf

Figure 204

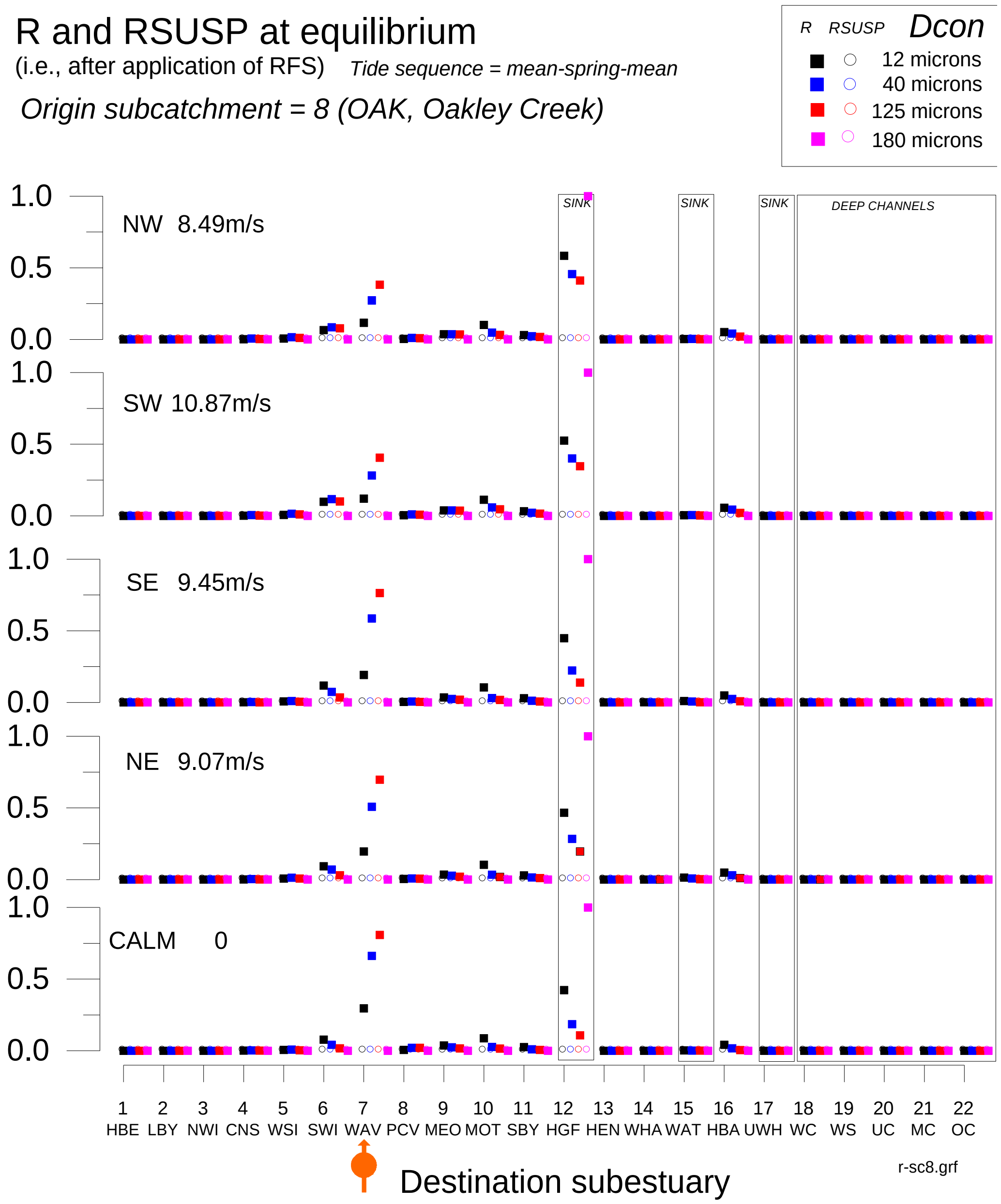
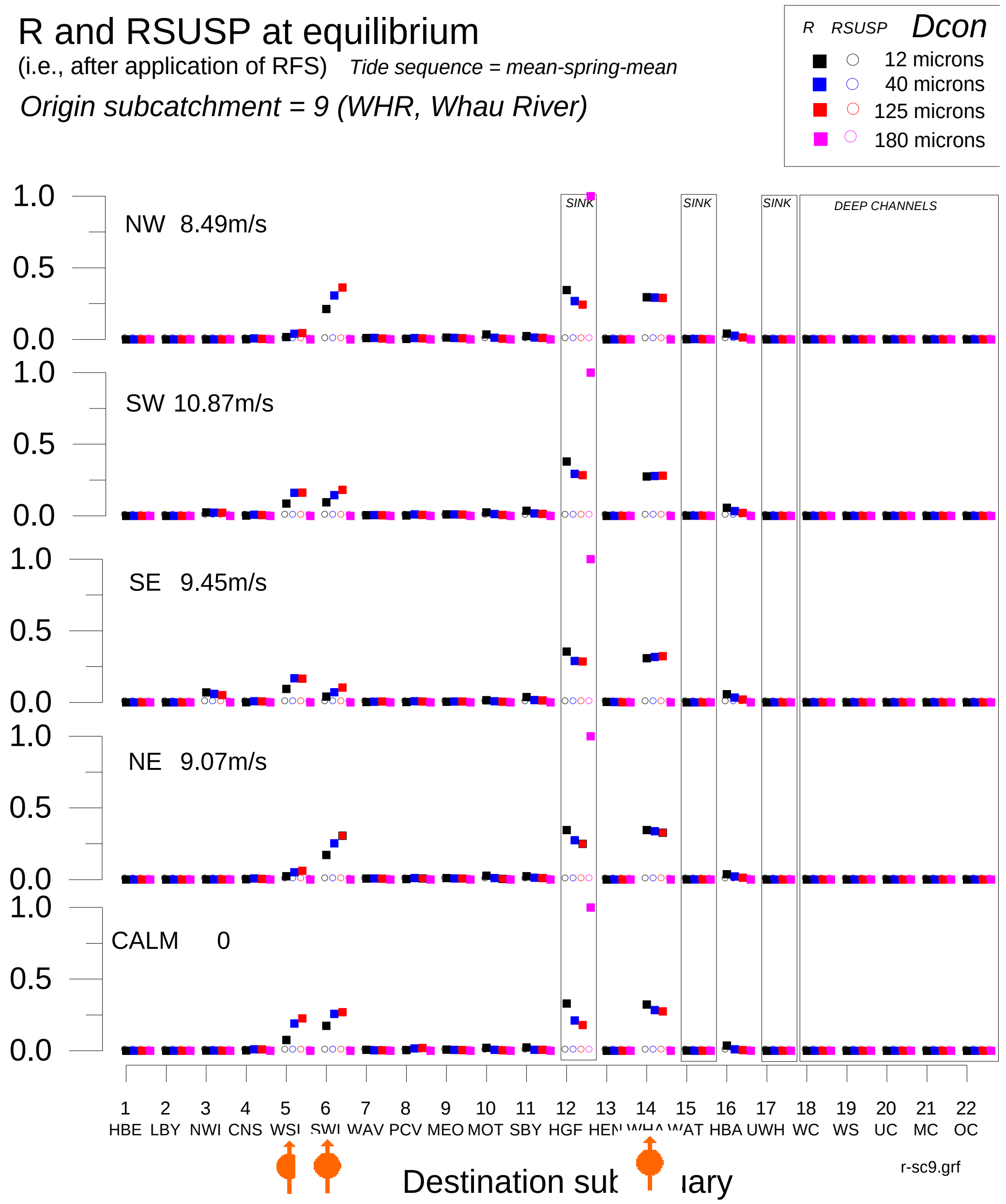
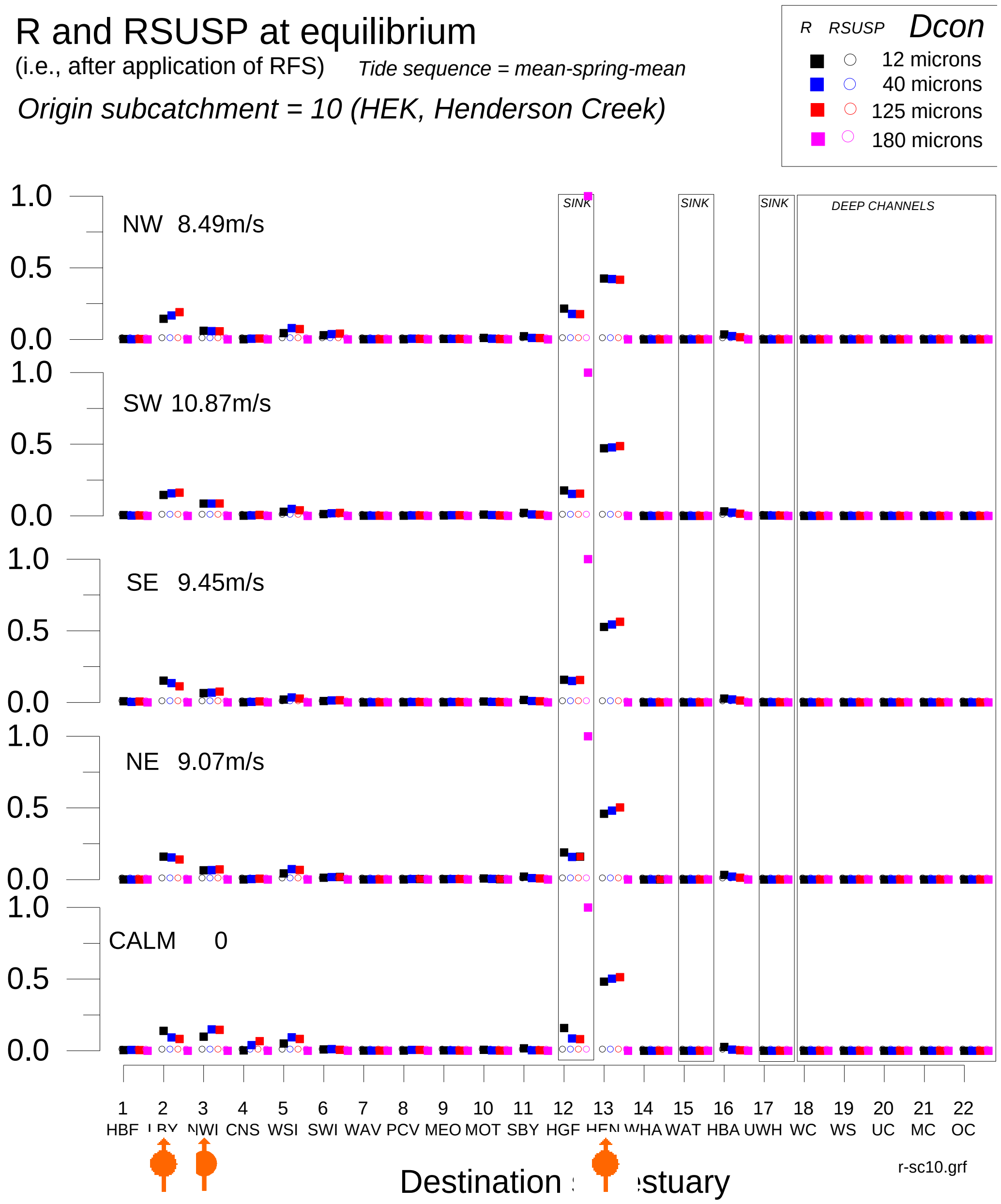

R and RSUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = mean-spring-mean
Origin subcatchment = 8 (OAK, Oakley Creek)
R RSUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
SINK
SINK
SINK
DEEP CHANNELS
1.0
0.5
0.0
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r-sc8.grf

Figure 205



R and RSUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = mean-spring-mean
Origin subcatchment = 9 (WHR, Whau River)
R
RSUSP
Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
SINK
DEEP CHANNELS
1.0
0.5
0.0
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subcatchment / estuary
r-sc9.grf

Figure 206



R and RSUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = mean-spring-mean
Origin subcatchment = 10 (HEK, Henderson Creek)
R RSUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
SINK
SINK
SINK
DEEP CHANNELS
1.0
0.5
0.0
1 HBF
2
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination
stuary
r-sc10.grf

Figure 207

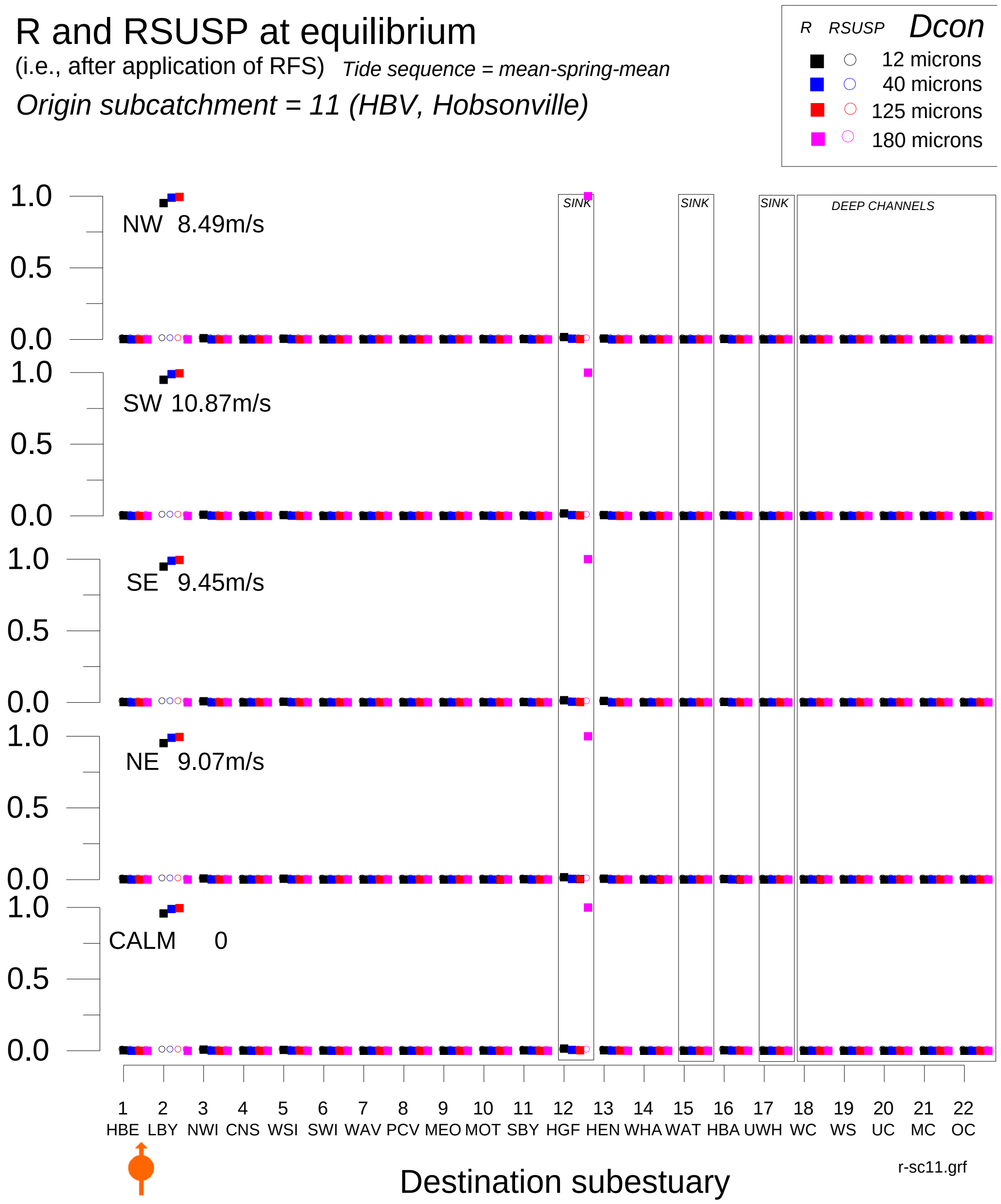
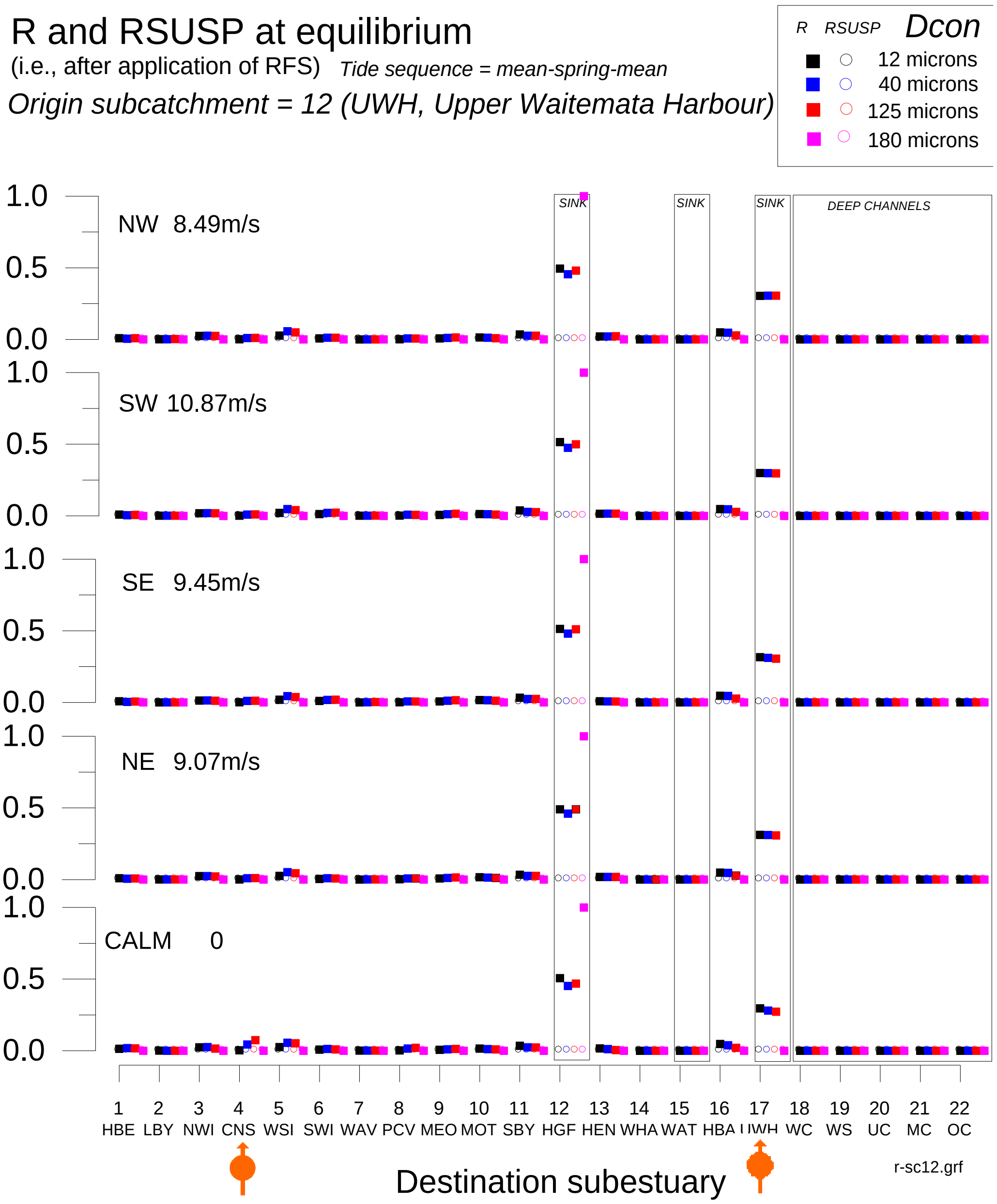
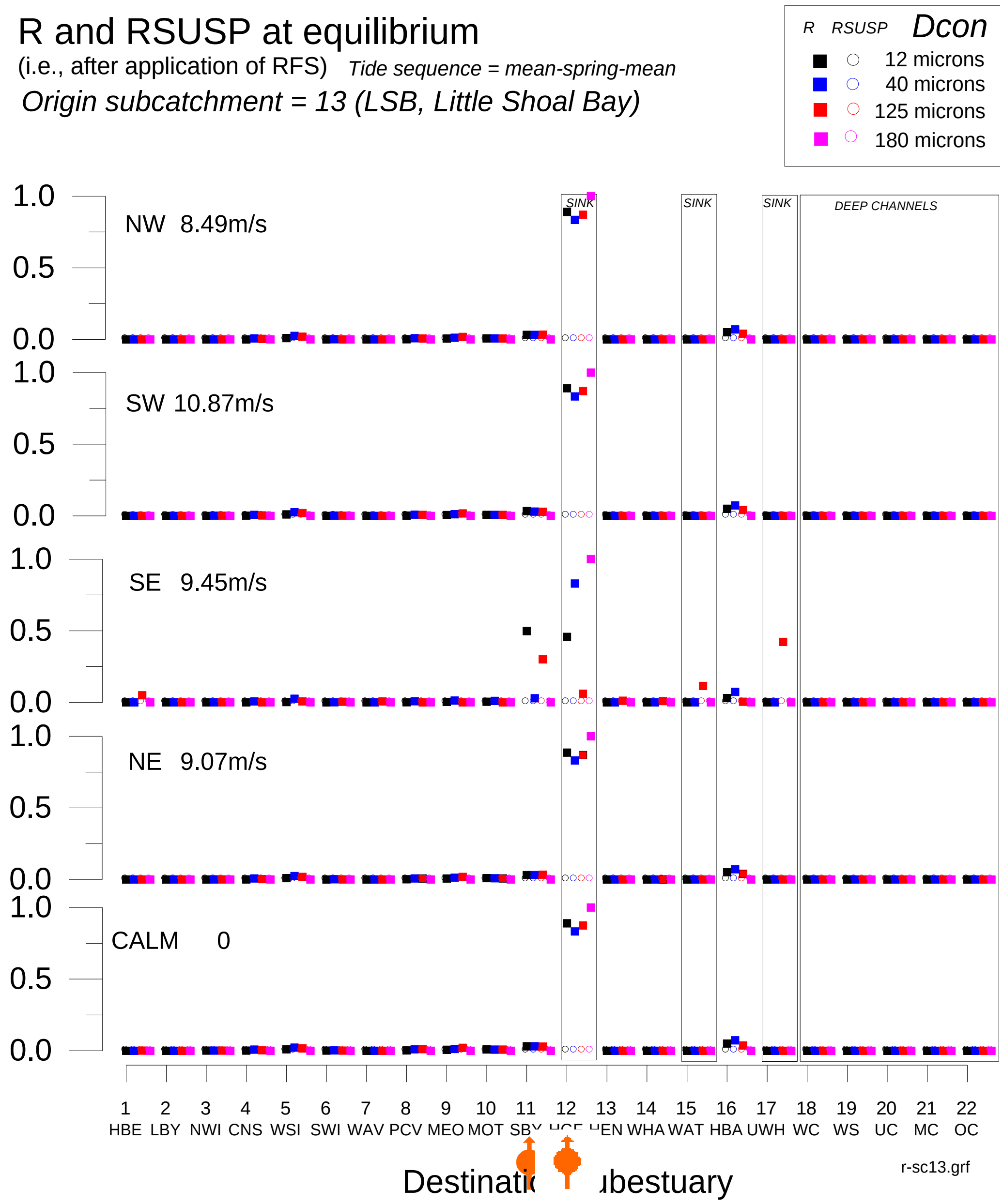

R and RSUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = mean-spring-mean
Origin subcatchment = 11 (HBV, Hobsonville)
R RSUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
1.0
0.5
0.0
SINK
SINK
SINK
DEEP CHANNELS
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r-sc11.grf

Figure 208



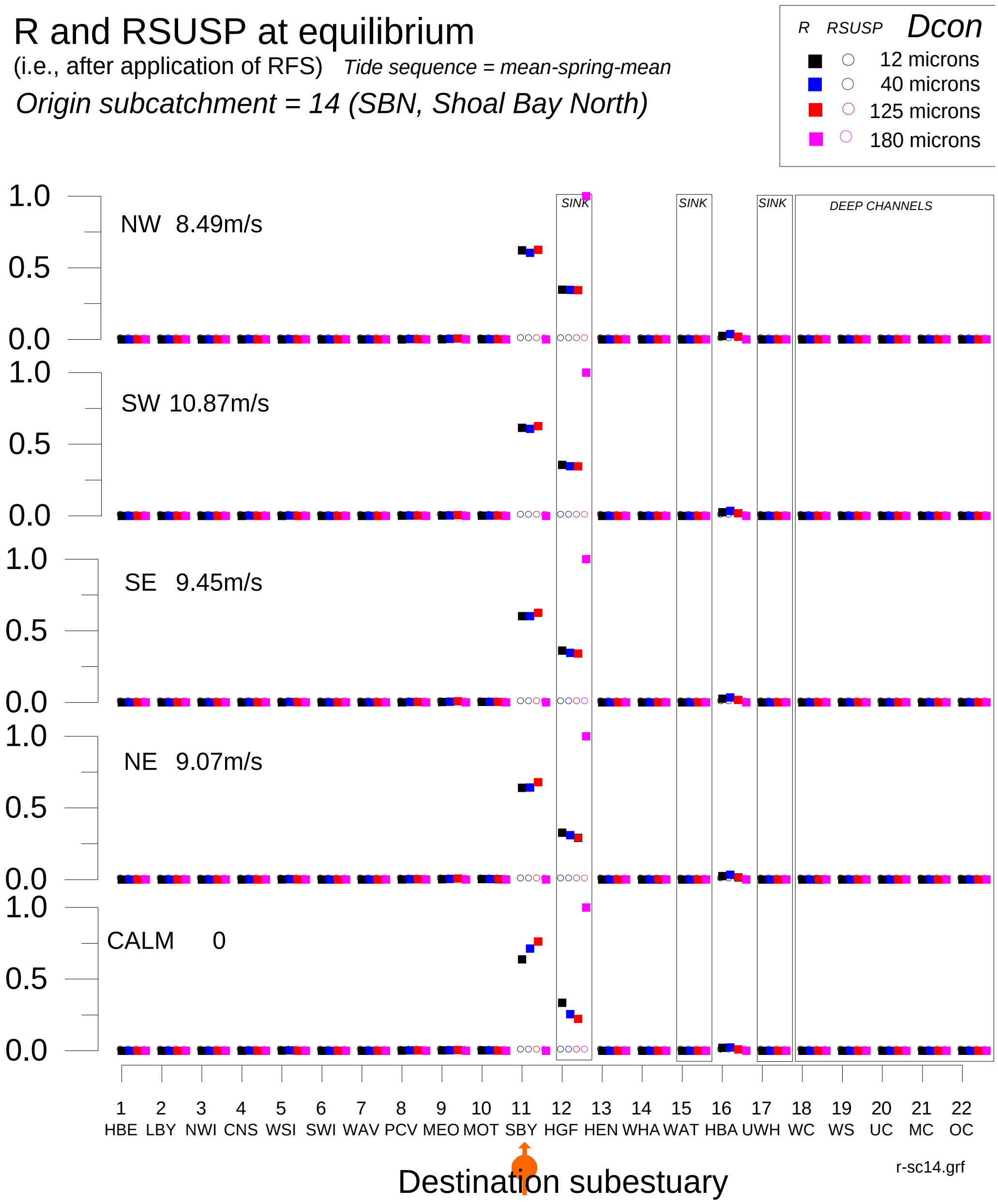
R and RSUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = mean-spring-mean
Origin subcatchment = 12 (UWH, Upper Waitemata Harbour)
R
RSUSP
Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
1.0
0.5
0.0
SINK
SINK
SINK
DEEP CHANNELS
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r-sc12.grf

Figure 209



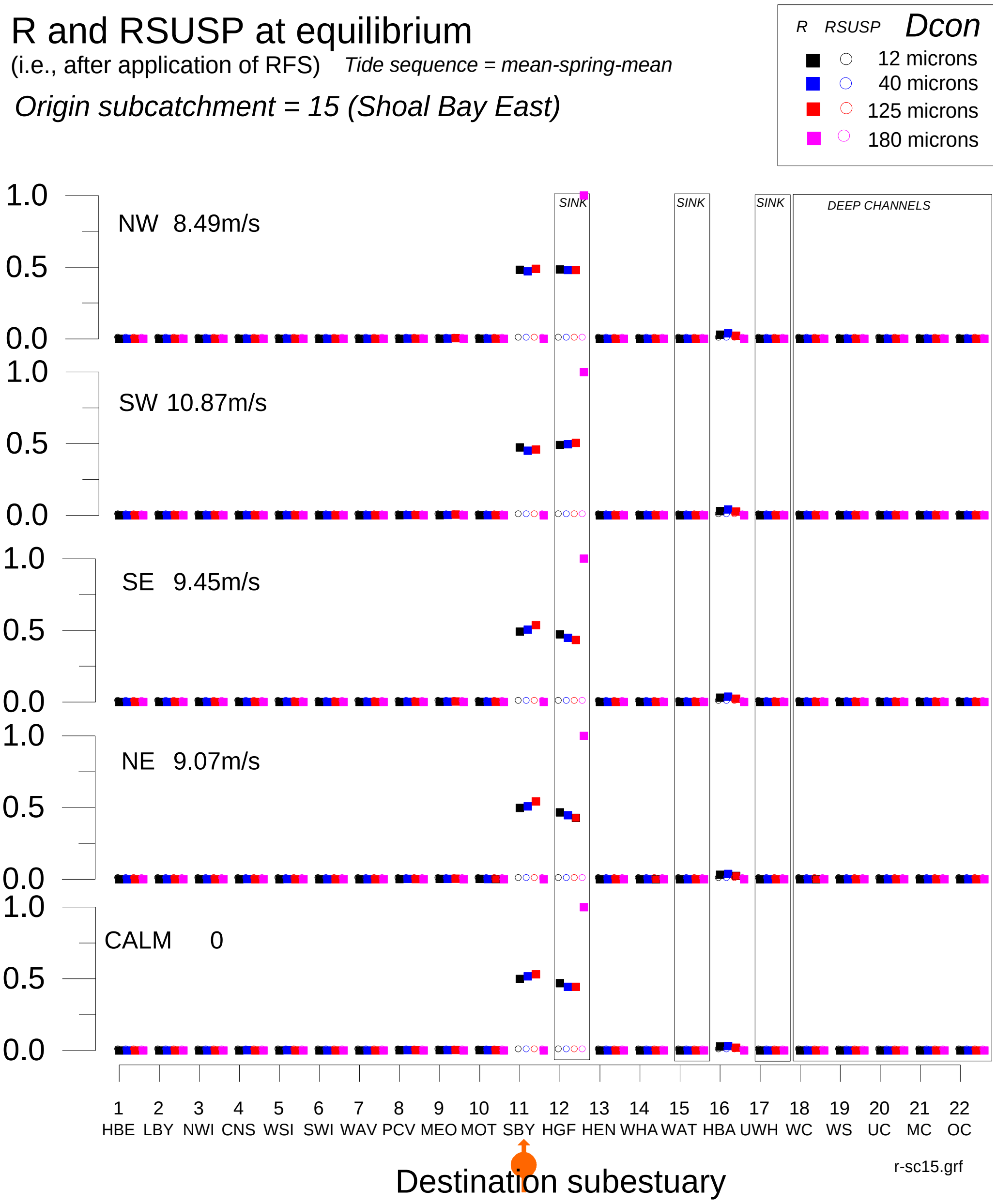
R and RSUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = mean-spring-mean
Origin subcatchment = 13 (LSB, Little Shoal Bay)
R RSUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
SINK
SINK
SINK
DEEP CHANNELS
1.0
0.5
0.0
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HCE
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r-sc13.grf

Figure 210



R and RSUSP at equilibrium
(i.e., after application of RFS) Tide sequence = mean-spring-mean
Origin subcatchment = 14 (SBN, Shoal Bay North)
R RSUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
SINK
SINK
SINK
DEEP CHANNELS
1.0
0.5
0.0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22
HBE LBY NWI CNS WSI SWI WAV PCV MEO MOT SBY HGF HEN WHA WAT HBA UWH WC WS UC MC OC
Destination subestuary
r-sc14.grf

Figure 211



R and RSUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = mean-spring-mean
Origin subcatchment = 15 (Shoal Bay East)
R
RSUSP
Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
SINK
SINK
SINK
DEEP CHANNELS
1.0
0.5
0.0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22
HBE LBY NWI CNS WSI SWI WAV PCV MEO MOT SBY HGF HEN WHA WAT HBA UWH WC WS UC MC OC
Destination subestuary
r-sc15.grf

Figure 212

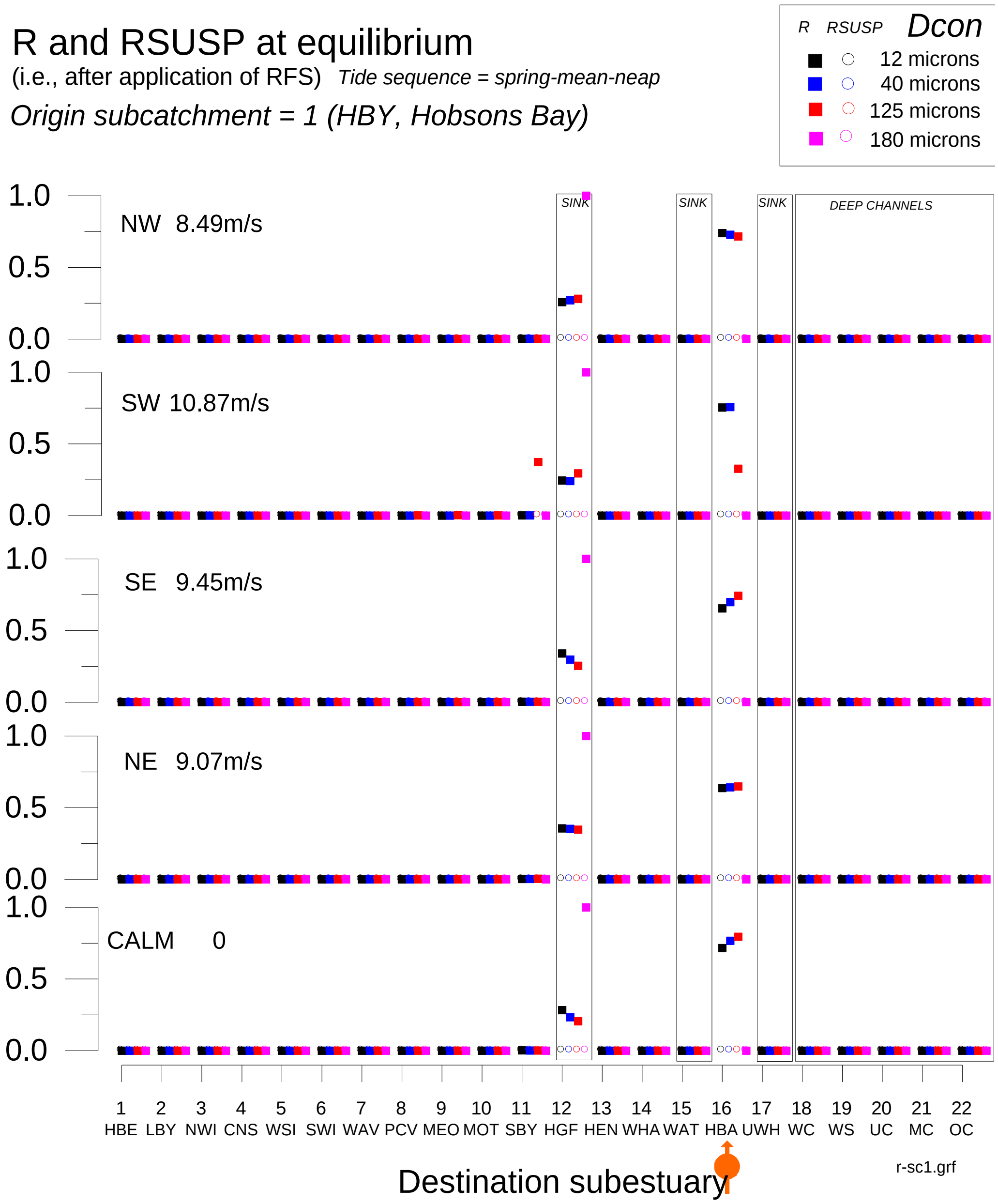

R and RSUSP at equilibrium
(i.e., after application of RFS) Tide sequence = spring-mean-neap
Origin subcatchment = 1 (HBY, Hobsons Bay)
R RSUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
SINK
SINK
SINK
DEEP CHANNELS
1.0
0.5
0.0
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r-sc1.grf

Figure 213

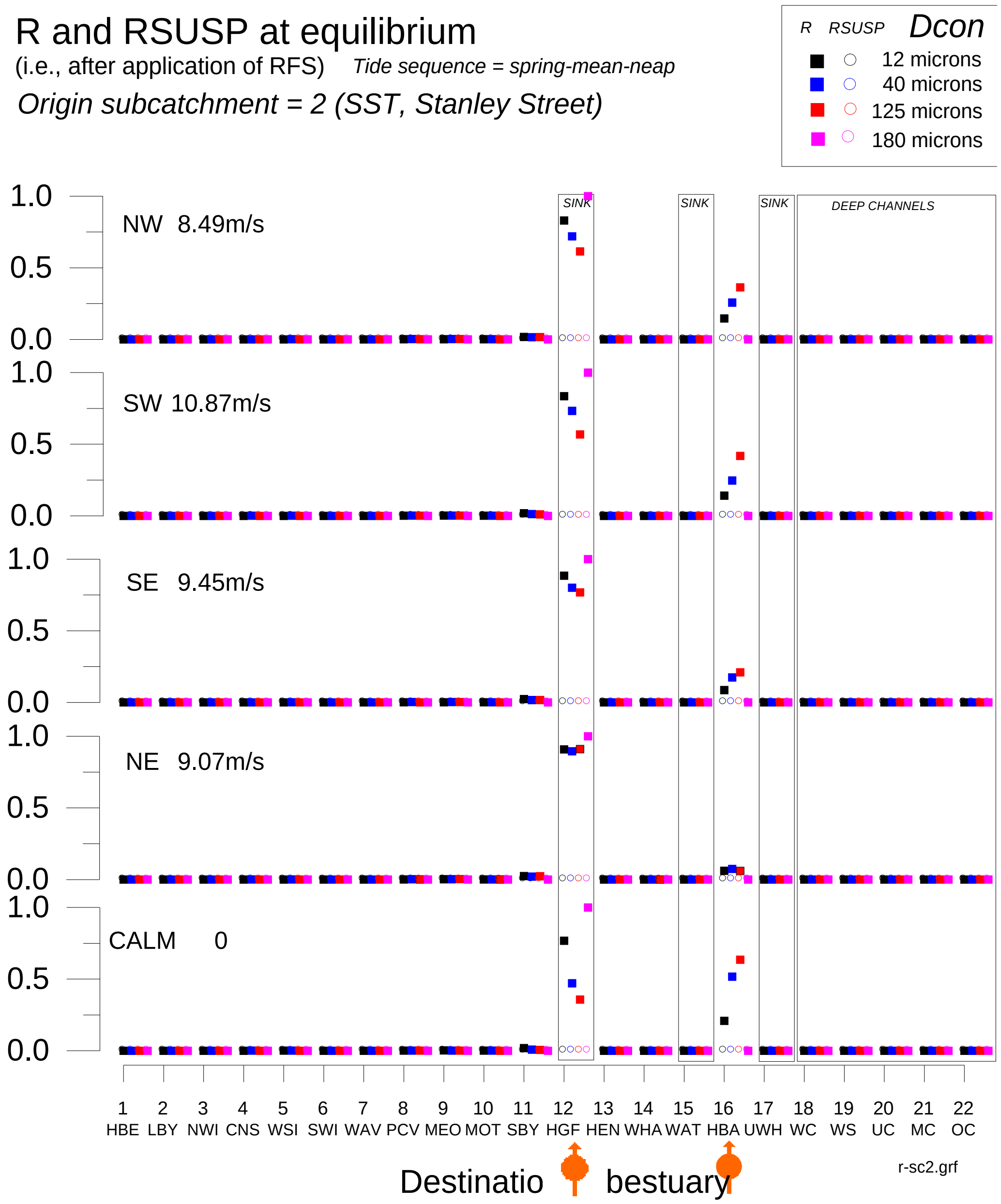
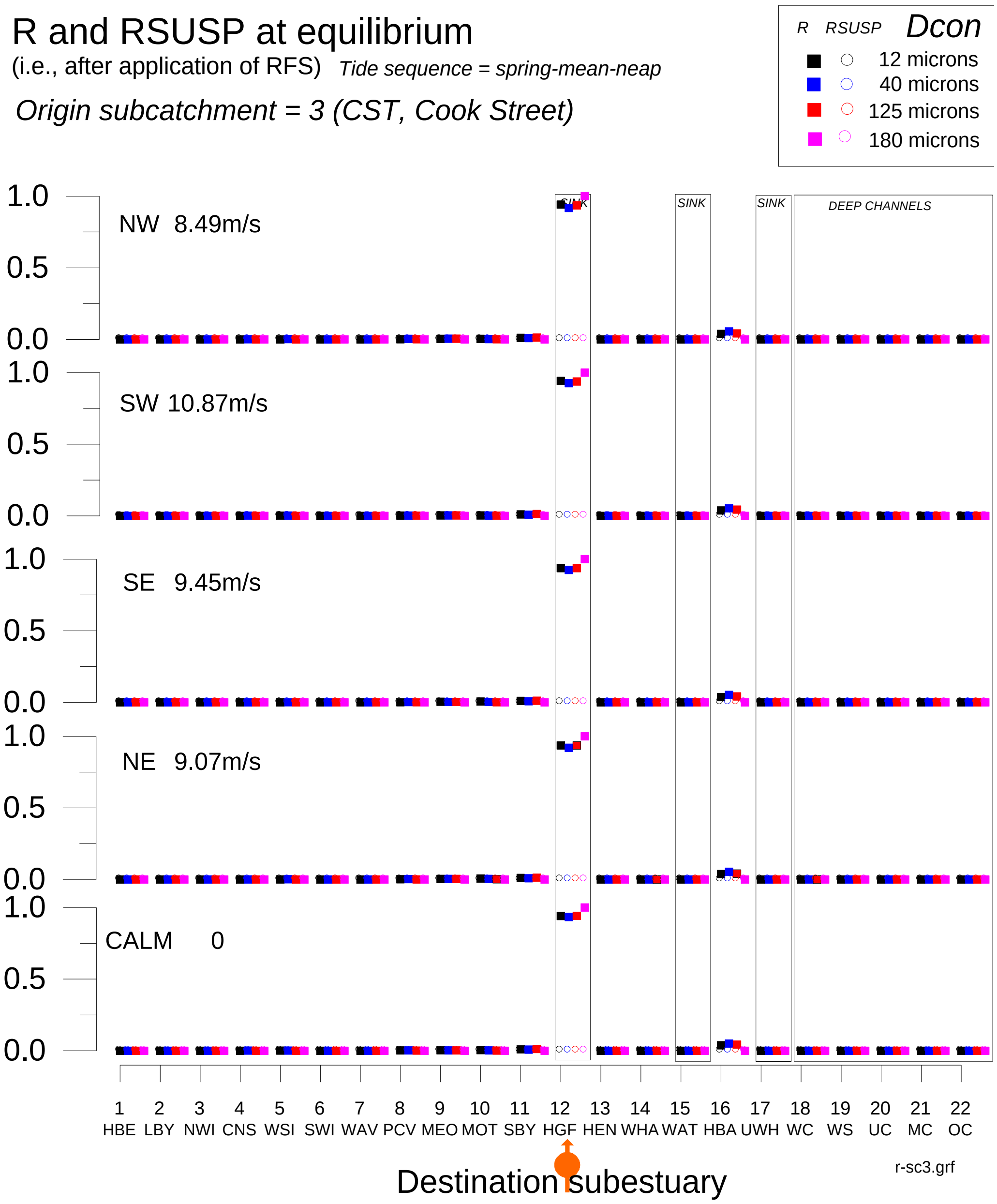
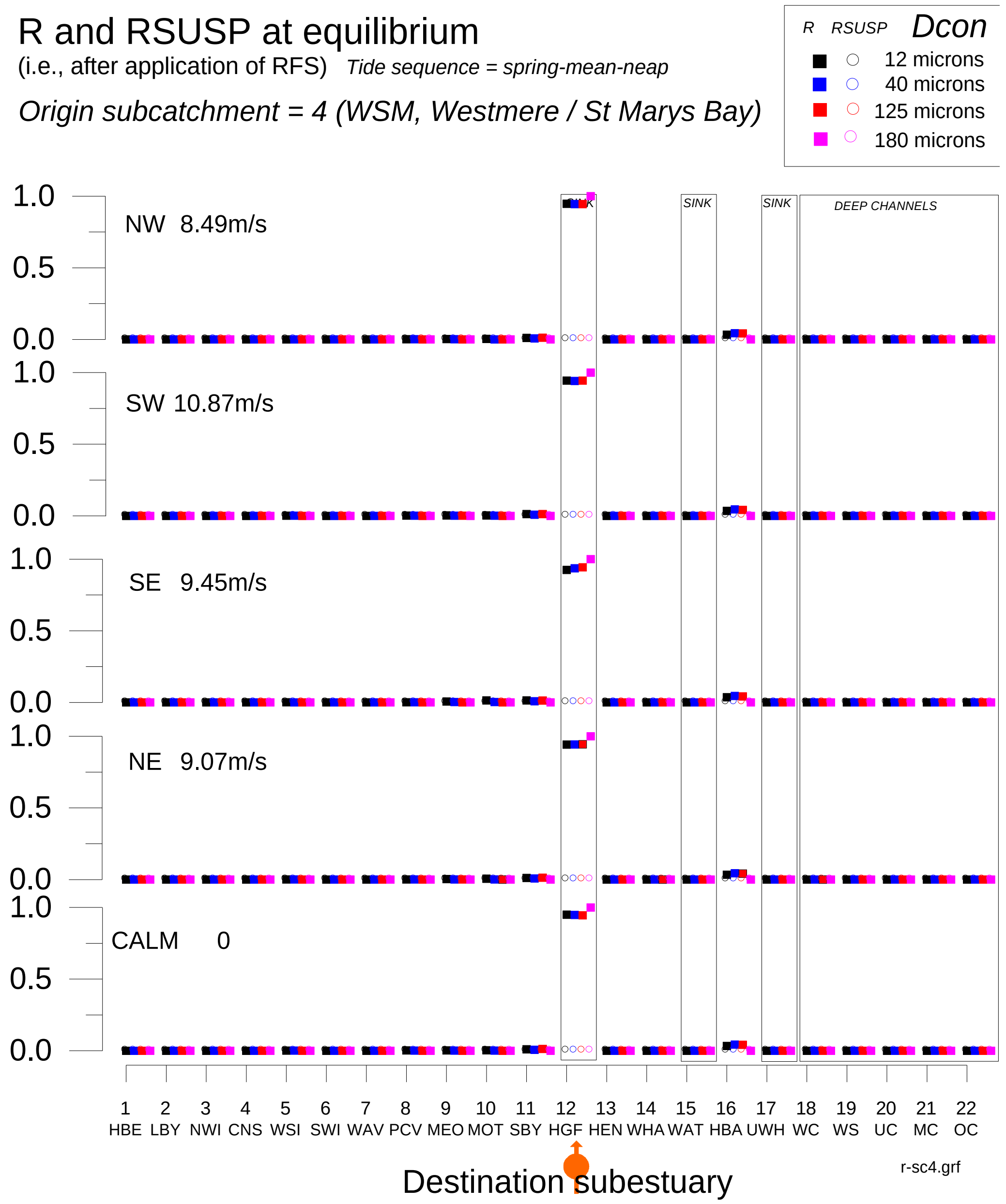

R and RSUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = spring-mean-neap
Origin subcatchment = 2 (SST, Stanley Street)
R RSUSP Dcon
12 microns
40 microns
125 microns
180 microns
SINK
SINK
SINK
DEEP CHANNELS
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
1.0
0.5
0.0
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destinatio
bestuary
r-sc2.grf

Figure 214



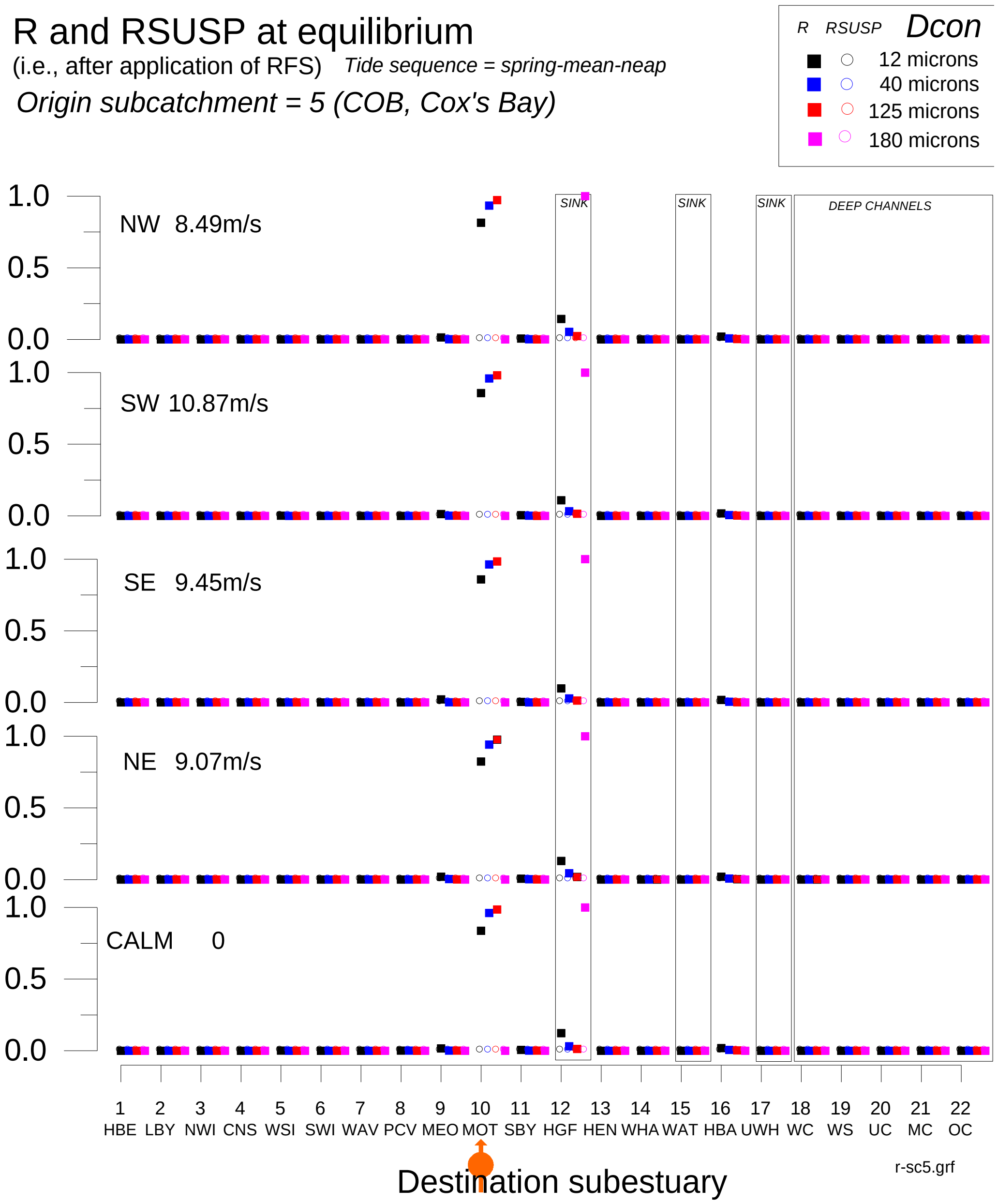
R and RSUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = spring-mean-neap
Origin subcatchment = 3 (CST, Cook Street)
R
RSUSP
Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
1.0
0.5
0.0
SINK
DEEP CHANNELS
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r-sc3.grf

**Figure 215**



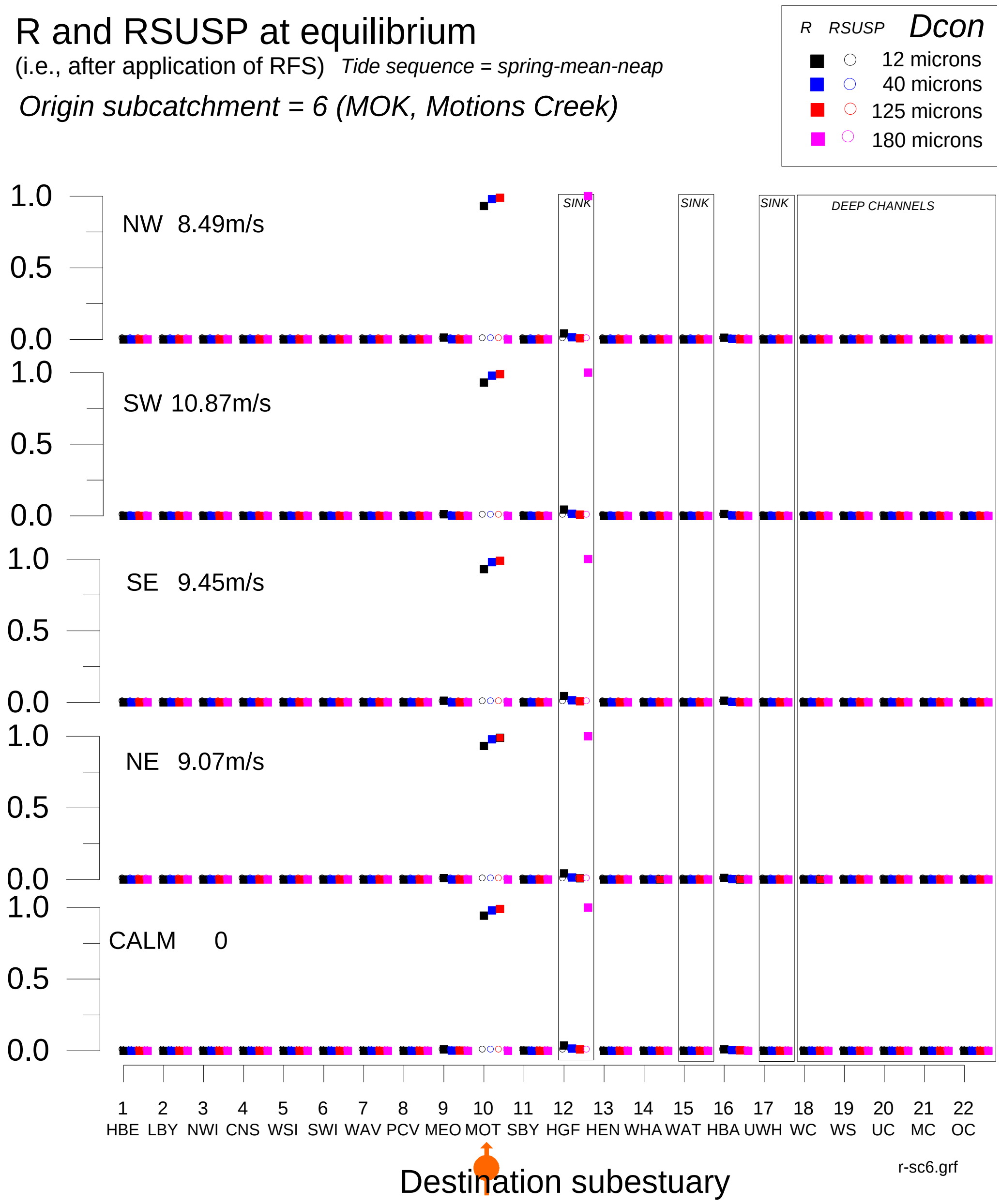
R and RSUSP at equilibrium
(i.e., after application of RFS) Tide sequence = spring-mean-neap
Origin subcatchment = 4 (WSM, Westmere / St Marys Bay)
R RSUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
1.0
0.5
0.0
SINK
SINK
SINK
DEEP CHANNELS
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r-sc4.grf

Figure 216



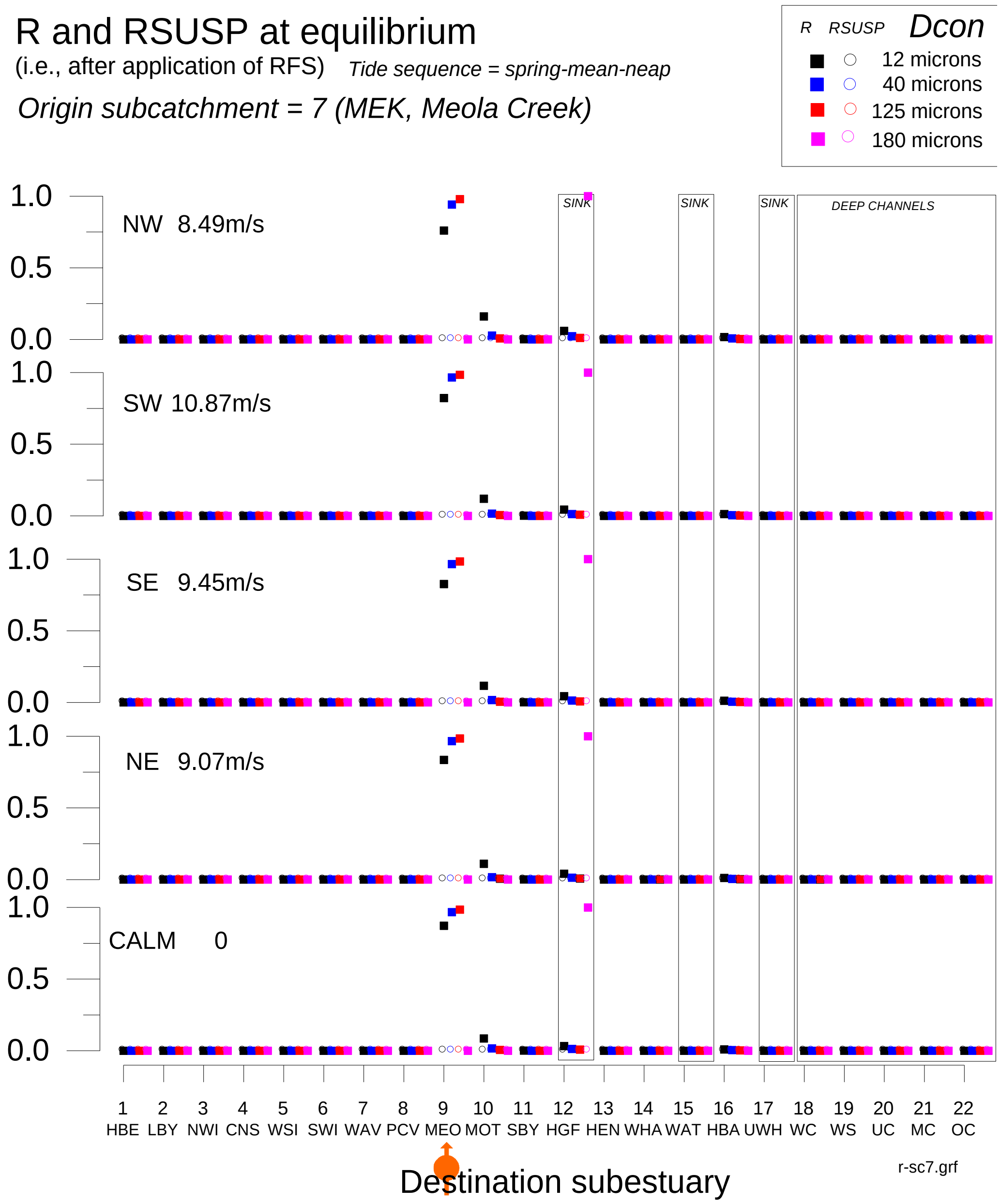
R and RSUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = spring-mean-neap
Origin subcatchment = 5 (COB, Cox's Bay)
R RSUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
1.0
0.5
0.0
SINK
SINK
SINK
DEEP CHANNELS
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22
HBE LBY NWI CNS WSI SWI WAV PCV MEO MOT SBY HGF HEN WHA WAT HBA UWH WC WS UC MC OC
Destination subestuary
r-sc5.grf

Figure 217



R and RSUSP at equilibrium
(i.e., after application of RFS) Tide sequence = spring-mean-neap
Origin subcatchment = 6 (MOK, Motions Creek)
R RSUSP Dcon
12 microns
40 microns
125 microns
180 microns
1.0
0.5
0.0
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
SINK
SINK
SINK
DEEP CHANNELS
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r-sc6.grf

Figure 218



R and RSUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = spring-mean-neap
Origin subcatchment = 7 (MEK, Meola Creek)
R RSUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
1.0
0.5
0.0
SINK
SINK
SINK
DEEP CHANNELS
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r-sc7.grf

Figure 219

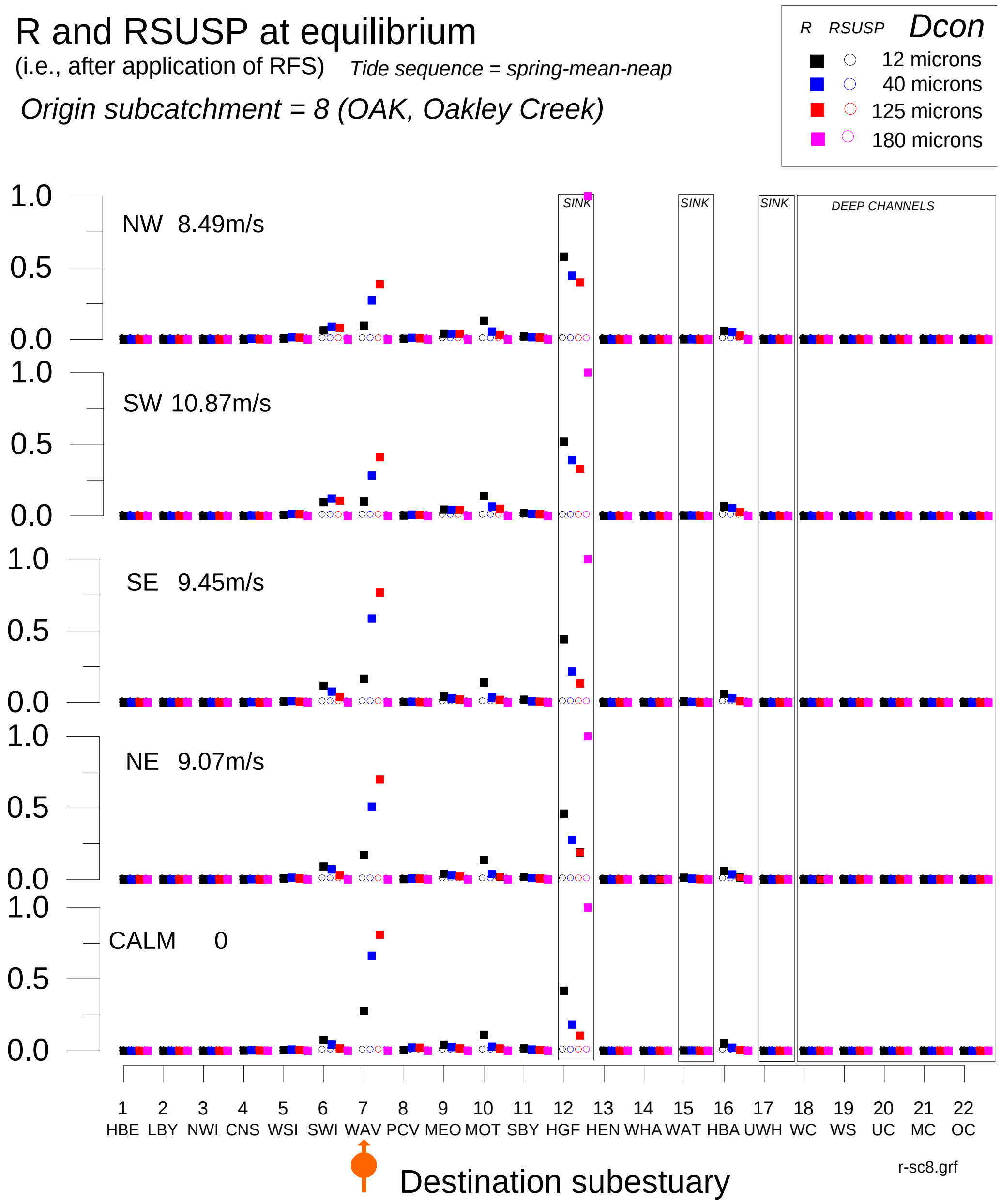

R and RSUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = spring-mean-neap
Origin subcatchment = 8 (OAK, Oakley Creek)
R
RSUSP
Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
SINK
SINK
SINK
DEEP CHANNELS
1.0
0.5
0.0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22
HBE LBY NWI CNS WSI SWI WAV PCV MEO MOT SBY HGF HEN WHA WAT HBA UWH WC WS UC MC OC
Destination subestuary
r-sc8.grf

Figure 220

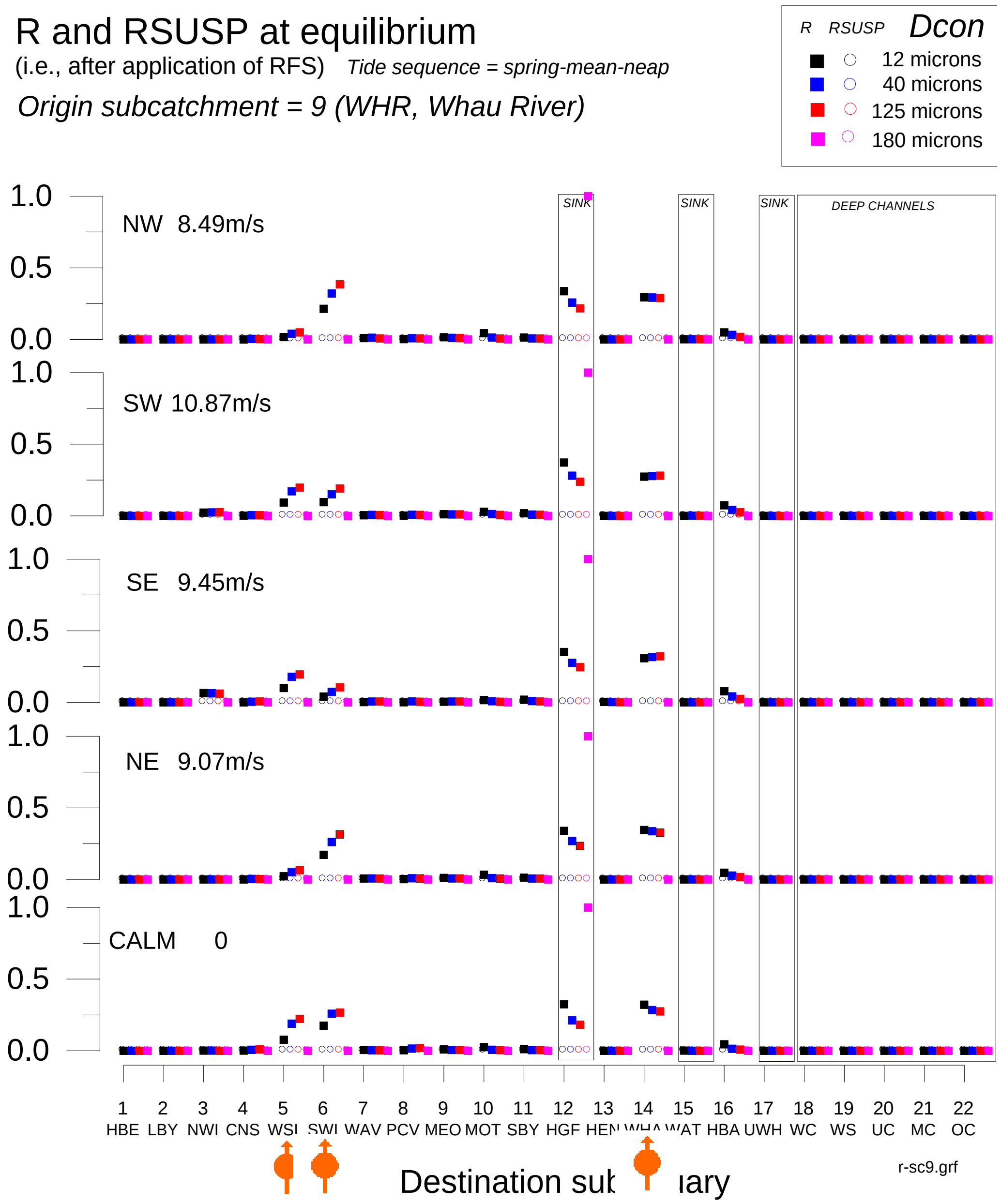

R and RSUSP at equilibrium
(i.e., after application of RFS) Tide sequence = spring-mean-neap
Origin subcatchment = 9 (WHR, Whau River)
R RSUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
SINK
DEEP CHANNELS
1.0
0.5
0.0
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13
14
15
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
r-sc9.grf

Figure 221

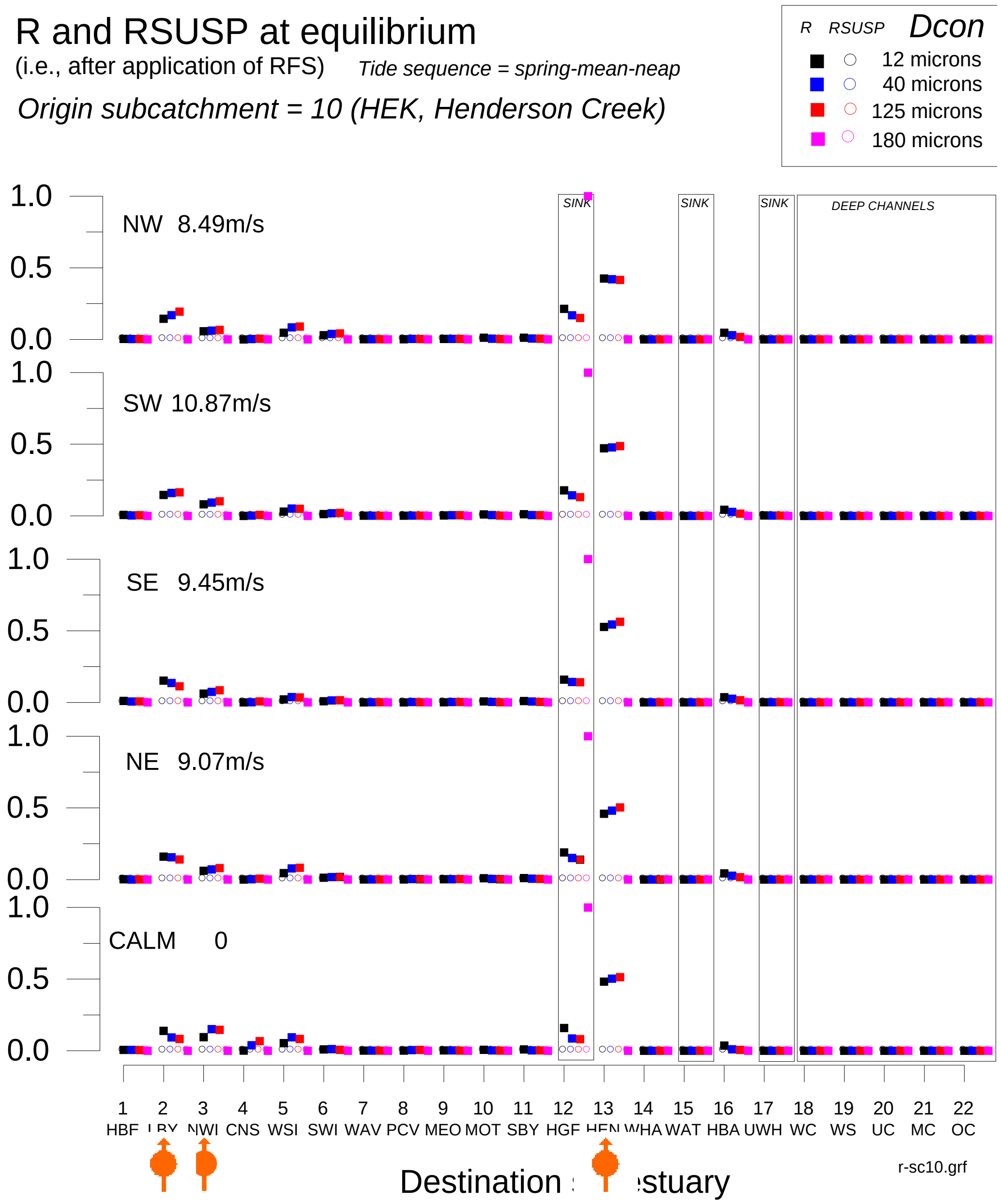

R and RSUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = spring-mean-neap
Origin subcatchment = 10 (HEK, Henderson Creek)
R RSUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
1.0
0.5
0.0
SINK
SINK
SINK
DEEP CHANNELS
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22
HBF NWI CNS WSI SWI WAV PCV MEO MOT SBY HGF WAT HBA UWH WC WS UC MC OC
Destination
r-sc10.grf

Figure 222

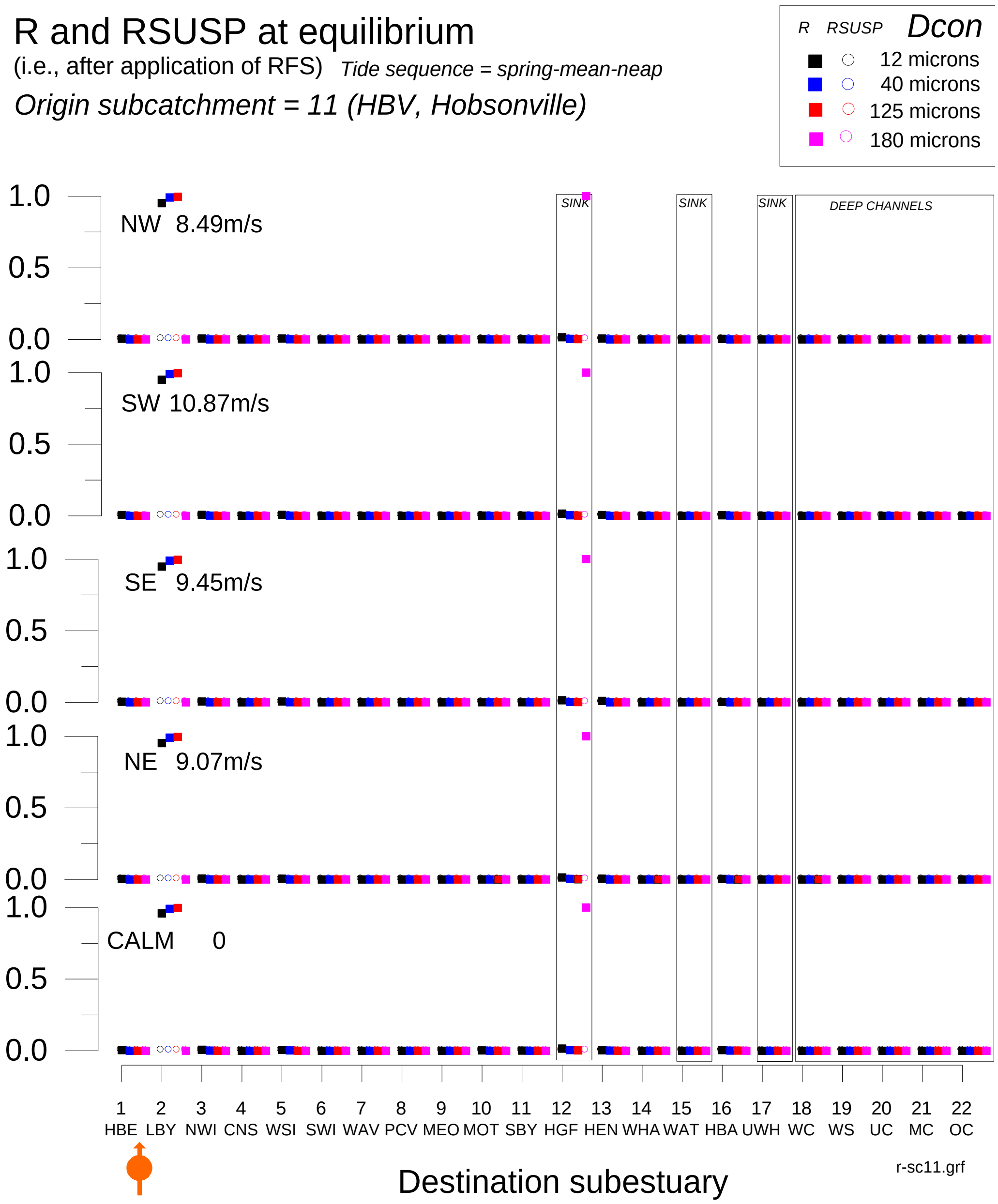
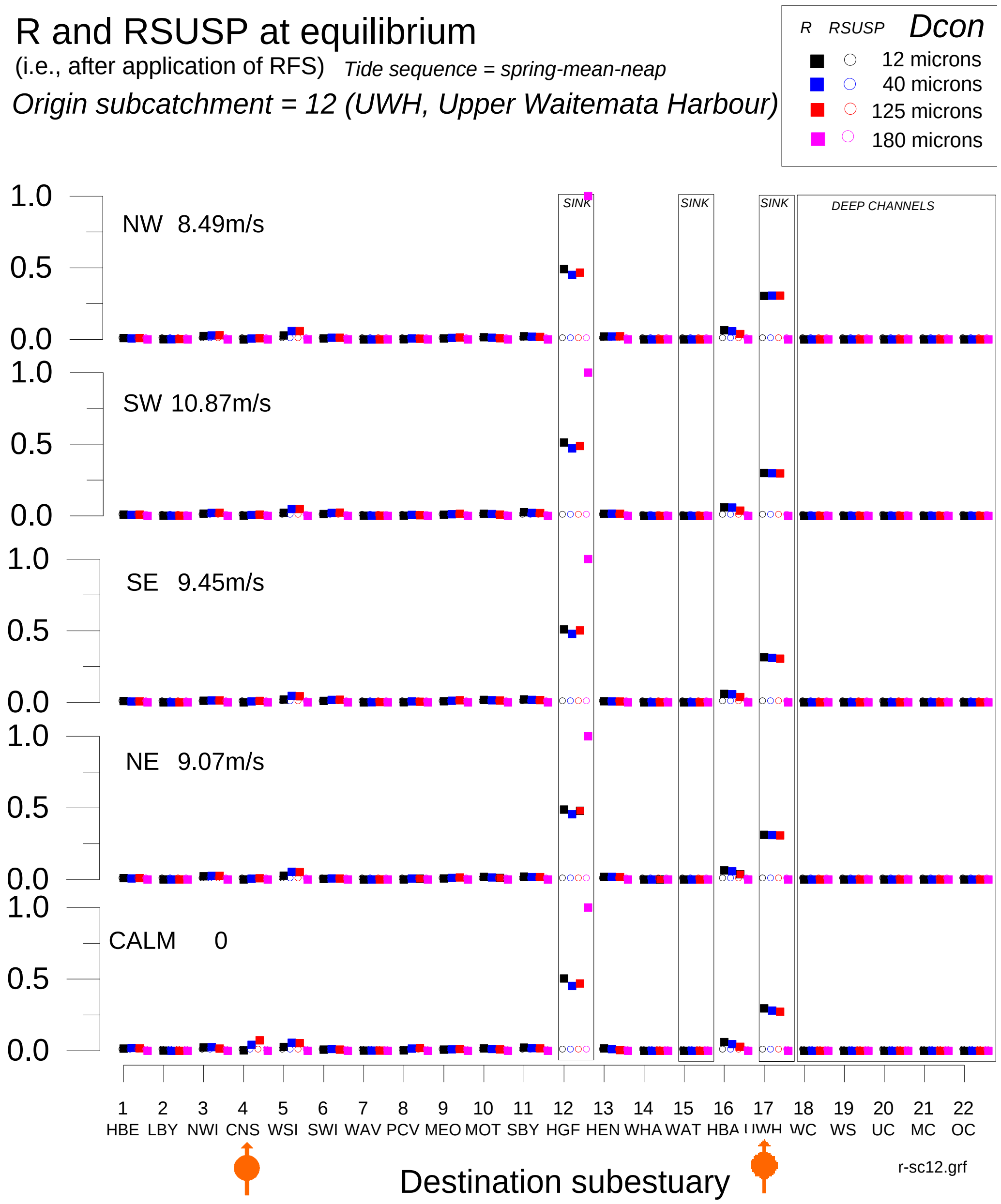
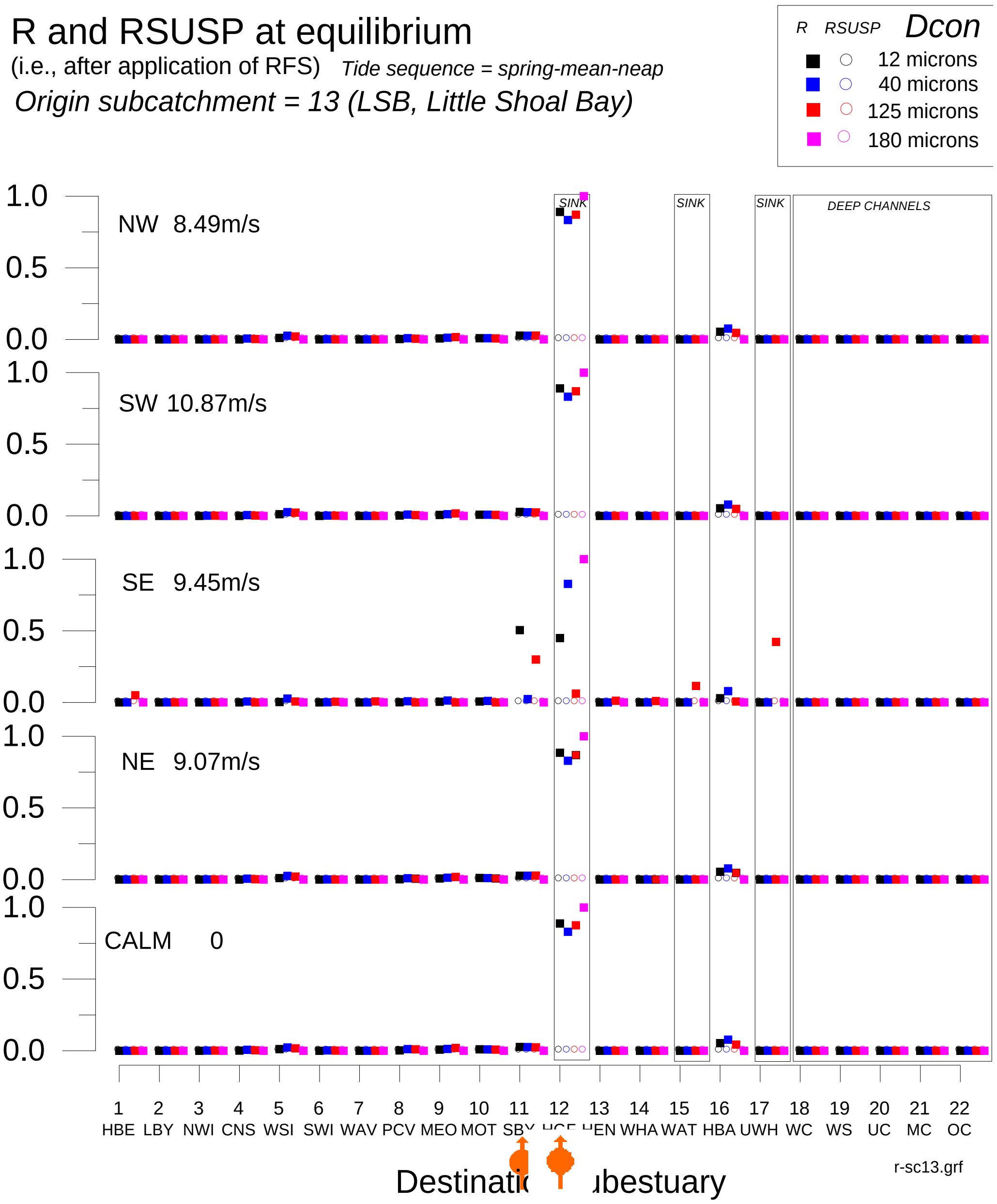

R and RSUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = spring-mean-neap
Origin subcatchment = 11 (HBV, Hobsonville)
R
RSUSP
Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
SINK
SINK
SINK
DEEP CHANNELS
1.0
0.5
0.0
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r-sc11.grf

Figure 223



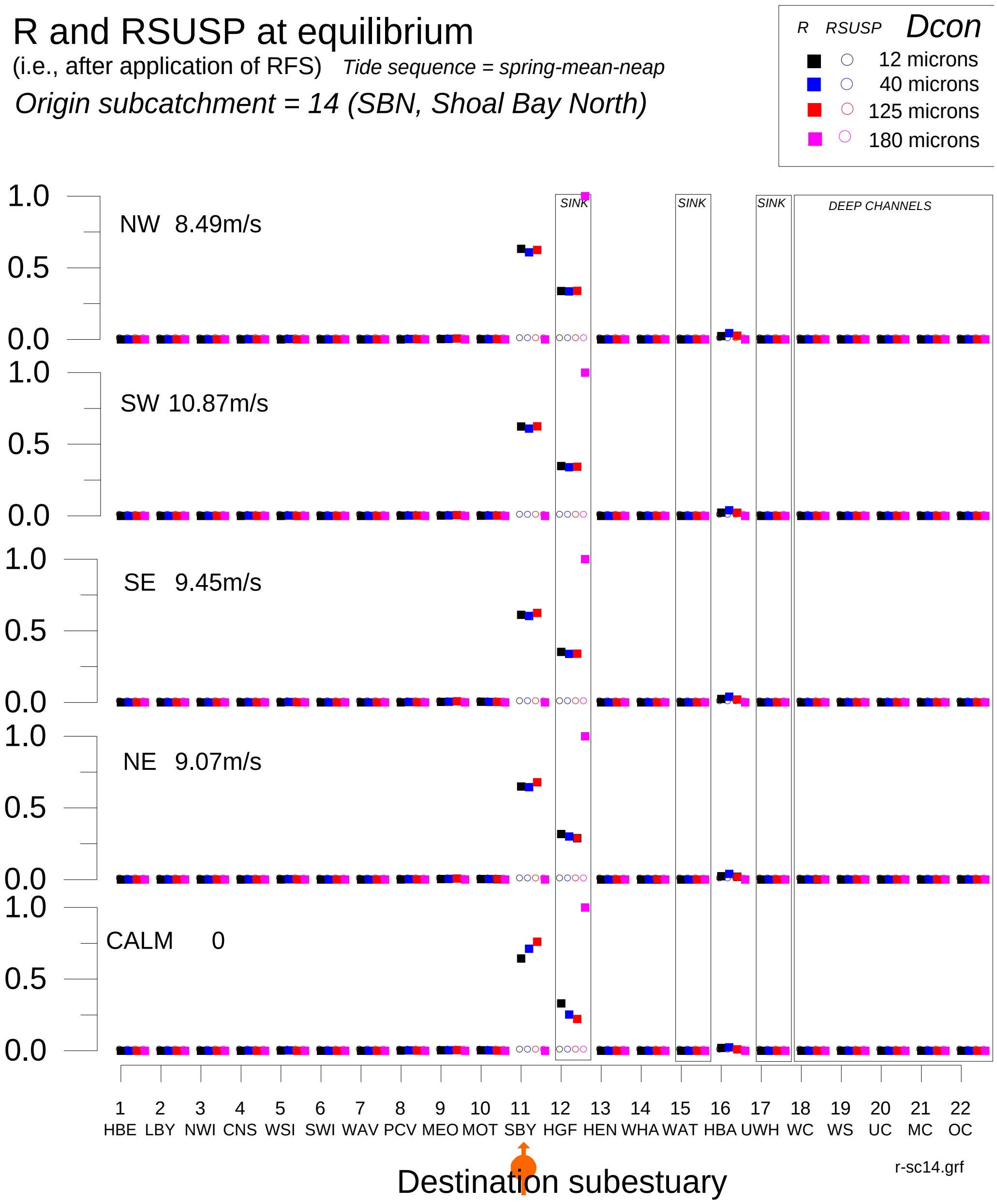
R and RSUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = spring-mean-neap
Origin subcatchment = 12 (UWH, Upper Waitemata Harbour)
R RSUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
1.0
0.5
0.0
SINK
SINK
SINK
DEEP CHANNELS
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r-sc12.grf

Figure 224



R and RSUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = spring-mean-neap
Origin subcatchment = 13 (LSB, Little Shoal Bay)
R RSUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
SINK
SINK
SINK
DEEP CHANNELS
1.0
0.5
0.0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22
HBE LBY NWI CNS WSI SWI WAV PCV MEO MOT
EN WHA WAT HBA UWH WC WS UC MC OC
r-sc13.grf

Figure 225



R and RSUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = spring-mean-neap
Origin subcatchment = 14 (SBN, Shoal Bay North)
R
RSUSP
Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
1.0
0.5
0.0
SINK
SINK
SINK
DEEP CHANNELS
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r-sc14.grf

Figure 226

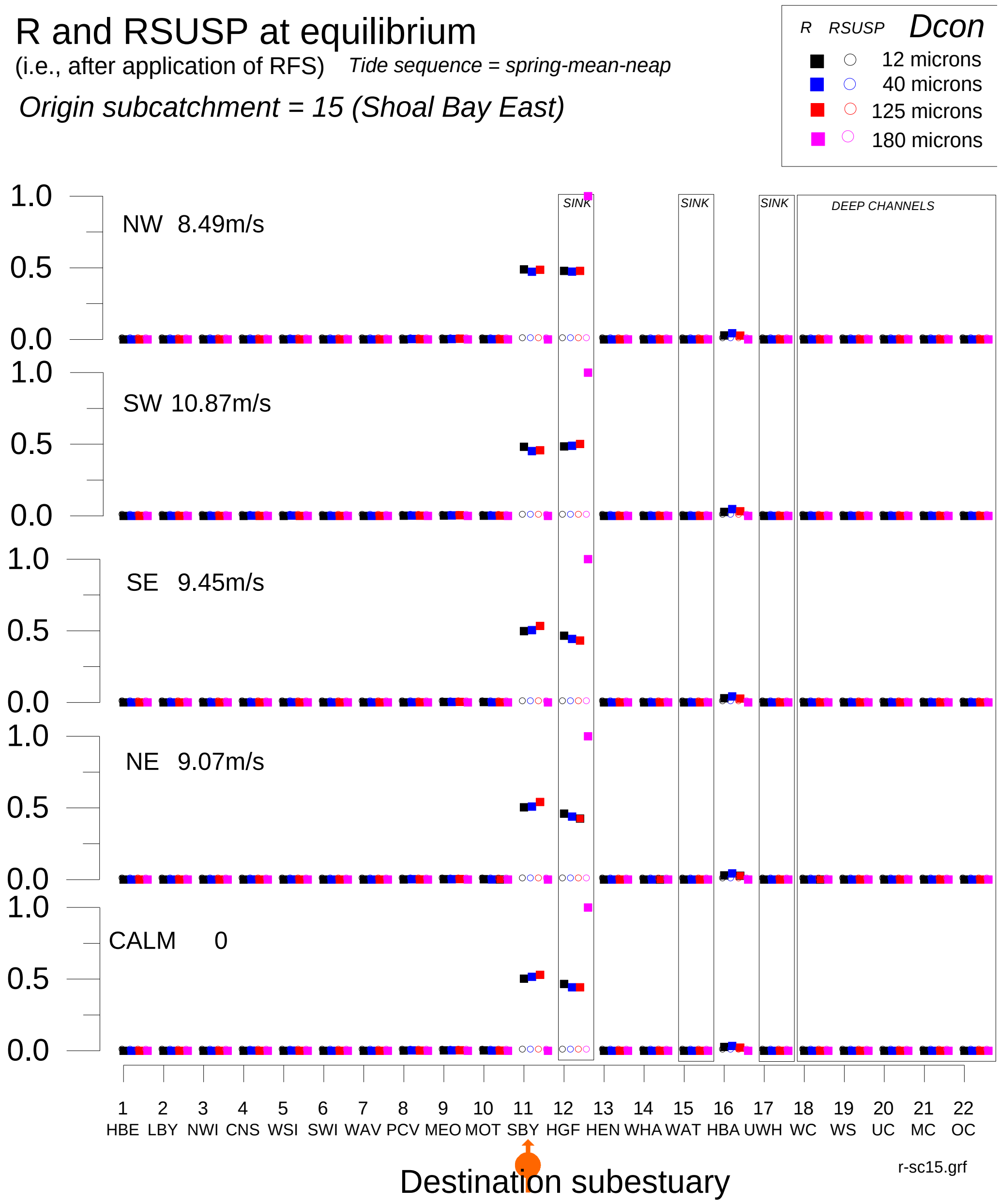

R and RSUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = spring-mean-neap
Origin subcatchment = 15 (Shoal Bay East)
R RSUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
1.0
0.5
0.0
SINK
SINK
SINK
DEEP CHANNELS
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r-sc15.grf

Figure 227

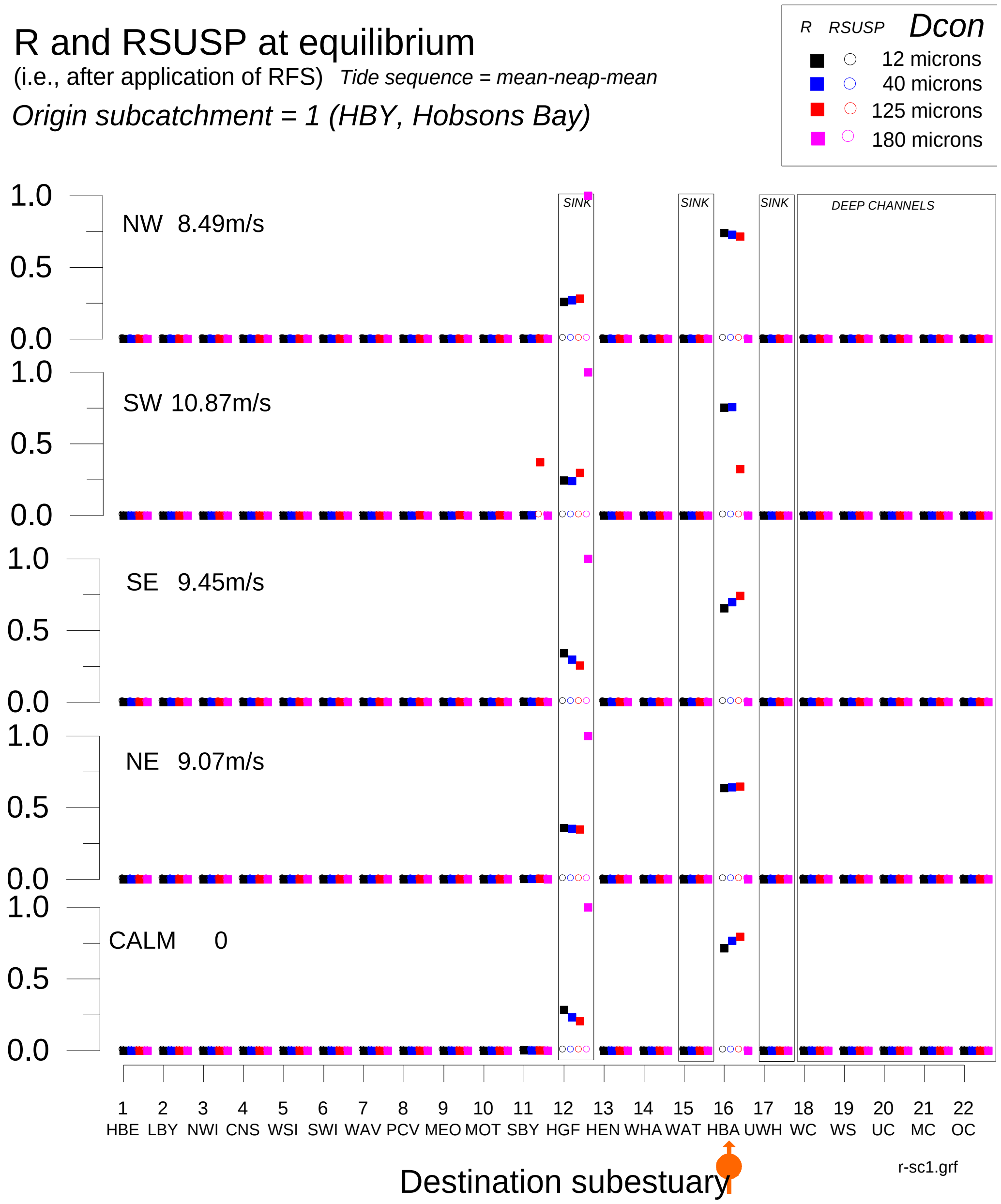
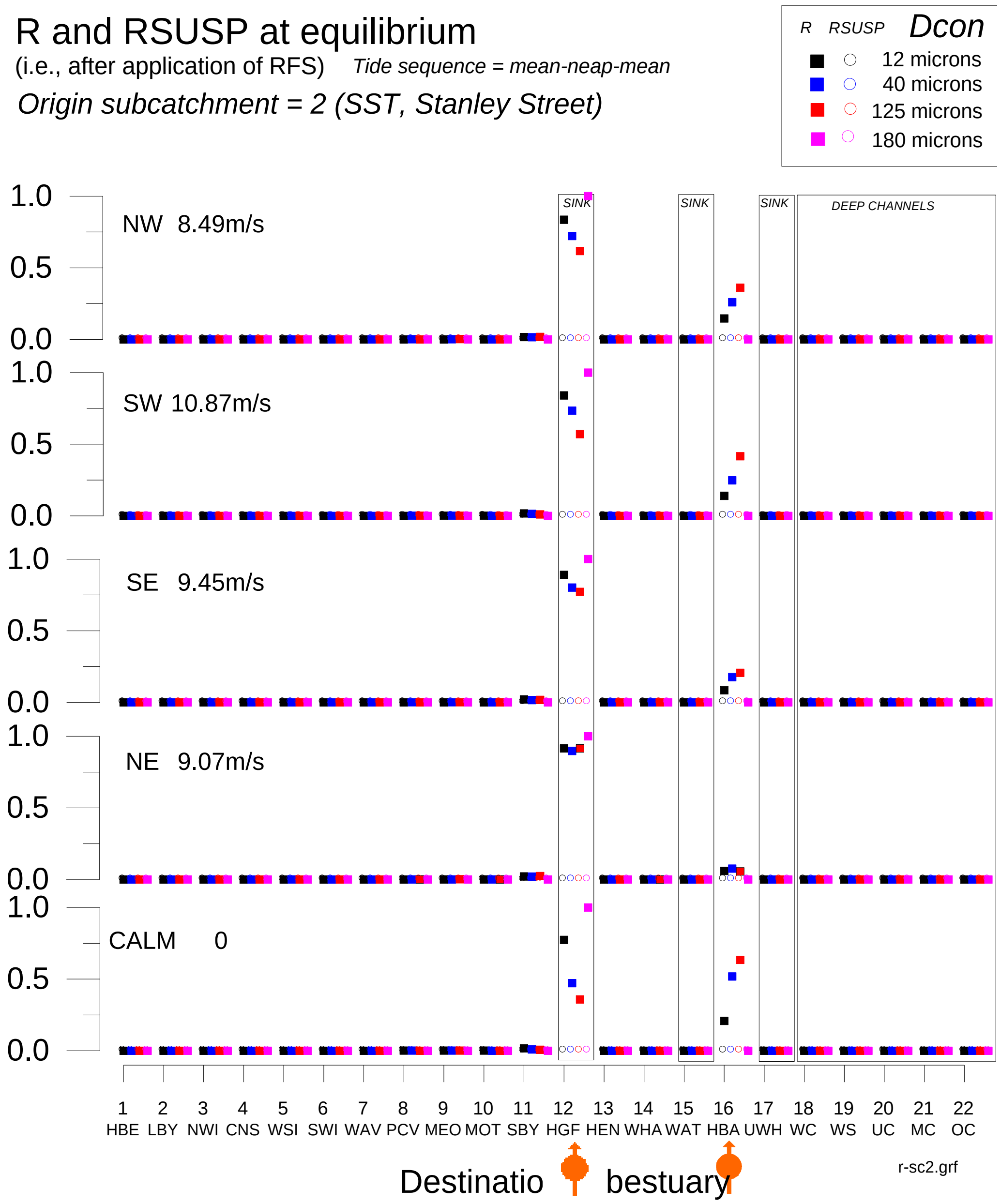

R and RSUSP at equilibrium
(i.e., after application of RFS) Tide sequence = mean-neap-mean
Origin subcatchment = 1 (HBY, Hobsons Bay)
R RSUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
SINK
SINK
SINK
DEEP CHANNELS
1.0
0.5
0.0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22
HBE LBY NWI CNS WSI SWI WAV PCV MEO MOT SBY HGF HEN WHA WAT HBA UWH WC WS UC MC OC
Destination subestuary
r-sc1.grf

Figure 228



R and RSUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = mean-neap-mean
Origin subcatchment = 2 (SST, Stanley Street)
R RSUSP Dcon
12 microns
40 microns
125 microns
180 microns
SINK
SINK
SINK
DEEP CHANNELS
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
1.0
0.5
0.0
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destinatio
bestuary
r-sc2.grf

Figure 229

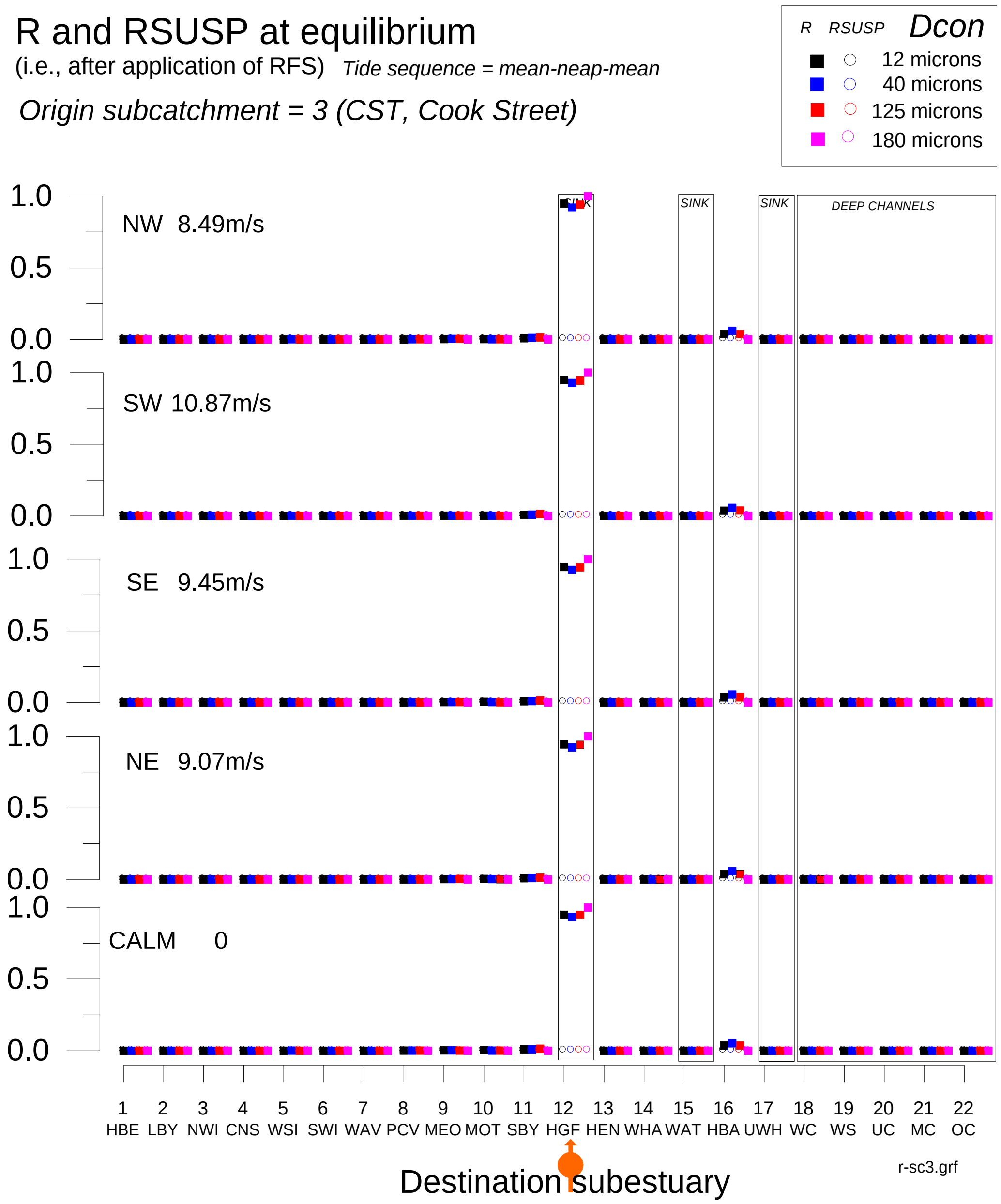
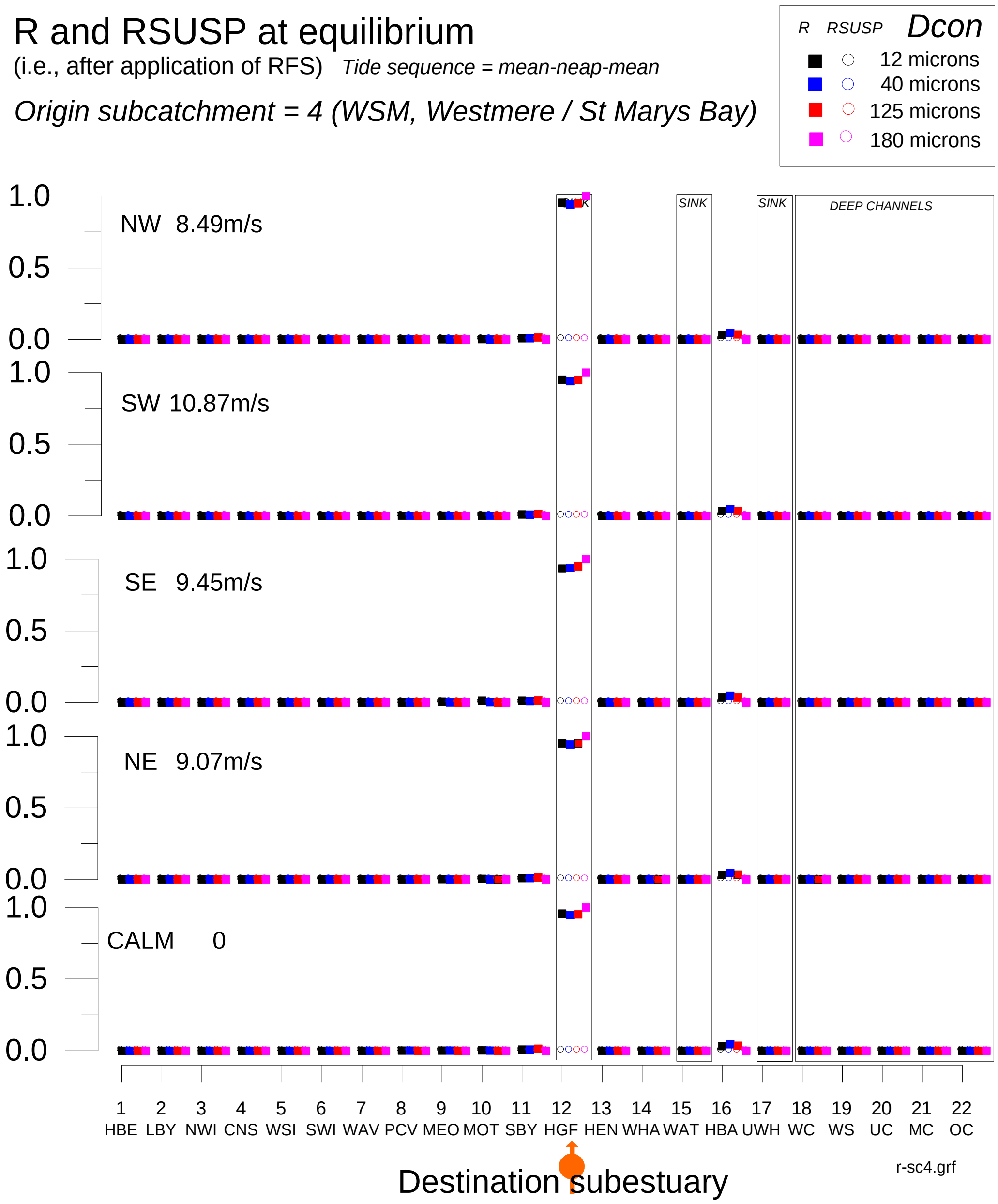

R and RSUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = mean-neap-mean
Origin subcatchment = 3 (CST, Cook Street)
R
RSUSP
Dcon
12 microns
40 microns
125 microns
180 microns
1.0
0.5
0.0
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
SINK
DEEP CHANNELS
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r-sc3.grf

Figure 230



R and RSUSP at equilibrium
(i.e., after application of RFS) Tide sequence = mean-neap-mean
Origin subcatchment = 4 (WSM, Westmere / St Marys Bay)
R RSUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
SINK
SINK
DEEP CHANNELS
1.0
0.5
0.0
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r-sc4.grf

**Figure 231**

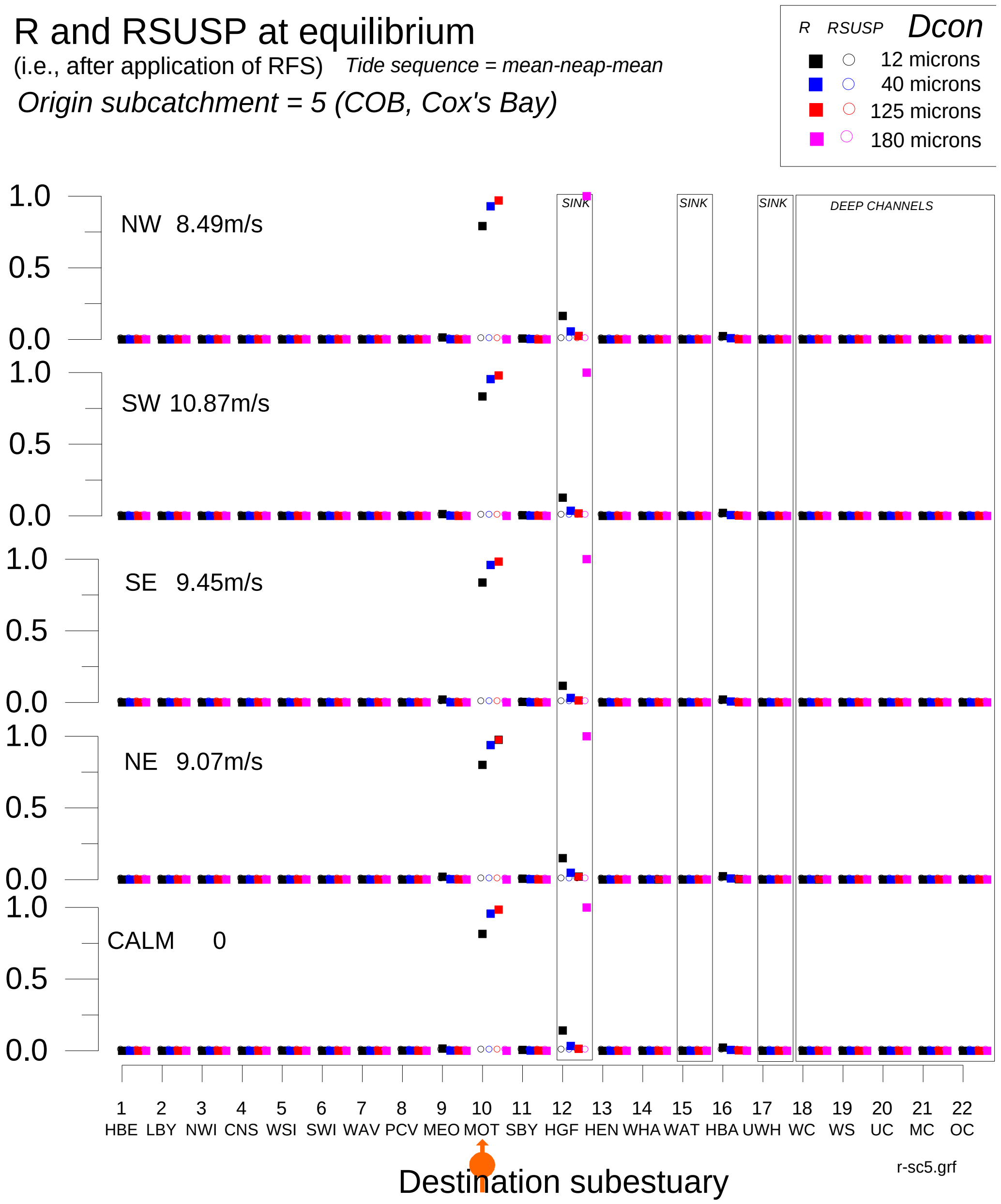
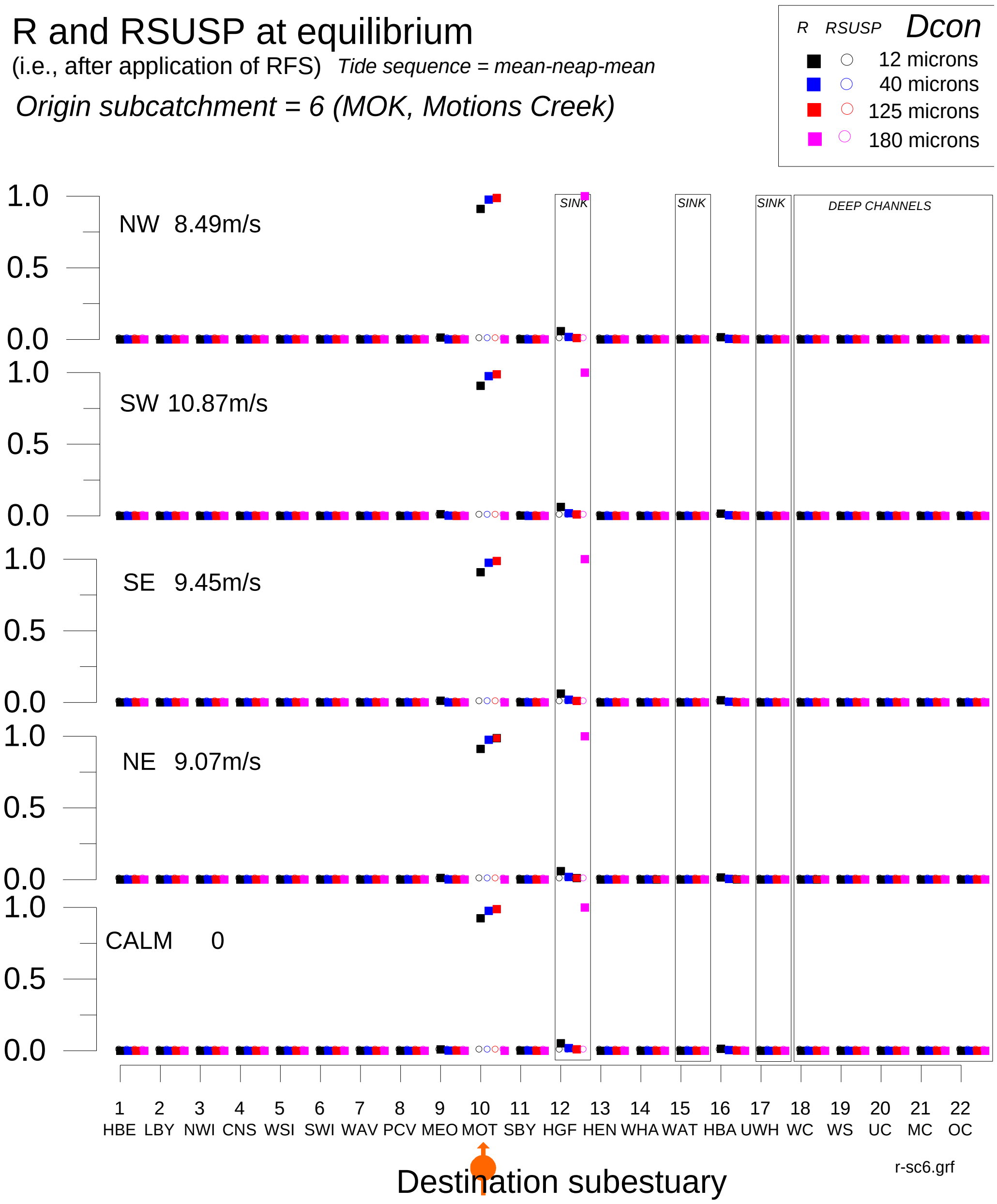
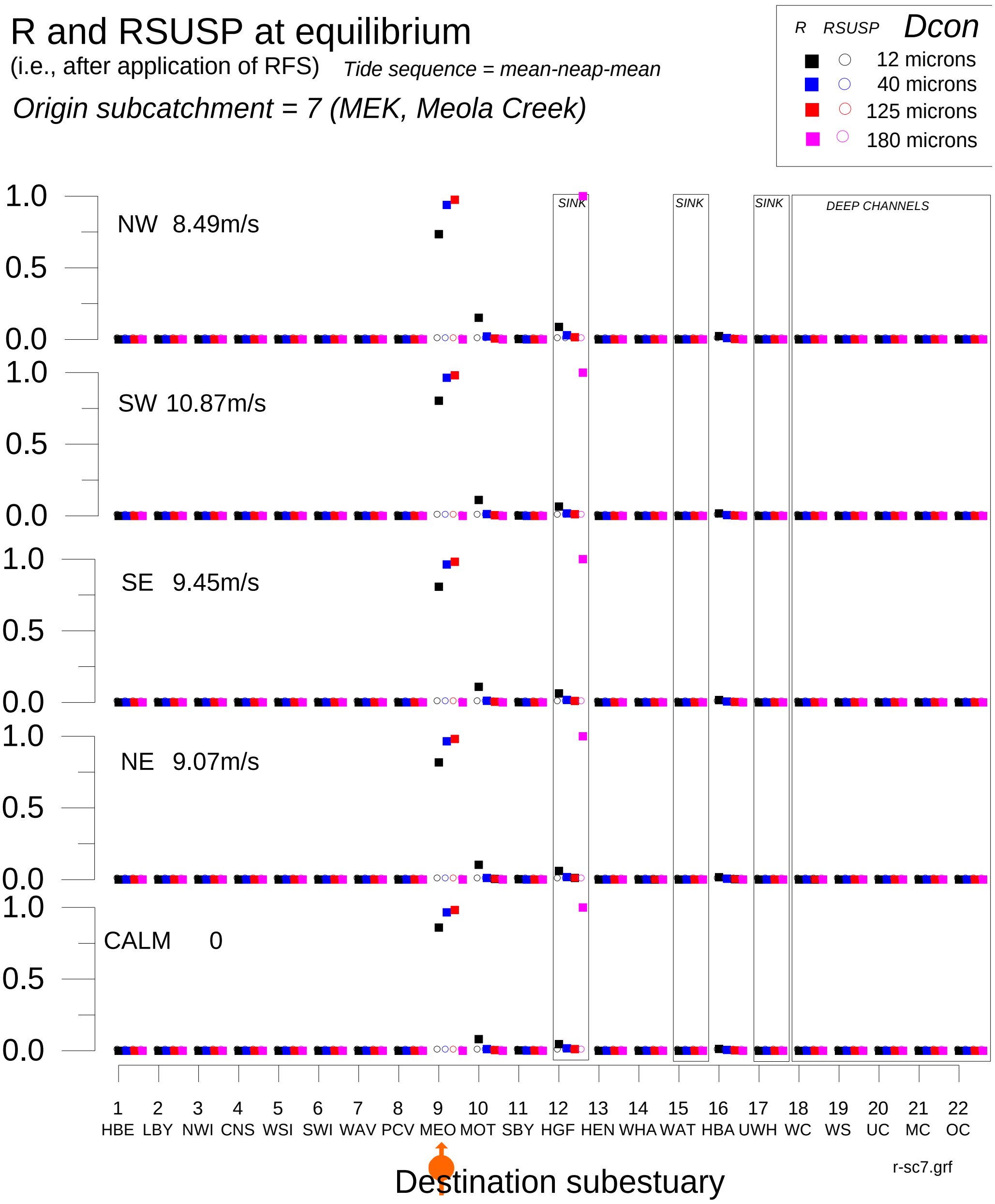

R and RSUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = mean-neap-mean
Origin subcatchment = 5 (COB, Cox's Bay)
R
RSUSP
Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
1.0
0.5
0.0
SINK
SINK
SINK
DEEP CHANNELS
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r-sc5.grf

Figure 232



R and RSUSP at equilibrium
(i.e., after application of RFS) Tide sequence = mean-neap-mean
Origin subcatchment = 6 (MOK, Motions Creek)
R RSUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
SINK
SINK
SINK
DEEP CHANNELS
1.0
0.5
0.0
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r-sc6.grf

Figure 233



R and RSUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = mean-neap-mean
Origin subcatchment = 7 (MEK, Meola Creek)
R RSUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
1.0
0.5
0.0
SINK
SINK
SINK
DEEP CHANNELS
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r-sc7.grf

Figure 234

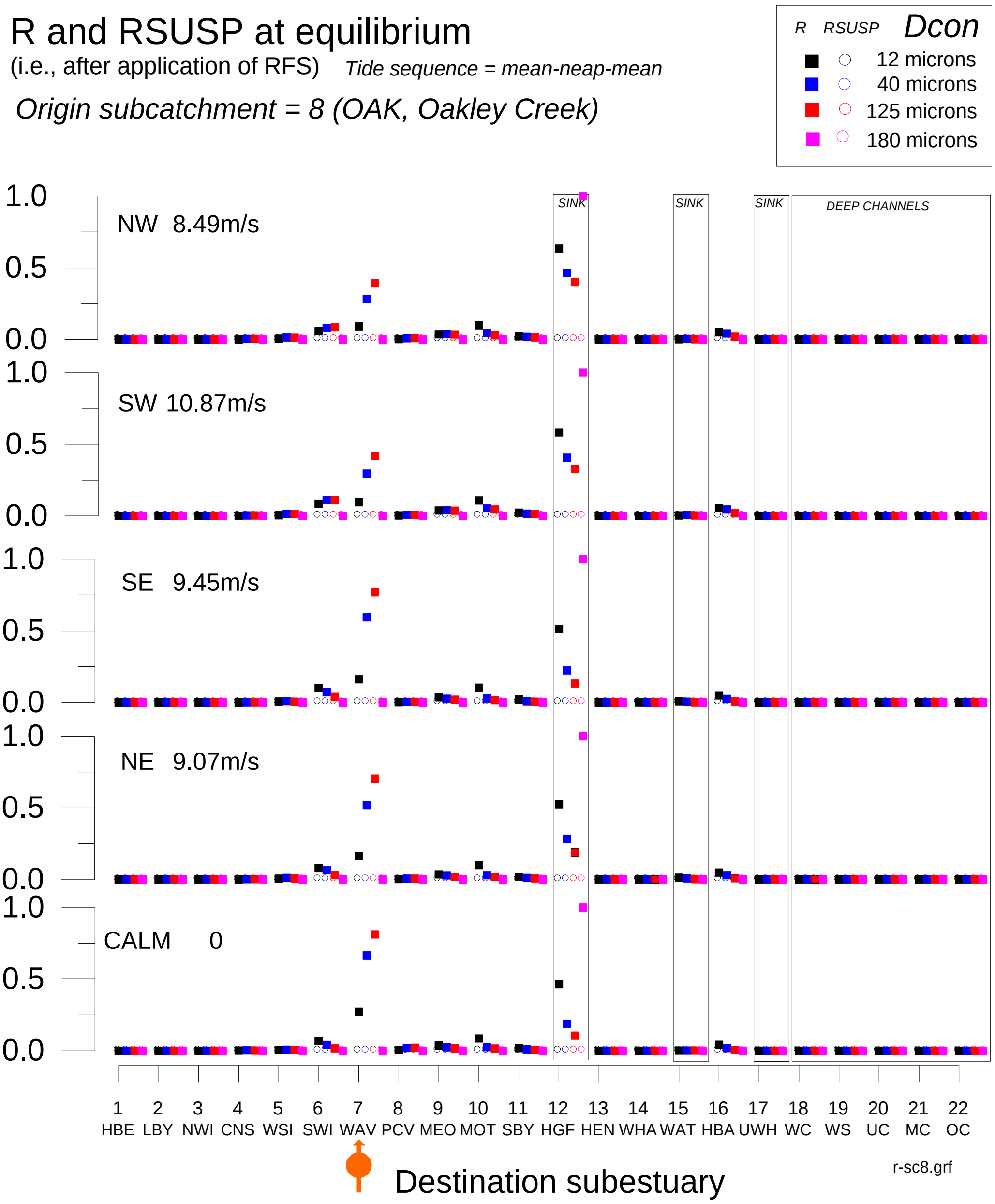

R and RSUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = mean-neap-mean
Origin subcatchment = 8 (OAK, Oakley Creek)
R RSUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
1.0
0.5
0.0
SINK
SINK
SINK
DEEP CHANNELS
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13 HEN
14 WHA
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
Destination subestuary
r-sc8.grf

Figure 235

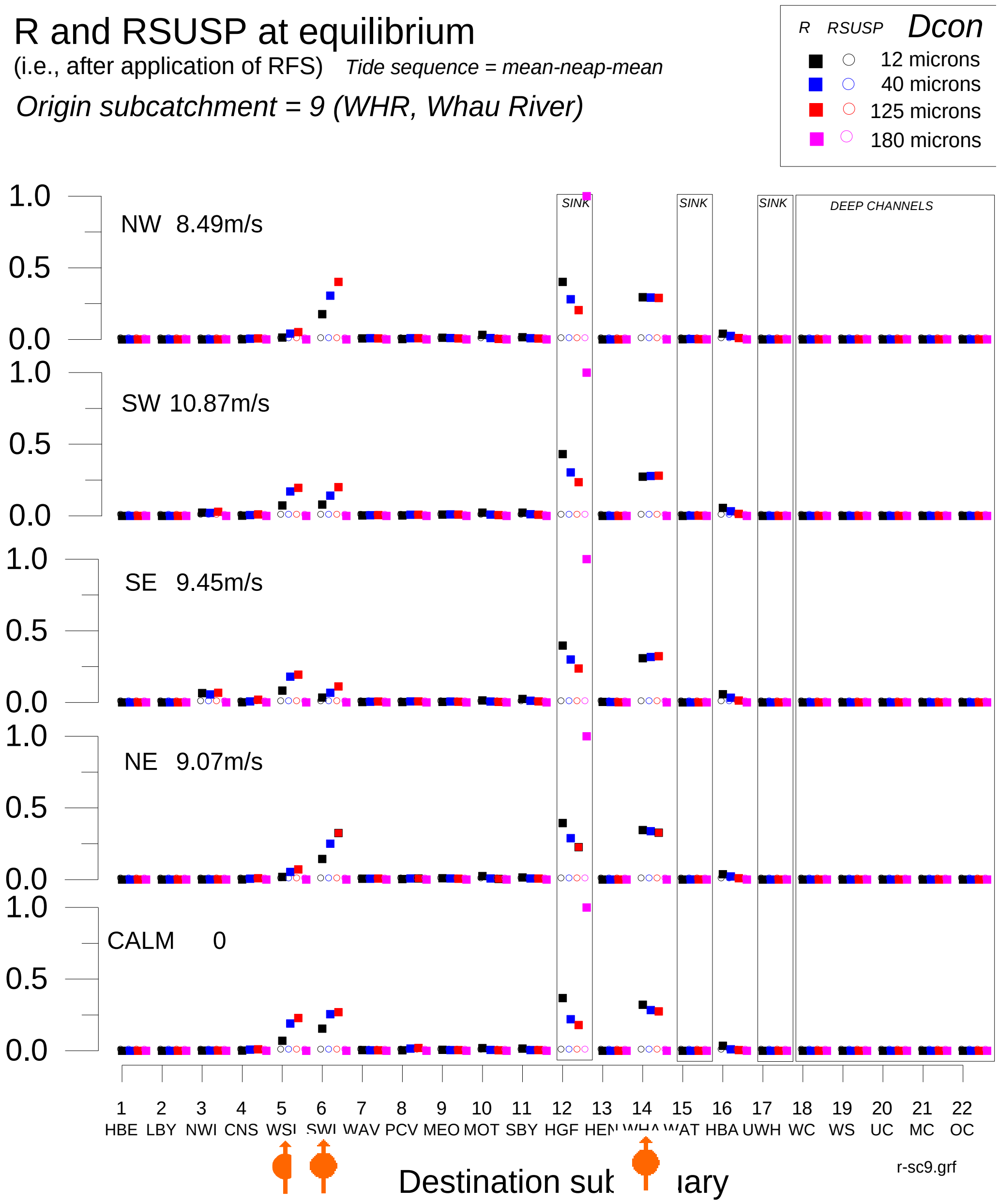
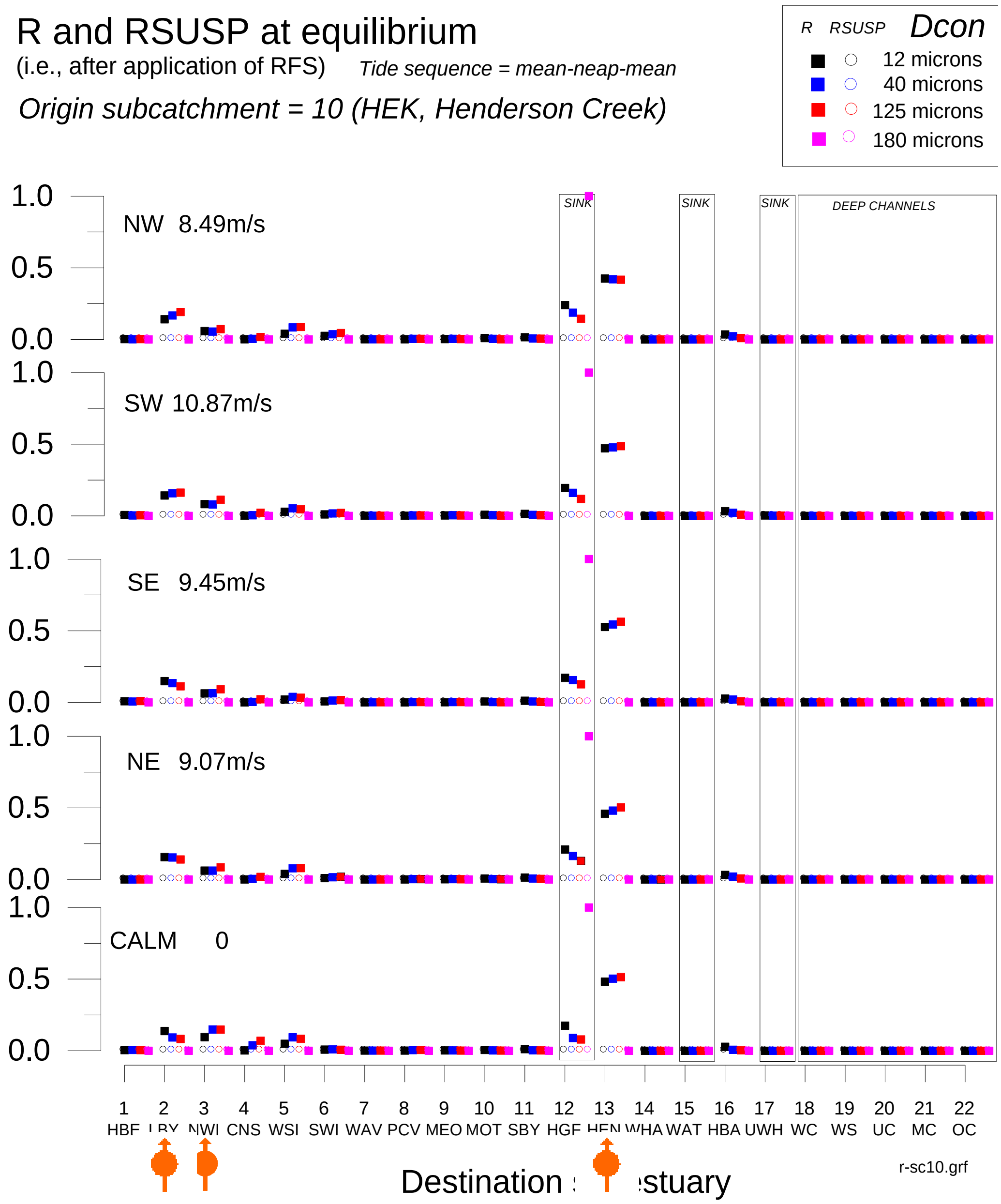

R and RSUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = mean-neap-mean
Origin subcatchment = 9 (WHR, Whau River)
R RSUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
SINK
SINK
SINK
DEEP CHANNELS
1.0
0.5
0.0
1 HBE
2 LBY
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13
14
15
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
r-sc9.grf

Figure 236



R and RSUSP at equilibrium
(i.e., after application of RFS)
Tide sequence = mean-neap-mean
Origin subcatchment = 10 (HEK, Henderson Creek)
R RSUSP Dcon
12 microns
40 microns
125 microns
180 microns
NW 8.49m/s
SW 10.87m/s
SE 9.45m/s
NE 9.07m/s
CALM 0
1.0
0.5
0.0
SINK
DEEP CHANNELS
1 HBF
2
3 NWI
4 CNS
5 WSI
6 SWI
7 WAV
8 PCV
9 MEO
10 MOT
11 SBY
12 HGF
13
14
15 WAT
16 HBA
17 UWH
18 WC
19 WS
20 UC
21 MC
22 OC
r-sc10.grf