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2015-16 Connectivity Indicators for the GHHP Gladstone Harbour Report Card

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Contents

Summary

The first ISP007 Report (Condie et al. 2015a) described a methodology for calculating connectivity indicators for Gladstone Harbour and included definition of a baseline (4-year average) and numerical scores and associated grades for 2013-14. The second report provided corresponding scores and grades for 2014-15 (Condie et al. 2015b). Here we report the connectivity scores and grades for 2015-16. The only significant change in methodology from 2014-15 has been the development of the CONNIE model for Gladstone Harbour. This model provides rapid estimation of dispersal patterns in the harbour and has been used to aid the interpretation of the connectivity scores. As an open-access online tool CONNIE will also assist stakeholders in exploring a much broader range of issues.

In 2015-16 flushing rates were marginally higher than the 4-year baseline average with more than half scoring A's or B's. However, Calliope Estuary, Middle Harbour and Boyne Estuary all had low flushing grades (E), resulting in a harbour average of C. Contaminant connectivity scores were very favourable with every zone receiving an A except Graham Creek (E) and a harbour-wide average of A. Falling contaminant loads contributed to this result in Western Basin, Inner Harbour, Calliope Estuary and South Trees Inlet. Ecological connectivity was low relative to the baseline period with six of the eleven zones scoring an E and a harbour average of D. The only zones to score above the baseline were Middle Harbour (A) and Outer Harbour (A), due mainly to their high potential for recruitment from other zones.

1. Introduction

This report for the Gladstone Healthy Harbour Partnership (GHHP) provides connectivity indicator scores for the 2015-16 GHHP Gladstone Harbour Report Card. The 2015-16 reporting year is the second year that connectivity scores will be formally reported. Previous reports described the methodology and results for 2013-14 (Condie et al. 2015a) and 2014-15 (Condie et al. 2015b).

A significance advance for current and future reporting periods is the release of the online dispersal modelling tool CONNIE (CONNectivity InterfacE) for the Gladstone Harbour region. This tool will not only aid with the interpretation of connectivity indicator scores, but will also provide industry, regulators and researchers with key information to assist in their operations.

2. Methods

Estimating connectivity scores

The methodology used to calculate connectivity indicators for Gladstone Harbour for 2015-16 was the same as that described by Condie et al. (2015a) with the modifications described by Condie et al. (2015b). In essence, hydrodynamic modelling, particle dispersal modelling, and network analysis at the scale of the Harbour Zones, has been used to compute three connectivity indicators: flushing rate, contaminant connectivity and ecological connectivity.

Flushing rate is based on the rate that particles seeded within a given zone decrease over time. Contaminant connectivity is a measure of the potential for a zone to export contaminants to other zones, taking into account known point source loads within that zone (as documented in the National Pollution Inventory and summarised in Appendix A). Ecological connectivity is a measure of the potential for a zone to both recruit larvae from other zones and to feed larvae from local spawning into other zones.

Grades and their corresponding numerical scores are summarised in Figure 2.1. Because there are no agreed targets for connectivity, all scores are expressed relative to a 4-year baseline period (Figure 2.2). Grades are therefore purely a measure of how a zone is performing relatively to its performance in the past. For example, a low contaminant connectivity grade in a relatively pristine zone such as Rodds Bay does not necessarily indicate that Rodds Bay exported significant contaminant loads to other zones. Rather, it indicates that exported loads were high relative to a low baseline. Equally, a high grade in an impacted zone such as Western Basin indicates that exported loads were low relative to a high baseline, but may still be high in absolute terms. This approach reflects the focus on indicators of connectivity, rather than on indicators of contaminant concentration (which are captured elsewhere by water quality and sediment quality indicators).

A	**Very good** (0.85 – 1.00)
B	**Good** (0.65 – 0.84)
C	**Satisfactory** (0.50 – 0.64)
D	**Poor** (0.25 – 0.49)
E	**Very poor** (0.00 – 0.24)

Figure 2.1. Definition of alphabetical grades based on the ranges of numerical scores and associated descriptors for each grade.

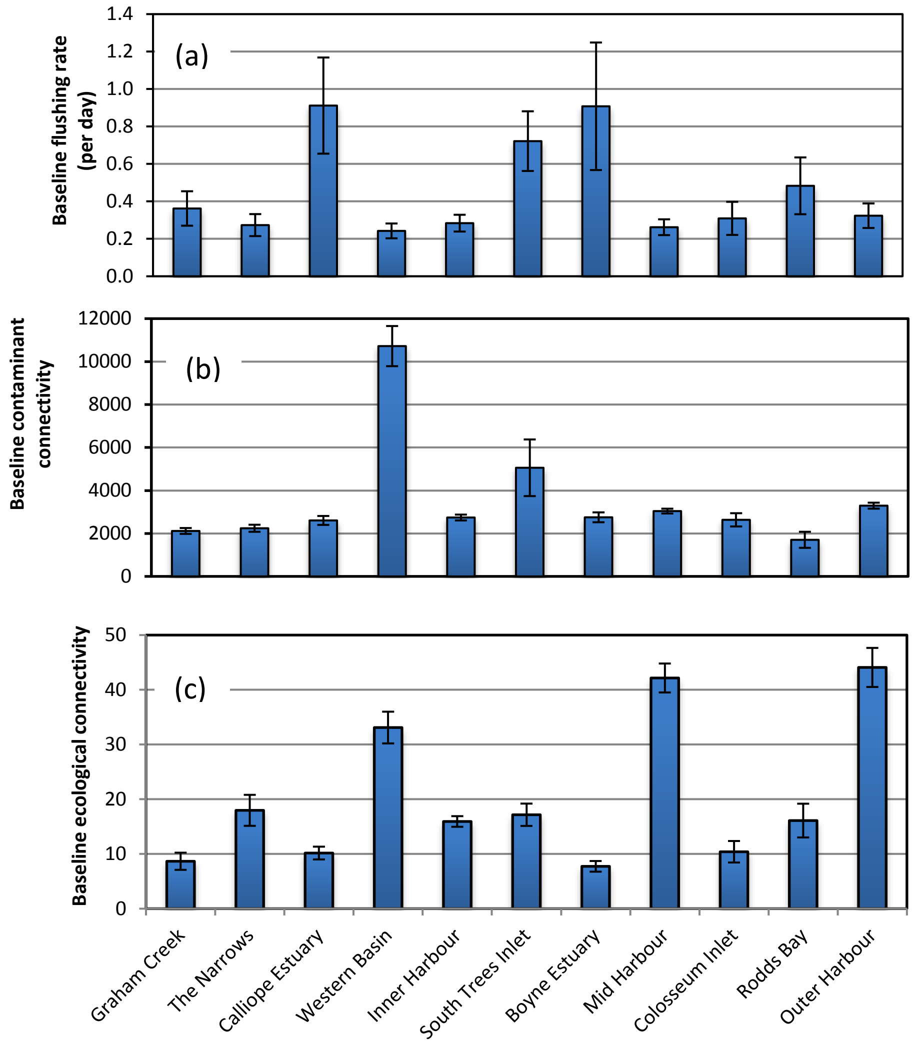


Figure 2.2. Baseline 4-year averages in each of the harbour zones for: (a) flushing rate; (b) contaminant connectivity; and (c) ecological connectivity. The error bars indicate one standard deviation. Details are provided in Condie et al. (2015a).

Implementation of CONNIE for Gladstone Harbour

The online dispersal modelling tool CONNIE has been implemented for the Gladstone Harbour region and is updated in near-real time (www.csiro.au/connie/). It uses currents from the hydrodynamic model (that is also used to generate the indicator scores), which includes forcing by tides, offshore sealevel, river discharges (Calliope and Boyne), winds and other atmospheric conditions (Condie et al. 2015a). Particle tracking techniques are used to estimate the connectivity between zones, as well as dispersal from any activity or facility in the harbour region. It includes an online graphical user-interface that allows users to easily define and run scenarios.

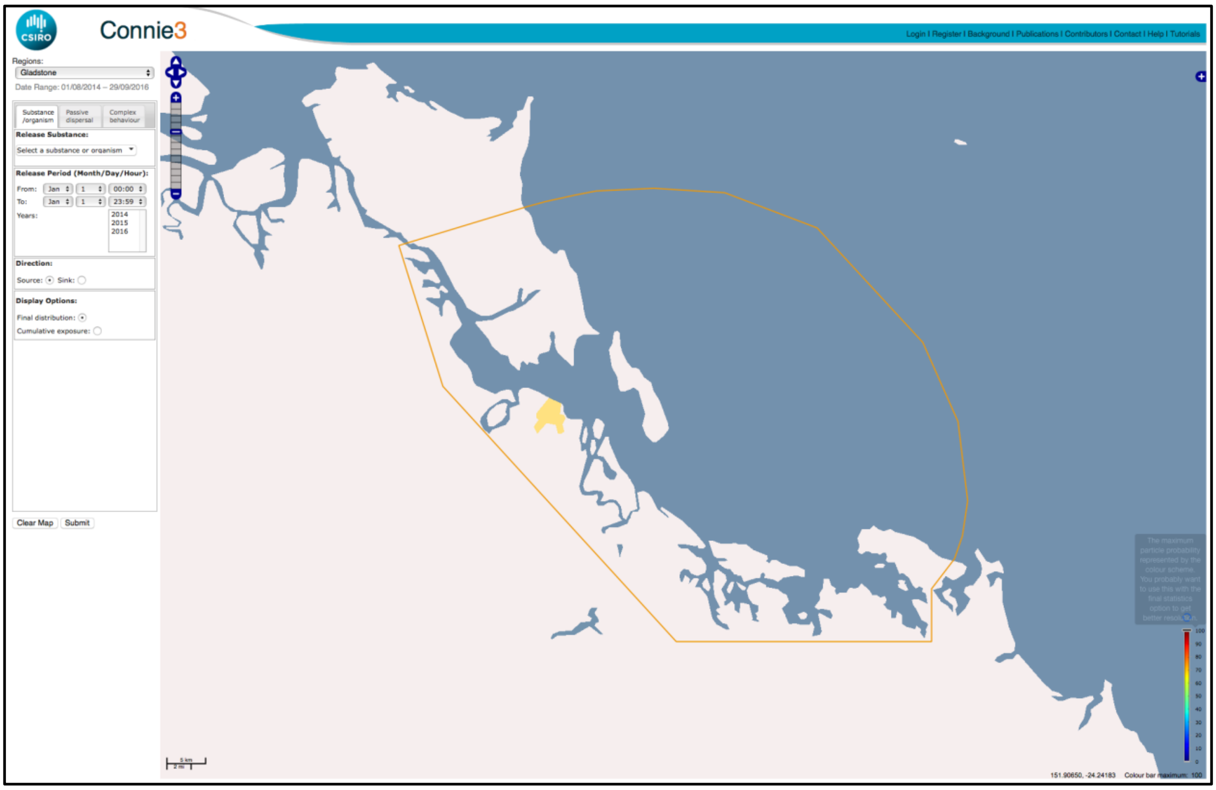
The Gladstone implementation of CONNIE has a spatial resolution of approximately 100 m. As it automatically updates in near-real time it creates a continuously expanding archive. The graphical user-interface includes key data layers of interest to government and industry, such as harbour zones, with the potential to include habitat layers in the future.

For each model run particles are seeded within the user-specified source (or sink) region at a constant rate of 100 particles per grid cell per day over the user-specified release period. They are subsequently tracked individually using a 4th-order Runge-Kutta ordinary differential equation (ODE) solver that linearly interpolates in time and horizontal space to find the horizontal velocity at the required depth and time. If the user specifies the direction as a ***source*** then particles are tracked forward in time from the release. If the user specifies the direction as a ***sink*** then particles are tracked backward in time.

An additional horizontal velocity component (constant or random) can be added to represent unresolved current fluctuations or biological behaviour. Vertical migration can also be represented as instantaneous jumps between vertical levels. If a particle moves into an area where the deeper vertical level is beneath the seafloor, it will remain stationary until returning to the shallower level.

Particle distributions are represented on a geographical grid according to the following two options. The ***final distribution*** of particles within cells at the end of the user-specified dispersal time is expressed as a percentage of all the particles released (results sum to 100% over all cells). The ***cumulative exposure*** of cells to particles over the user-specified dispersal time is also expressed as a percentage of all the particles released (results sum to > 100% over all cells). If the user specifies a sink run, then these two options respectively show the initial upstream distribution and cumulative upstream exposure.

CONNIE utilises a map with familiar zoom and click-and-drag functionalities (Figure 2.3). On this map sources or sinks can be selected by clicking inside cells on a geographical grid. They can be deselected individually by clicking on cells a second time, or deselected all at once using the ***clear map*** button. Static data layers such as the harbour zones can also be shown by clicking on ⊕ (top right of the map) and opening the map legend (Figure 2.3). After the user has specified other dispersal parameters (as described below) calculations are initiated using the ***submit*** button.



Regions: Gladstone

Date Range: 01/08/2014 – 29/09/2016

Release Substance: Select a substance or organism

Release Period (Month/Day/Hour):

From: Jan 1 00:00

To: Jan 1 23:59

Years: 2014 2015 2016

Direction: Source: ● Sink: ○

Display Options: Final distribution: ● Cumulative exposure: ○

The maximum particle probability represented by the colour scheme. You probably want to use this with the final statistics option to get better resolution.

151.90650, -24.24183 Colour bar maximum: 100

Figure 2.3: The online interface for CONNIE is accessible at www.csiro.au/connie/.

CONNIE allows the user to select from three operating modes using tabs on the top left of the user-interface (Figure 2.4). Listed in order of increasing demands on the user to specify model parameters these modes are:

i. Select from a list of substances and organisms for which behaviours have been predefined on the basis of information from the scientific literature.

ii. Assume passive dispersal with the user specifying only the depth and the dispersal time.

iii. Specify more complex combinations of physical and biological behaviours including vertical migration, horizontal propulsion, influence of wind, and chemical decay or biological mortality.

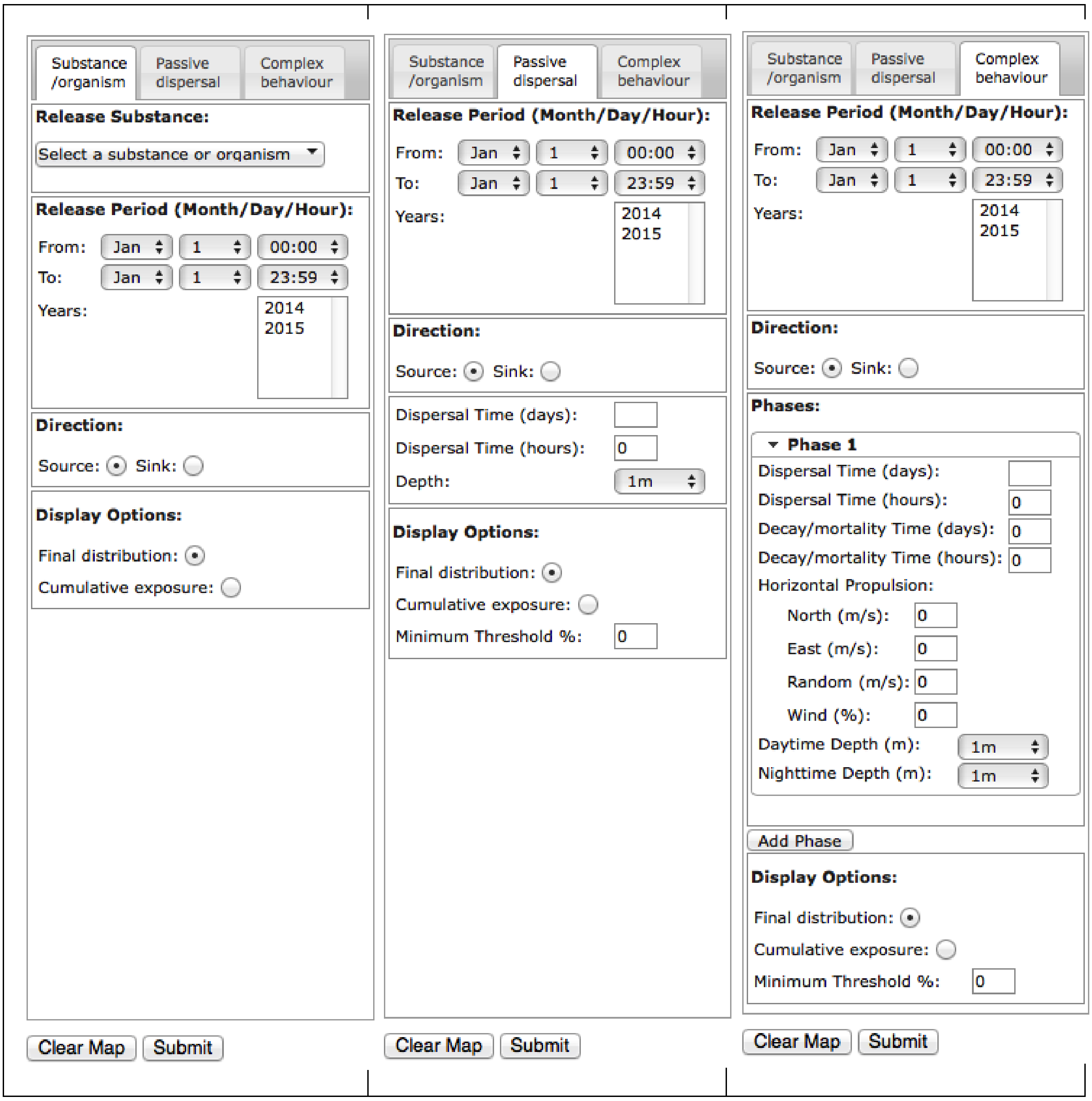
On completion of an online run users can save the results by clicking one of the three download options (lower left of the user-interface):

i. ***Download last results image***, which can be saved as a graphics file.

ii. ***Download last results data***, which can be saved as a CSV file.

iii. ***Download last results for Google Earth***, which can be saved as KML file.

If users are logged-in then outputs in all three formats are also available under ***Saved Results***.



Release Substance:

Select a substance or organism

Release Period (Month/Day/Hour):

From: Jan 1 00:00

To: Jan 1 23:59

Years: 2014 2015

Direction:

Source: ● Sink: ○

Display Options:

Final distribution: ●

Cumulative exposure: ○

(a)

Release Period (Month/Day/Hour):

From: Jan 1 00:00

To: Jan 1 23:59

Years: 2014 2015

Direction:

Source: ● Sink: ○

Dispersal Time (days):

Dispersal Time (hours): 0

Depth: 1m

Display Options:

Final distribution: ●

Cumulative exposure: ○

Minimum Threshold %: 0

(b)

Release Period (Month/Day/Hour):

From: Jan 1 00:00

To: Jan 1 23:59

Years: 2014 2015

Direction:

Source: ● Sink: ○

Phases:

Phase 1

Dispersal Time (days):

Dispersal Time (hours): 0

Decay/mortality Time (days): 0

Decay/mortality Time (hours): 0

Horizontal Propulsion:

North (m/s): 0

East (m/s): 0

Random (m/s): 0

Wind (%): 0

Daytime Depth (m): 1m

Nighttime Depth (m): 1m

Add Phase

Display Options:

Final distribution: ●

Cumulative exposure: ○

Minimum Threshold %: 0

(c)

Figure 2.4: Fields from the CONNIE interface corresponding to the three modes of operation. (a) Select from a list of substances and organisms for which behaviours have been predefined. (b) Assume passive dispersal with the user specifying only the depth and dispersal time. (c) Specify more complex combinations of physical and biological behaviours.

The ***Substance/organism*** mode of operation (Figure 2.4a) only requires the user to:

i. Select a substance or organism of interest from a list.

ii. Specify a particle release period (date and time). Multiple years can be selected to generate seasonal averages.

iii. Select an option for dispersal either downstream from a source or upstream to a sink.

iv. Select an option to display either the final distribution of particles or the cumulative exposure of cells to particles (on the geographical grid).

The list of substances and organisms currently available was chosen on the basis of stakeholder interests and availability of relevant data. It can be further expanded as required. Parameter values and associated references for each substance or organism can also be viewed within CONNIE3 by selecting ⓘ adjacent to the name of the substance or organism.

The ***Passive dispersal*** mode of operation (Figure 2.4b) requires the user to:

i. Specify a particle release period (dates and times). Multiple years can be selected to generate seasonal averages.

ii. Select an option for dispersal either downstream from a source or upstream to a sink.

iii. Specify a dispersal time (days and/or hours).

iv. Select a fixed water depth at which the dispersal occurs.

v. Select an option to display either the final distribution of particles or the cumulative exposure of cells to particles (on the geographical grid).

vi. Specify a minimum threshold for percentages to be shown on the display. This feature is typically used when concentrations below some level are not of relevance or concern.

The ***Complex behaviour*** mode of operation (Figure 2.4c) requires the user to:

i. Specify a particle release period (date and time). Multiple years can be selected to generate seasonal averages.

ii. Select an option for dispersal either downstream from a source or upstream to a sink.

iii. Specify a dispersal time (days and/or hours).

iv. If applicable, specify an exponential decay time or a mortality time (days and/or hours). This parameter can be used to model chemical transformation or mortality of biological organisms.

v. If applicable, specify any horizontal propulsion velocity to be added to the ocean current velocities. This may be in the form of constant north and east components, an uncorrelated random walk, a percentage of wind, or some combination of the three. A constant velocity may represent sustained swimming or propulsion of a vessel. The uncorrelated random walk or Brownian motion (Willis 2011) assumes all directions have equal probability and speeds are selected randomly from a Gaussian distribution where the specified speed corresponds to one standard deviation. This can be used to model either small scale physical mixing processes unresolved by the hydrodynamic model, or biological behaviours such as active foraging in relatively productive environments (Humphries et al. 2010). Windage can be used to model the direct influence of wind on floating objects or surface slicks and therefore is generally only used in combination with the shallowest available depth.

vi. Select a daytime depth and a night-time depth. This can be used to model diurnal vertical migration, typically applied to organisms that feed near the surface at night and move to deeper levels in the day to avoid visual predators.

vii. Select an option to display either the final distribution of particles or the cumulative exposure of cells to particles (on the geographical grid).

viii. Specify a minimum threshold for percentages to be shown on the display. This feature is typically used when concentrations below some level are not of relevance or concern.

If the modelled substance or organism undergoes physical or chemical changes, or develops through multiple life-stages, then an arbitrary number of phases can be defined by selecting *Add phase* before adding different specifications for iii–vi.

Calculating connectivity matrices

CONNIE has been used to calculate a connectivity matrix for exchanges between harbour zones. Information in this form has assisted in the interpretation and communication of the connectivity scores and grades.

The connectivity matrix has a row and a column for each harbour zone. Each row corresponds to a harbour zone from which particles were released (source) and each column corresponds to a destination harbour zone (sink). The resulting matrix elements represent the percentage of particles from the release zone found in the destination zone after 20-days of dispersal. Particles were released on the first day of each month and tracked for 20-days, consistent with the calculations used for contaminant connectivity and ecological connectivity (Condie et al. 2015a). Results are presented as averages over the 12-months of 2015-16.

When comparing connectivity measures, it should be emphasised that the connectivity matrix provides a relative measure across zones (i.e. spatial), whereas connectivity scores are relative to the baseline period (i.e. temporal). Hence, while the two measures are not directly comparable, they play complimentary roles in interpreting connectivity patterns.

3. Results

Connectivity scores

The connectivity indicators are shown as numerical scores in Table 3.1 and as alphabetical grades in Table 3.2. In 2015-16 rainfall was close to the baseline average. Flushing rates were slightly higher than the 4-year baseline average with more than half scoring A's or B's (Tables 3.2). However, Calliope Estuary, Middle Harbour and Boyne Estuary all had low flushing (E), resulting in a harbour average of C.

Contaminant connectivity scores were very favourable (i.e. low export of contaminants to other zones). Every zone received an A except Graham Creek (E), with a harbour-wide average of A (Table 3.2). In Western Basin, Inner Harbour, Calliope Estuary and South Trees Inlet falling contaminant loads (based on National Pollution Inventory data) contributed to this result. The poor score in Graham Creek was mainly associated with increased transport into Western Basin relative to the baseline, probably due to differences in wind patterns (contaminant loads were unchanged from the nominal diffuse loads used throughout the baseline period).

Ecological connectivity was low relative to the baseline period with six of the eleven zones scoring an E and a harbour average of D (Table 3.2). The only zones to score above the baseline were Middle Harbour (A) and Outer Harbour (A), reflecting both high import and export from other zones.

Table 3.1. Numerical connectivity scores for each zone and harbour-wide averages for 2015-16.

Zone		**Connectivity indicator scores for 2014-15**			
		Flushing rate	**Contaminant connectivity**	**Ecological connectivity**	**Average connectivity**
1	The Narrows	1.00	1.00	0.00	0.67
2	Graham Creek	1.00	0.11	0.00	0.37
3	Western Basin	1.00	1.00	0.50	0.83
4	Boat Creek	No data available			
5	Inner Harbour	0.61	1.00	0.27	0.63
6	Calliope Estuary	0.16	1.00	0.00	0.39
7	Auckland Inlet	No data available			
8	Middle Harbour	0.00	1.00	1.00	0.67
9	South Trees Inlet	1.00	1.00	0.03	0.68
10	Boyne Estuary	0.00	1.00	0.00	0.33
11	Outer Harbour	0.51	1.00	1.00	0.84
12	Colosseum Inlet	1.00	1.00	0.00	0.67
13	Rodds Bay	0.66	0.99	0.28	0.64
	Harbour average	0.63	0.92	0.28	0.61

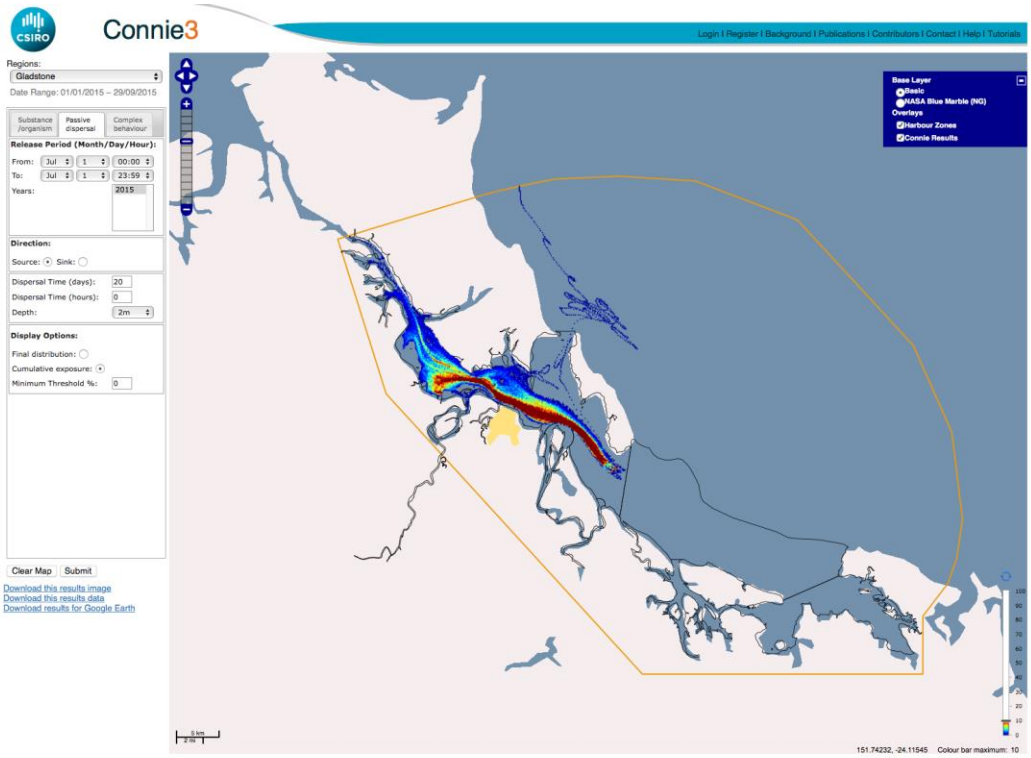
Table 3.2. Connectivity grades for each zone and harbour-wide averages for 2015-16. Definitions and descriptors of each grade are provided in Figure 2.1.

Zone		**Connectivity indicator scores for 2014-15**			
		Flushing rate	**Contaminant connectivity**	**Ecological connectivity**	**Average connectivity**
1	The Narrows	A	A	E	B
2	Graham Creek	A	E	E	D
3	Western Basin	A	A	C	B
4	Boat Creek	No data available			
5	Inner Harbour	C	A	D	C
6	Calliope Estuary	E	A	E	D
7	Auckland Inlet	No data available			
8	Middle Harbour	E	A	A	B
9	South Trees Inlet	A	A	E	B
10	Boyne Estuary	E	A	E	D
11	Outer Harbour	C	A	A	B
12	Colosseum Inlet	A	A	E	B
13	Rodds Bay	B	A	D	C
	Harbour average	C	A	D	C

Average connectivity (combining flushing rate, contaminant connectivity and ecological connectivity) was mostly higher than the baseline period with six zones scoring B (Table 3.2). The only zones below the baseline were Graham Creek (D), Calliope Estuary (D) and Boyne Estuary (D). Graham Creek had poor contaminant and ecological connectivity, whereas Calliope Estuary and Boyne Estuary had poor flushing and ecological connectivity. As expected the average across all indicators and all zones was similar to the baseline (C).

CONNIE outputs

Examples of CONNIE outputs are shown for releases from Western Basin in July 2015 and January 2016. These runs are very similar to those used to generate the connectivity scores. In July exchanges were predominantly with Inner Harbour and Mid Harbour, with lower levels into The Narrows, Graham Creek and Calliope Estuary (Figure 3.1a). In January, exchanges extended into the Outer Harbour, with more significant export out of the harbour area (Figure 3.1b). These patterns are at largely driven by seasonal wind patterns, with southeasterly transport increasing over summer as the opposing southeasterly trade winds diminish.



Regions: Gladstone

Date Range: 01/01/2015 – 29/09/2015

Release Period (Month/Day/Hour):

From: Jul 1 00:00

To: Jul 1 23:59

Years: 2015

Direction:

Source: ● Sink: ○

Dispersal Time (days): 20

Dispersal Time (hours): 0

Depth: 2m

Display Options:

Final distribution: ○

Cumulative exposure: ●

Minimum Threshold %: 0

● Basic

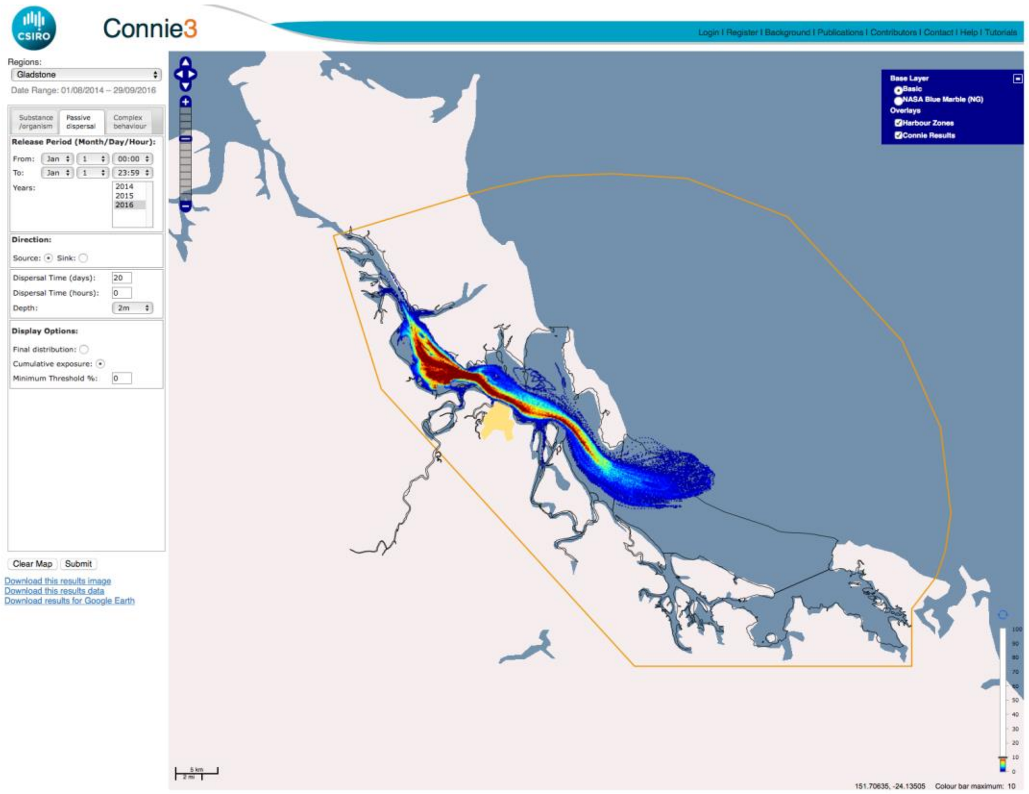
○ NASA Blue Marble (NG)

☑ Harbour Zones

☑ Connie Results

151.74232, -24.11545 Colour bar maximum: 10

(a)



Regions: Gladstone

Date Range: 01/08/2014 – 29/09/2016

Release Period (Month/Day/Hour):

From: Jan 1 00:00

To: Jan 1 23:59

Years: 2014 2015 2016

Direction:

Source: ● Sink: ○

Dispersal Time (days): 20

Dispersal Time (hours): 0

Depth: 2m

Display Options:

Final distribution: ○

Cumulative exposure: ●

Minimum Threshold %: 0

● Basic

○ NASA Blue Marble (NG)

☑ Harbour Zones

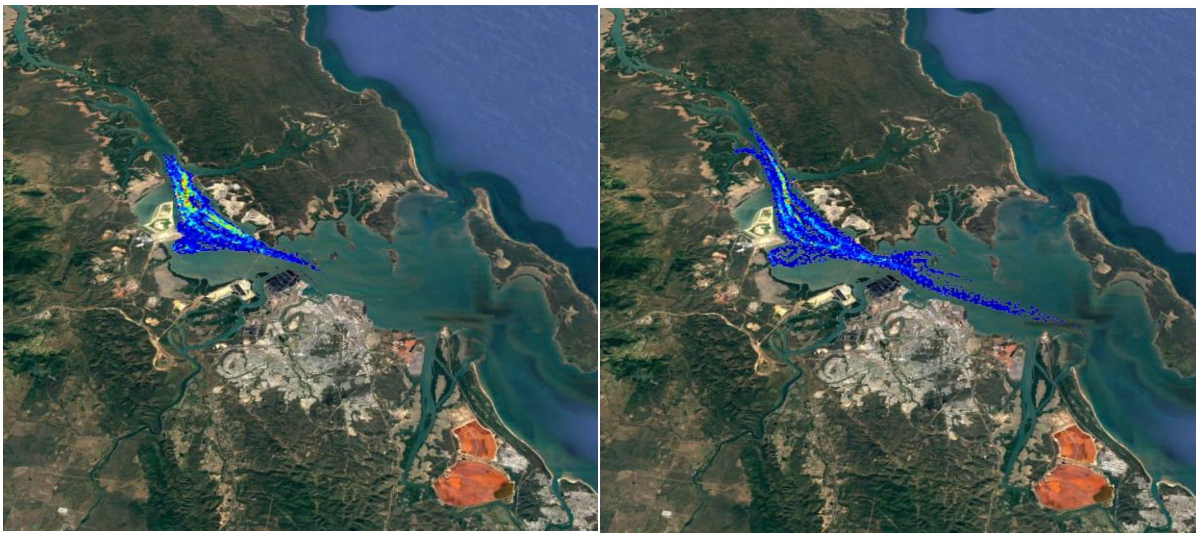
☑ Connie Results

151.70635, -24.13505 Colour bar maximum: 10

(b)

Figure 3.1: CONNIE output corresponding to 20-day dispersal at 2 m depth following releases from Western Basin on (a) 1 July 2015 and (b) 1 January 2016. Dark red indicates > 10% of released particles travelled through that cell, whereas dark blue indicates less < 2%. Note that these *cumulative exposure* maps show the entire dispersal path, whereas connectivity matrices use particle positions at the end of the dispersal time (equivalent to *final distribution* in CONNIE).

Potential applications of CONNIE extend well beyond the connectivity indicators. A simple example is the dispersal of silt from an area adjacent to the bund wall in Western Basin (Figure 3.2). Dispersal is constrained by settling of the silt and, as in the previous example, more restricted during the dry season (Figure 3.2a) than the wet season (Figure 3.2b).



(a) (b)

Figure 3.2: CONNIE estimates of the dispersal of silt from the eastern side of the bund wall in Western Basin for releases on (a) the 1 of July 2015 and (b) the 1 January 2016. The results are visualised in Google Earth with dark red indicating that > 5% of released particles travelled through the cell, whereas dark blue indicates less < 1%.

The connectivity matrix

The connectivity matrix indicates relatively high levels of retention (> 20%) and therefore relatively low flushing rates in all zones except Outer Harbour (values on the diagonal in Table 3.3). However, this does not necessarily imply low flushing rate scores since they are calculated relative to flushing rates over the baseline period (Table 3.2). For example, South Trees Inlet had the lowest flushing (71% retention) of any of the zones in 2015-16, but still achieved an A for flushing rate because these rates were even lower over the baseline period.

Not surprisingly the highest exchanges were between neighbouring zones, with particularly high levels (> 20%) between The Narrows and Western Basin, Calliope Estuary and Western Basin, and Boyne Estuary and Middle Harbour. Estuaries and more open harbour zones tended to show contrasting connectivity characteristics. For example, Calliope Estuary had a high level of retention (50%) but received almost no particles from other zones, whereas Middle Harbour received particles from every other zone due to its central location in the network. The high ecological connectivity score achieved in Middle Harbour (Table 3.2) further indicates that the receipt of particles was significantly higher than over the baseline period.

Information from the connectivity matrix has been represented geographically in Figure 3.3. In addition to the trends evident in the connectivity matrix, export out of the harbour system (after 20-days of dispersal) is shown, revealing high export from Graham Creek, Middle Harbour, Outer Harbour, Colosseum Inlet and Rodds Bay. While Graham Creek had significant retention (28%), three quarters of the particles that did escape continued around the southern end of Curtis Island (through Western Basin, Inner Harbour and Mid Harbour) and out of the harbour.

Table 3.3. Connectivity matrix for the harbour zones averaged across the 12-months of 2015-16. The numbers represent the percentage of all particles released from each source zone that were found in the sink zone after 20-days of dispersal. Colour coding has been included to more easily distinguish high from low values, but is not intended to imply that either is more desirable.

☐ <1%
▨ 1-5%
▨ 5-10%
▨ 10-20%
▨ 20-50%
▨ 50-100%

		Sink Zone												
		The Narrows	Graham Creek	Western Basin	Boat Creek	Inner Harbour	Calliope Estuary	Auckland Inlet	Middle Harbour	South Trees Inlet	Boyne Estuary	Outer Harbour	Colosseum Inlet	Rodds Bay
Source Zone	The Narrows	39	1	27		3			1					
	Graham Creek	1	28	13		2			2					
	Western Basin	2	1	64		9	1		4			2		
	Boat Creek	No data available												
	Inner Harbour			18		38			15	2		7		
	Calliope Estuary			25		2	50		1			1		
	Auckland Inlet	No data available												
	Middle Harbour			3		9			38	4		7		
	South Trees Inlet					4			5	71		3		
	Boyne Estuary					1			48	2	23	1		
	Outer Harbour					2			19	2		18		
	Colosseum Inlet								6	2		6	40	
	Rodds Bay								4	1		8		29

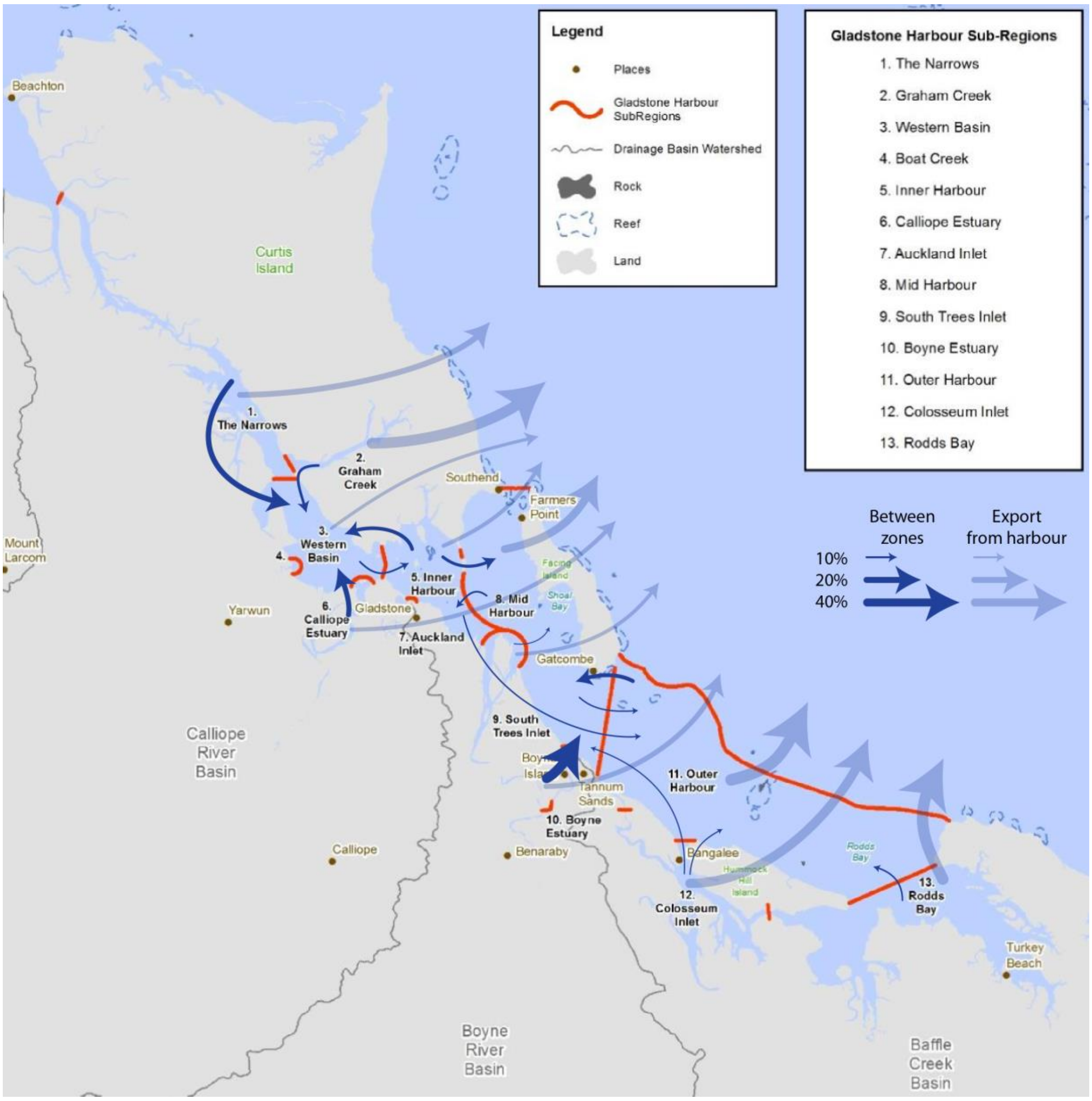


Figure 3.3: Geographical representation of particle exchanges after 20-days of dispersal, averaged over 12-months in 2015-16 (dark blue arrows). For clarity, exchanges representing less than 5% of the total are not shown. Export out of the harbour (after 20-days) is indicated by transparent arrows.

4. Discussion

Interpretation of 2015-16 scores

All connectivity scores are relative to the baseline period. High flushing rate scores in The Narrows, Graham Creek and Colosseum Inlet (Table 3.2) can be attributed to strong export of particles in 2015-16 (Table 3.3, Figure 3.3). In contrast, Western Basin and South Trees Inlet show relatively low export of particles (Table 3.3), but also achieved high flushing rate scores because of their very low historical export levels (i.e. historical high retention levels). At the other extreme, Middle Harbour and Boyne Estuary were relatively well flushed, but rates were low by historical standards resulting in a low score.

The contaminant connectivity score was low in Graham Creek because transport into Western Basin was high relative to the baseline average (also reflected in the high flushing rate score in Graham Creek; Table 3.2). In all other zones contaminant connectivity scores were very high. In Western Basin, Inner Harbour, Calliope Estuary and South Trees Inlet this is at least partially attributable to low point source contaminant inputs relative to the baseline period (reductions > 70%). In the remaining zones, high scores were associated with lower flushing (Middle Harbour, Boyne Estuary; Table 3.2) or high export from the harbour area (Mid Harbour, Outer Harbour, Colosseum Inlet, Rodds Bay; Figure 3.3).

Low ecological connectivity scores in all of the estuaries and inlets (Table 3.3) was associated with water exchanges (rather than habitat changes) contributing to low recruitment potential relative to the baseline period (Table 3.3). Middle Harbour and Outer Harbour scored highly due to both high recruitment potential and, to a lesser extent, potential for larval transport into neighbouring zones (Table 3.3).

Comparison with 2014-15

The indicator scores provide a measure of conditions in 2015-16 relative to the 4-year baseline period. We can also compare 2015-16 with results from the previous year (2014-15). The annual rainfall in 2014-15 (968 mm) was above the baseline average, whereas the wet season arrived almost two months later in 2015-16 giving an annual rainfall (889 mm) close to the baseline average.

Table 4.1 indicates changes from 2014-15 to 2015-16. All grades deteriorated or remained the same for flushing rate (at least in part due to lower rainfall), with a major decline in Boyne Estuary. In contrast, contaminant connectivity improved or remained the same, the largest change being for South Trees Inlet. Changes in ecological connectivity were mixed, with significant deterioration in Graham Creek offset by improvements in Middle Harbour and Outer Harbour and smaller improvements in Western Basin and Inner Harbour (Table 4.1). The overall average connectivity grade deteriorated slightly in three zones (Graham Creek, Boyne Estuary and Rodds Bay) and improved slightly in three zones (Middle Harbour, South Trees Inlet and Outer Harbour).

Table 4.1. Change in connectivity indicator grades from 2014-15 to 2015-16. (● = no change; ↑ = higher grade; ↓ = lower grade; with number of arrows representing the number of grade steps).

Zone		**Change in connectivity indicator scores from 2014-15 to 2015-16**			
		Flushing rate	**Contaminant connectivity**	**Ecological connectivity**	**Average connectivity**
1	The Narrows	●	●	●	●
2	Graham Creek	●	●	↓↓↓	↓
3	Western Basin	●	↑	↑	●
4	Boat Creek				
5	Inner Harbour	↓	●	↑	●
6	Calliope Estuary	↓	↑	●	●
7	Auckland Inlet				
8	Middle Harbour	●	●	↑↑	↑
9	South Trees Inlet	●	↑↑	●	↑
10	Boyne Estuary	↓↓↓	●	●	↓
11	Outer Harbour	●	↑	↑↑↑	↑
12	Colosseum Inlet	●	●	●	●
13	Rodds Bay	↓	↑	●	↓
	Harbour average	↓	↑	●	●

Summary

With near-average rainfall, 2015-16 flushing rates scores showed no broad trend, but were highly variable across the zones. Contaminant connectivity mainly scored very high and ecological connectivity tended to score quite low. This combination indicates that retention was relatively high in some zones, but a high proportion of particles that did escape from their starting zone were subsequently transported entirely out of the harbour. These conditions limit the potential for larvae to recruit to nursery habitats in other harbour zones and thereby tend to reduce ecological connectivity scores. They also reduce the potential for contamination of neighbouring zones. For historically impacted zones, such as Western Basin and Calliope Estuary, contaminant connectivity scores were further enhanced by a general downward trend in contaminant loads (Appendix A).

Appendix A: Annual loads from the National Pollution Inventory

Table A1: Relative aquatic ecotoxicology (Wright et al. 1998) and annual loads from industrial facilities (listed) reported by the National Pollution Inventory (www.npi.gov.au) for years 2010-11 to 2014-15.

	Substance (including compounds)	**Relative aquatic eco-toxicology**	**Annual Loads (kg)**																			
			Calliope Estuary Gladstone Power Station					**Western Basin** Yarwun Site Stuart Project Rio Tinto Alcan Yarwun					**Inner Harbour** Gladstone Terminal Port Central					**South Trees Inlet** Boyne Smelters Queensland Alumina				
			2010-2011	2011-2012	2012-2013	2013-2014	2014-2015	2010-2011	2011-2012	2012-2013	2013-2014	2014-2015	2010-2011	2011-2012	2012-2013	2013-2014	2014-2015	2010-2011	2011-2012	2012-2013	2013-2014	2014-2015
Metals	Arsenic	0.20			10.0	2.7		91.5	93.5	208	257	12.0						560	568	543	270	
	Beryllium	1.0							17.6	40.3												
	Cadmium	2.0	0.84					8.61			11.9	0.12						18.6	6.8	5.8	22.6	
	Chromium	0.33		8.1	17.9	13.3		14.1		21.8			0.58		0.03	0.01	0.01					
	Copper	1.0	7.0		25.1	8.1					18.1		0.15	0.03	0.03	0.05		18		84.3	363	
	Iron	0.005																				
	Lead	0.20			6.9	1.62							0.04	0.01	0.01	0.01		1.3		23.1	0.41	
	Manganese	0.10	46			129													58.0			
	Mercury	16.7	0.7						0.01			0.05										
	Nickel	0.17		15.6					11.7				0.16	0.01	0.02		0.01		54.5	192		
	Vanadium	0.05																				
	Zinc	0.125	35	21.3	18.8			363	485	695	708		2.0	0.08	0.30	0.01		380	288	3780	257	
Other substances	Ammonia	0.24						5906	6833	6279	6321											
	Benzene	0.10													0.11							
	Carbon tetrachloride	0.42																				
	Chlorine	0.50						132	128	117												
	Chlorobenzene	1.0																				
	Chloroform	0.42																				
	Cyanide	0.10																				
	Dichloroethane	0.50																				
	Fluoride	0.01						16412	13504	29928	49940	570000						134000	129240	239500	111000	102000
	Formaldehyde	1.0																				
	Hexochlorobenzene	167																				
	Hexochlorobutadiene	50																				
	Methylenechloride	0.50																				
	Nitrobenzene	0.25																				
	Nitrophenol	0.50																				
	Tetrachloroethylene	0.50																				
	Toluene	0.13											0.01	0.01	0.52	0.02	0.01					
	Trichloroethylene	0.50																				
	Xylene	0.17											0.01	0.01	0.28	0.01	0.01					

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