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2016-17 Connectivity Indicators for the GHHP Gladstone Harbour Report Card

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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 and third reports provided corresponding scores and grades for 2014-15 (Condie et al. 2015b) and 2015-16 (Condie et al. 2017). Here we use the same methodology to report the connectivity scores and grades for 2016-17, covering the 11 zones resolved by the underlying hydrodynamic model (excludes Boat Creek and Auckland Inlet).

In 2016-17 flushing rates were mostly higher than the 4-year baseline average with seven of the eleven scoring an A. Only Calliope Estuary, Middle Harbour and Boyne Estuary had low flushing grades (D or E) and the harbour average was B. With the exception of The Narrows and South Trees Inlet, contaminant connectivity scores were also favourable with a harbour-wide average of B. Contributing to this result, contaminant loads in the main industrialised zones (Western Basin, Inner Harbour, Calliope Estuary and South Trees Inlet) were again much lower than over the baseline period. Ecological connectivity was low relative to the baseline period with nine of the eleven zones scoring a D or E, and a harbour average of E.

When the three connectivity indicators were combined, five zones scored B, four zones a C, and two zones a D (Calliope Estuary and South Trees Inlet), with an overall harbour average of C as in previous reporting years.

1. Introduction

This report for the Gladstone Healthy Harbour Partnership (GHHP) provides connectivity indicator scores for the 2016-17 GHHP Gladstone Harbour Report Card. The 2016-17 reporting year is the third year that connectivity scores will be formally reported. Previous reports described the methodology and results for 2013-14 (Condie et al. 2015a), 2014-15 (Condie et al. 2015b) and 2015-16 (Condie et al. 2017). As was the case for 2015-16, the online dispersal modelling tool CONNIE (www.csiro.au/connie/) has been utilised in interpreting connectivity indicator scores.

2. Methods

Estimating connectivity scores

The methodology used to calculate connectivity indicators for Gladstone Harbour for 2016-17 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 (Figure 2.1), has been used to compute three connectivity indicators: flushing rate, contaminant connectivity and ecological connectivity.

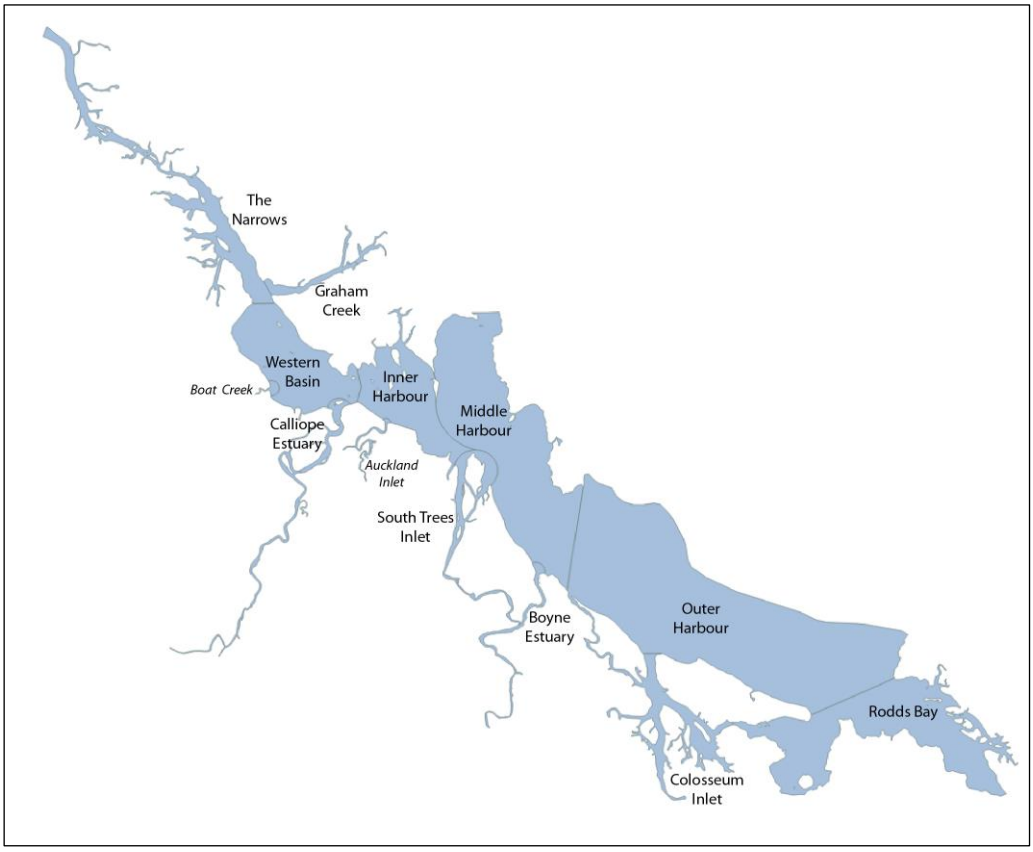


Figure 2.1. Gladstone harbour zones identified by GHHP. Those used to calculate connectivity indicators are labelled in large plain font, while those not adequately supported by flow data or resolved by the hydrodynamic model are labelled in small italic font (Boat Creek and Auckland Inlet).

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 and their eco-toxicology 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 2.2. Because there are no agreed targets for connectivity, all scores are expressed relative to a fixed 4-year baseline spanning the period September 2010 to August 2014 (Condie et al. 2015a). 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).

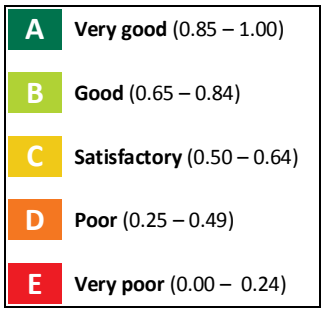


Figure 2.2. Definition of alphabetical grades based on the ranges of numerical scores and associated descriptors for each grade.

Calculating connectivity matrices

The CONNIE dispersal modelling framework (Condie et al. 2017) 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 2016-17.

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 2016-17 rainfall was 16% above the baseline average. However, this was mainly due to record rainfall in March associated with Cyclone Debbie following a dryer than average summer. Flushing rates were mostly higher than the 4-year baseline average with 7 of the 11 zones scoring A's (Tables 3.2). Relatively lower flushing in Calliope Estuary, Middle Harbour and Boyne Estuary (D or E) resulted in a harbour average of B.

Contaminant connectivity scores were also quite favourable (i.e. low export of contaminants to other zones) with 7 of the 11 zones again scoring A's (Tables 3.2). The Narrows and South Trees Inlet were the only zones with unfavourable scores and the harbour-wide average was B. The only significant point contaminant loads (based on National Pollution Inventory data) were in Western Basin and South Trees Inlet. Whereas Western Basin has fallen by almost a factor of four relative the baseline period (score A), South Trees Inlet has fallen by less than a factor of two which was insufficient to offset less favourable flow conditions (score E). The poor score in The Narrows was mainly associated with high export into Western Basin (since contaminant loads were unchanged from the nominal diffuse loads used throughout the baseline period).

Table 3.1. Numerical connectivity scores for each zone and harbour-wide averages for 2016-17. There are no scores available for Boat Creek or Auckland Inlet because these small waterways are not resolved by the underlying hydrodynamic model.

Zone		Connectivity indicator scores for 2016-17			
		Flushing rate	**Contaminant connectivity**	**Ecological connectivity**	**Average connectivity**
1	The Narrows	1.00	0.00	0.50	0.65
2	Graham Creek	1.00	1.00	0.00	0.67
3	Western Basin	1.00	1.00	0.29	0.76
4	Boat Creek	No data available			
5	Inner Harbour	1.00	0.80	0.40	0.73
6	Calliope Estuary	0.22	1.00	0.12	0.45
7	Auckland Inlet	No data available			
8	Middle Harbour	0.41	1.00	0.50	0.67
9	South Trees Inlet	1.00	0.00	0.01	0.34
10	Boyne Estuary	0.50	1.00	0.13	0.54
11	Outer Harbour	0.66	0.58	0.42	0.55
12	Colosseum Inlet	1.00	1.00	0.00	0.67
13	Rodds Bay	0.91	1.00	0.13	0.68
	Harbour average	0.79	0.76	0.23	0.59

Table 3.2. Connectivity grades for each zone and harbour-wide averages for 2016-17. Definitions and descriptors of each grade are provided in Figure 2.2.

Zone		Connectivity indicator scores for 2016-17			
		Flushing rate	Contaminant connectivity	Ecological connectivity	Average connectivity
1	The Narrows	A	E	C	C
2	Graham Creek	A	A	E	B
3	Western Basin	A	A	D	B
4	Boat Creek	No data available			
5	Inner Harbour	A	B	D	B
6	Calliope Estuary	E	A	E	D
7	Auckland Inlet	No data available			
8	Middle Harbour	D	A	C	C
9	South Trees Inlet	A	E	E	D
10	Boyne Estuary	D	A	E	C
11	Outer Harbour	B	C	D	C
12	Colosseum Inlet	A	A	E	B
13	Rodds Bay	A	A	E	B
	Harbour average	B	B	E	C

Ecological connectivity was low relative to the baseline period with six of the eleven zones scoring an E, no zones scoring above a C, and a harbour average of D (Table 3.2). This is consistent with high flushing, which tends to carry larvae out of the harbour rather than onto local nursery habitats. However, in parts of the system where flushing was also relatively low, such as Calliope Estuary, Middle Harbour and Boyne Estuary, low ecological connectivity was associated with limited potential to export larvae to other zones (also consistent with the high contaminant grades in these zones).

Average connectivity (combining flushing rate, contaminant connectivity and ecological connectivity) was similar or slightly higher than the baseline period, with four zones scoring a C and five a B (Table 3.2). The only zones below the baseline were Calliope Estuary (D), due to poor flushing and ecological connectivity, and South Trees Inlet (D), due to poor contaminant and ecological connectivities. As in all the previous years, the average across all indicators and all zones was similar to the baseline (C).

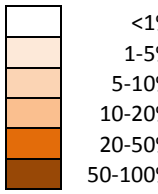
The connectivity matrix

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, similar to the previous year (Condie et al. 2017), South Trees Inlet had the lowest flushing (75% retention) of any of the zones in 2016-17, but still achieved an A for flushing rate because these rates were even lower over the baseline period.

The highest exchanges were between neighbouring zones, with particularly high levels (> 20%) from The Narrows and Calliope Estuary into Western Basin; and from Boyne Estuary and Outer Harbour into Middle Harbour. In general, estuaries and inlets received very few particles from other zones, whereas Middle Harbour received particles from every other zone due to its central location in the network. An ecological connectivity score of C in Middle Harbour (Table 3.2) is an indication that these conditions are typical of most years.

Table 3.3. Connectivity matrix for the harbour zones averaged across the 12-months of 2016-17. 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.



Source Zone \ 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
The Narrows	38	1	24		3			1					
Graham Creek	1	28	11		2			2					
Western Basin	2		63		9	1		5			1		
Boat Creek	No data available												
Inner Harbour			17		35			18	2		5		
Calliope Estuary			25		2	47		2			1		
Auckland Inlet	No data available												
Middle Harbour			3		6			40	3		7		
South Trees Inlet					2			5	75		2		
Boyne Estuary								50	2	23	1		
Outer Harbour					1			21	1		15		
Colosseum Inlet								5	1		8	40	
Rodds Bay								4	1		8	1	29

4. Discussion

Interpretation of 2016-17 grades

All connectivity scores are relative to the baseline period. The high flushing rate grades can be explained as follows. The Narrows and Graham Creek had relatively high particle export to Western Basin, which in turn exported into Inner Harbour and Middle Harbour (Table 3.3). Inner Harbour returned particles to Western Harbour, as well as exporting to Outer Harbour. South Trees Inlet had lower export (mainly into Middle Harbour), but still high relative to the baseline period. Finally, the high grades achieved at Colosseum Inlet and Rodds Bay were associated with exports into Middle Harbour and Outer Harbour. In contrast, while Calliope Estuary and Boyne Estuary had high exports, their baseline exports were higher again, resulting in grades E and D respectively.

The contaminant connectivity grades were generally high, the notable exceptions being The Narrows and South Trees Inlet (Table 3.2). In The Narrows, contaminant inputs remained at background levels, so the low score was associated with exports mainly into Western Basin (Table 3.3). Even in South Trees Inlet contaminant inputs (load x potency) were only 56% of the average over the baseline period. However, with low historical export, even a modest increase (Table 3.3) resulted in a grade of E.

Low ecological connectivity grades in the estuaries and inlets (Table 3.2) were associated with water exchanges (rather than habitat changes). High flushing contributed to the low recruitment potential relative to the baseline period. However, the relatively dry summer may have provided more favourable spawning conditions than is reflected by these annual grades.

Comparison with previous years

The indicator scores provide a measure of conditions in 2016-17 relative to the 4-year baseline period. We can also compare 2016-17 with results from the previous year (2015-16). The annual rainfall in 2016-17 (1189 mm) was well above the 2015-16 value (889 mm), although a large proportion of this was concentrated around Cyclone Debbie.

Table 4.1 indicates changes from 2015-16 to 2016-17. All grades improved or remained the same for flushing rate (in part due to higher rainfall), with the largest improvement in Inner Harbour. In contrast, contaminant connectivity generally deteriorated or remained the same, the largest falls being for The Narrows and South Trees Inlet. The only counter example was Graham Creek where there was a large improvement in contaminant connectivity. Ecological connectivity also tended to deteriorate, the largest change being in Outer Harbour. The only improvement was in The Narrows. The overall average connectivity grade deteriorated in four zones, which was offset by improvements in four zones.

Table 4.2 provides a summary of all grades for all zones across the 4-years that they have been calculated. With some exceptions, the past 3-years are broadly similar and in the majority of zones characterised by high flushing and contaminant connectivity grades, and poor ecological connectivity grades. In terms of average connectivity, the best performing zones over the 4-years were The Narrows in the north and Colosseum Inlet and Rodds Bay in the south, whereas the worst performing zones were Calliope Estuary and South Trees Inlet in the central region of the harbour.

Table 4.1. Change in connectivity indicator grades from 2015-16 to 2016-17. (● = no change; ↑ = higher grade; ↓ = lower grade; with number of arrows representing the number of grade steps).

Zone		Change in connectivity indicator scores from 2015-16 to 2016-17			
		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

Flushing rate and contaminant connectivity grades were generally high in 2016-17, whereas ecological connectivity scored poorly. This combination indicates that a high proportion of particles were flushed out of the harbour. Extreme rainfall around Cyclone Debbie drove peak flushing over March, although other factors such as winds and offshore conditions contributed to more sustained flushing required to achieve these grades. These conditions limited potential for contamination of neighbouring zones, as well as the potential for larvae to recruit to nursery habitats in other harbour 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).

Table 4.2. Connectivity grades for each zone and harbour-wide averages for all years reported to date. Definitions and descriptors of each grade are provided in Figure 2.2.

Zone		Connectivity indicator scores for 2016-17															
		Flushing rate				Contaminant connectivity				Ecological connectivity				Average connectivity			
		13/14	14/15	15/16	16/17	13/14	14/15	15/16	16/17	13/14	14/15	15/16	16/17	13/14	14/15	15/16	16/17
1	The Narrows	C	A	A	A	A	A	A	E	E	E	E	C	C	B	B	C
2	Graham Creek	C	A	A	A	C	E	E	A	C	B	E	E	C	C	D	B
3	Western Basin	D	A	A	A	C	B	A	A	D	D	C	D	D	B	B	B
4	Boat Creek	No data available															
5	Inner Harbour	D	B	C	A	B	A	A	B	C	E	D	D	C	C	C	B
6	Calliope Estuary	D	D	E	E	C	B	A	A	C	E	E	E	C	D	D	D
7	Auckland Inlet	No data available															
8	Middle Harbour	C	E	E	D	B	A	A	A	C	C	A	C	C	C	B	C
9	South Trees Inlet	D	A	A	A	E	C	A	E	C	E	E	E	D	C	B	D
10	Boyne Estuary	A	B	E	D	B	A	A	A	D	E	E	E	B	C	D	C
11	Outer Harbour	C	C	C	B	C	B	A	C	C	D	A	D	C	C	B	C
12	Colosseum Inlet	C	A	A	A	B	A	A	A	D	E	E	E	C	B	B	B
13	Rodds Bay	C	A	B	A	C	B	A	A	D	D	D	E	C	B	C	B
	Harbour average	C	B	C	B	C	B	A	B	D	D	D	E	C	C	C	C

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 2015-16. Note that 2016-17 loads were not available for this reporting period and therefore 2015-16 have been used as the best available indicator of likely 2016-17 loads (Condie et al. 2015b).

Substance (including compounds)		**Relative aquatic eco-toxicology**	**Annual Loads (kg)**																	
			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	2015-2016	2010-2011	2011-2012	2012-2013	2013-2014	2014-2015	2015-2016	2010-2011	2011-2012	2012-2013	2013-2014	2014-2015	2015-2016
Metals	Arsenic	0.20	91.5	93.5	208	257	12.0								560	568	543	270		440
	Beryllium	1.0		17.6	40.3															
	Cadmium	2.0	8.61			11.9	0.12								18.6	6.8	5.8	22.6		
	Chromium	0.33	14.1		21.8			4.0	0.58		0.03	0.01	0.01	0.01						
	Copper	1.0				18.1			0.15	0.03	0.03	0.05			18		84.3	363		
	Iron	0.005																		
	Lead	0.20							0.04	0.01	0.01	0.01		0.01	1.3		23.1	0.41		
	Manganese	0.10														58.0				
	Mercury	16.7		0.01			0.05													
	Nickel	0.17		11.7					0.16	0.01	0.02		0.01	0.01		54.5	192			
	Vanadium	0.05																		
	Zinc	0.125	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	56000							134000	129240	239500	111000	102000	100000
	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	0.01						

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