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Development of management bands for ecosystem metabolism in non-wadeable rivers

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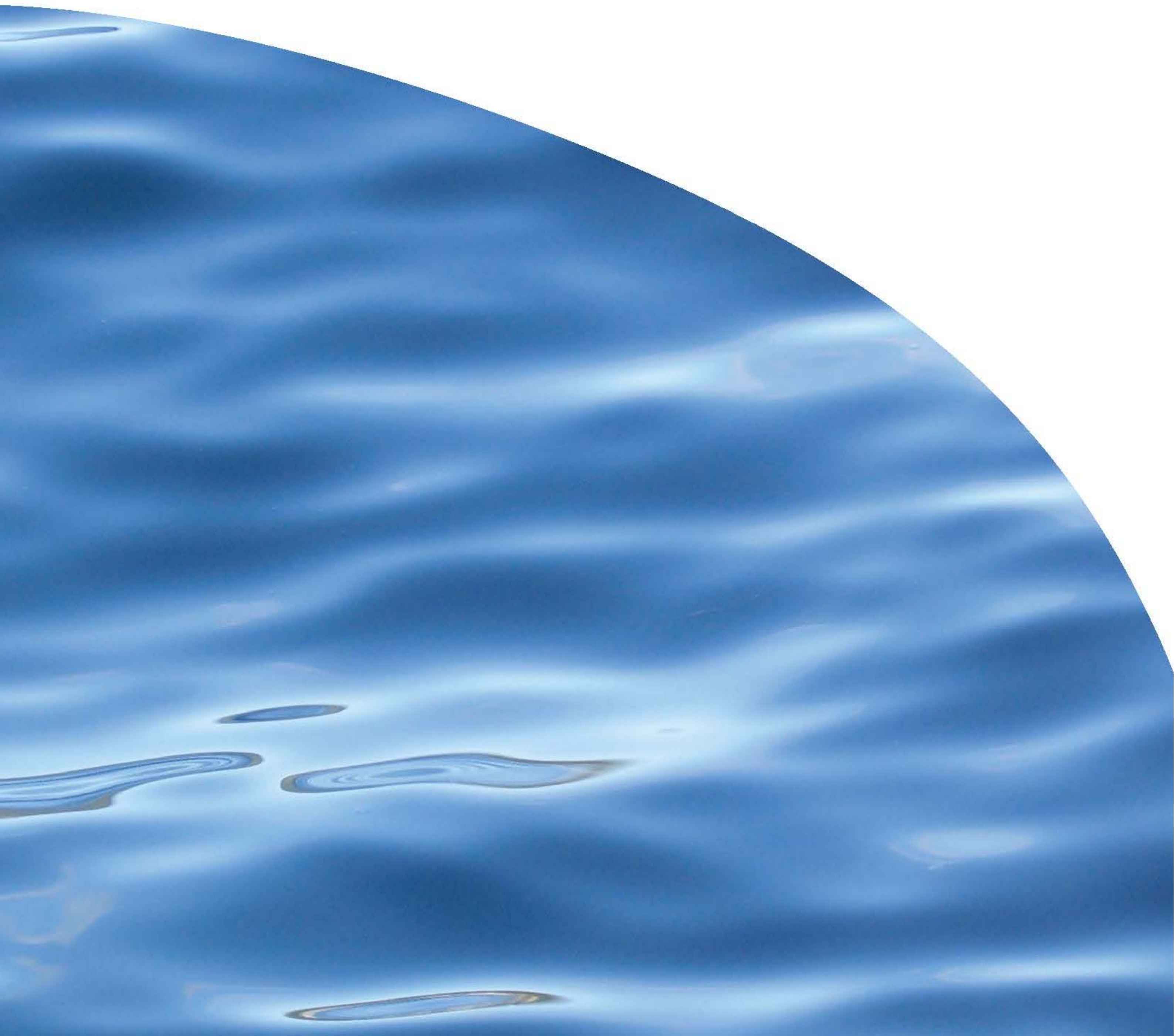

DEVELOPMENT OF MANAGEMENT BANDS FOR ECOSYSTEM METABOLISM IN NON-WADEABLE RIVERS

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EXECUTIVE SUMMARY

A recent review of ecosystem metabolism data suggested that non-wadeable rivers consistently exhibited higher gross primary production (GPP) and a decreased range in ecosystem respiration (ER) than rates observed in wadeable rivers and streams. Subsequently, non-wadeable rivers are more likely to be assessed as having poorer ecosystem health than wadeable rivers when existing management bands are applied. Waikato Regional Council are interested in developing appropriate monitoring and reporting tools for assessing non-wadeable river ecosystem health and commissioned this report to inform management bands for ecosystem metabolism in non-wadeable rivers.

In this report guideline values for assessing ecosystem metabolism were explored for non-wadeable rivers using a compiled dataset representing 682 sites. Exploration of compiled data revealed a strong negative relationship between GPP and ER and native vegetation cover confirming the suitability of ecosystem metabolism metrics as sensitive indicators of catchment condition. This relationship also confirms the suitability of selecting reference sites based on catchment land cover. Subsequently, values of GPP and ER at reference sites defined by > 75% native vegetation cover were used to inform management benchmarks. Impacted sites were assessed using benchmarks based on data from all reference sites (n = 172), from non-wadeable river reference sites (n = 24), and compared to the recommended benchmarks of Young *et al.* (2008).

Overall, higher GPP was observed at open compared to closed canopy sites, and in New Zealand compared to overseas, but the effects were not as important as the effects of river type (reference vs. impact) and river size (wadeable vs. non-wadeable) in determining higher rates of GPP. Likewise higher ER was observed at impacted, open-canopied New Zealand sites, but there was no significant difference between rates observed in wadeable compared to non-wadeable rivers.

Benchmarks for GPP based on various groupings of reference sites varied little and this suggested that the current management bands are suitable for non-wadeable rivers. Benchmarks for ER varied widely depending on the set of reference sites used to inform them and this suggested that new management bands are proposed for non-wadeable rivers.

The following recommended management bands are based on these analyses:

Metric	Good/Healthy	Satisfactory	Poor
GPP (g O_2 m^{-2} d^{-1})	< 3.0	3.0 – 8.0	> 8
ER (g O_2 m^{-2} d^{-1})	1.6 – 3	0.6 – 1.6 or 3 – 13.0	< 0.6 or > 13.0

Application of recommended ecosystem metabolism bands to data from 28 non-wadeable Waikato rivers show that the majority of sites have ‘Satisfactory’ ecosystem health.

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1. INTRODUCTION

1.1. Ecosystem metabolism in non-wadeable rivers

Ecosystem metabolism—the combination of primary production (photosynthesis) and ecosystem respiration—is a measure of how much organic carbon is produced and consumed in river ecosystems. Ecosystem metabolism responds to a wide variety of factors including light intensity, water temperature, nutrient concentrations, organic pollution, chemical contaminants, flow fluctuations and loss of riparian vegetation. This sensitivity to factors that can be affected by human impacts makes ecosystem metabolism a good functional indicator of river ecosystem health. However, some of these factors also vary naturally with river size and therefore it is necessary to determine relevant benchmarks, for wadeable versus non-wadeable rivers for example.

Ecosystem health 'bands' for ecosystem metabolism were originally developed using data from a broad range of river sizes (Young *et al.* 2008). The 25th percentile of the distribution of gross primary production (GPP) data at reference sites, classified *a priori*, was used to determine the reference benchmark and subsequently all sites with GPP less than the reference benchmark were assigned 'Good' river ecosystem health. The distribution of data from all sites was used to determine the benchmarks for attributing data to 'Satisfactory' or 'Poor' river ecosystem health. This is a standard approach for defining management bands and has been applied previously to biological indicators (Stark & Maxted 2007). A slightly amended approach was used to determine management benchmarks for ecosystem respiration (ER) based on the non-linear response to human pressures, *i.e.* ER values can be less or greater than reference values.

To develop ecosystem health bands for ecosystem metabolism, Young *et al.* (2008) used data from 213 reference sites (from Wiley *et al*. 1990; Young & Huryn 1996, 1999; Webster and Meyer 1997; Wilcock *et al*. 1998; Young 1998; Mulholland *et al*. 2001, 2006; Hall & Tank 2003; McTammany *et al*. 2003, 2007; Houser *et al*. 2005; Meyer *et al*. 2005; Ortiz-Zayas *et al*. 2005; Bott *et al*. 2006; Gucker *et al*. 2006) and 82 impact sites (from the same references).

A recent literature review identified a difference in the distribution of metabolism data observed in wadeable versus non-wadeable rivers (Clapcott *et al.* 2012). The comparison of New Zealand data suggested that non-wadeable rivers consistently exhibited higher GPP and a decreased range in ER than rates observed in wadeable rivers and streams (Figure 1). Subsequently, non-wadeable rivers were more likely to be assessed as having poorer ecosystem health than wadeable rivers when the management bands proposed in Young *et al.* (2008) were applied. Whether this pattern was due to a lack of reference sites in the non-wadeable data was not examined.

There is merit in investigating whether river size is an independent predictor of ecosystem metabolism, supporting the need to develop separate management bands for these larger rivers. Several conceptual models support the idea that rivers will have greater GPP than streams based on higher light levels, due to the absence of shading from riparian vegetation, thereby fuelling periphyton and macrophyte growth. Although in very large rivers depth and turbidity is predicted to decrease light availability, and hence GPP (Thorp & Delong 1994). Ecosystem respiration is hypothesised to be relatively greater than GPP (*i.e.* P/R < 1) in non-wadeable rivers due to a dominance of heterotrophic communities fuelled by warmer and deeper water, as well as nutrients and organic matter from upstream (Vannote *et al.* 1980) and surrounding floodplains (Junk *et al.* 1989). Empirical studies have further shown a positive correlation between ecosystem metabolism and stream order (Meyer & Edwards 1990).

The goal of this study was to collate additional metabolism data from national and international studies and determine whether stream size was a significant predictor of ecosystem metabolism. Additional data on catchment and riparian condition was also gathered where possible.

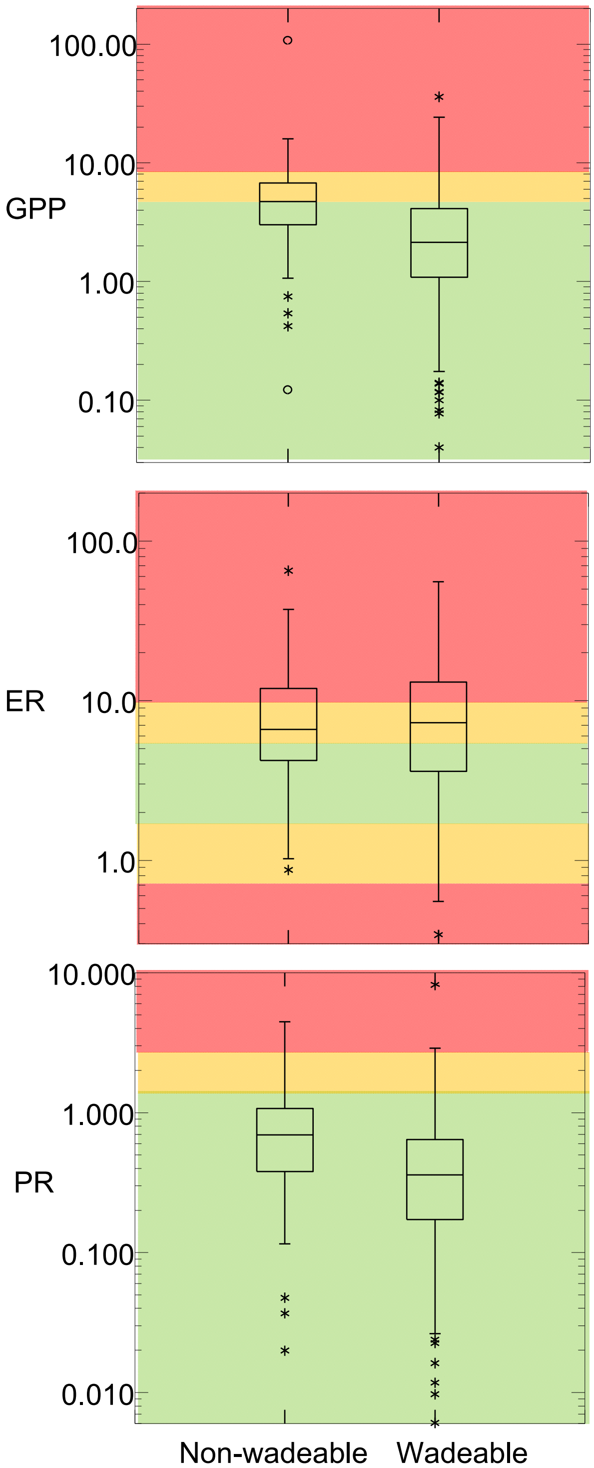

Figure 1. Range in gross primary production (GPP) (g O_2 m^{-2} d^{-1}), ecosystem respiration (ER) (g O_2 m^{-2} d^{-1}) and production to respiration (P/R) ratios measured at non-wadeable (n = 70) and wadeable (n = 139) rivers in New Zealand collated from a variety of studies. Colour bands represent good (green), satisfactory (orange) and poor (red) river health according to the recommended criteria of Young *et al.* (2008). Note the logarithmic scale on the y-axes. From Clapcott *et al*. (2012).

2. METHODS

2.1. Data collation

I compiled published data from the international literature. Relevant studies were identified using a Web of Science® search of publications from all years using search terms including 'ecosystem metabolism, river/stream metabolism, gross primary productivity, GPP, ecosystem respiration, ER'. Citations as well as reference lists of identified studies were also explored. Additionally I collated metabolism data for New Zealand from reports or unpublished studies conducted by Cawthron Institute.

Thirteen hundred and eighty-one data points included single and replicate estimates of GPP and ER calculated from diurnal patterns in dissolved oxygen using the single or two station open-channel methods. I calculated site averages using only data from late spring to early autumn for New Zealand studies (n = 302). For international studies, I used summer means where possible or annual means when reported as such (n = 380). I calculated summary P/R ratios for each site.

Spatial coordinates were available for 282 New Zealand sites and were used to identify the NZREACH number for the study reach and information on land use was compiled from Land Cover Database v3. Land cover categories were summarised to calculate the proportion of urban, light and heavy pasture, exotic forest and native forest in the upstream catchment. For international sites, land cover information was not consistently available so sites were assigned to a 'reference' or 'impact' (agriculture, urban, forestry) category based on the dominant land use reported. Average stream depth was used to assign sites to 'wadeable' (< 1 m) or 'non-wadeable' (> 1 m) categories. The percentage of riparian shading (> 50%) supplemented by photosynthetic active radiation values were used to assign sites to 'open' or 'closed' riparian shade categories.

2.2. Data analysis

I used general linear modelling to identify any relationships between ecosystem metabolism variables and land cover (% native forest or category reference vs. impact), river type (wadeable vs. non-wadeable), and riparian shading (open vs. closed). GPP and ER were log+1 transformed to meet the model assumptions of normality.

I used the method of Young *et al*. (2008) to recalculate metabolism bands for different datasets:

- All data
- Non-wadeable data.

3. RESULTS

3.1. Patterns in ecosystem metabolism

3.1.1. All data

The compilation of data resulted in a similar number of sites in New Zealand and overseas. There were three times as much data for wadeable compared to non-wadeable rivers and for impact compared to reference sites (Table 1). This reflects the focus of most studies on small (≤ 3rd order), impacted streams.

Table 1. Number of sites in each category. Total number of sites = 682.

Categorical variable	Descriptor	No. sites
Country	New Zealand	302
	Other	380
River type	Non-wadeable	132
	Wadeable	550
Canopy cover	Closed	171
	Open	459
	Unknown	52
Land use	Impact	510
	Reference	172

Site means for GPP ranged from 0 to 107.1 g O_2 m^{-2} d^{-1} and for ER from 0.1 to 65.8 g O_2 m^{-2} d^{-1}. While P/R ratios ranged from 0 to 37, the majority of sites (81%) were net heterotrophic with P/R ratios less than 1. Proportionally, more non-wadeable sites had P/R ratios greater than 1 (35%), compared to wadeable sites (15%).

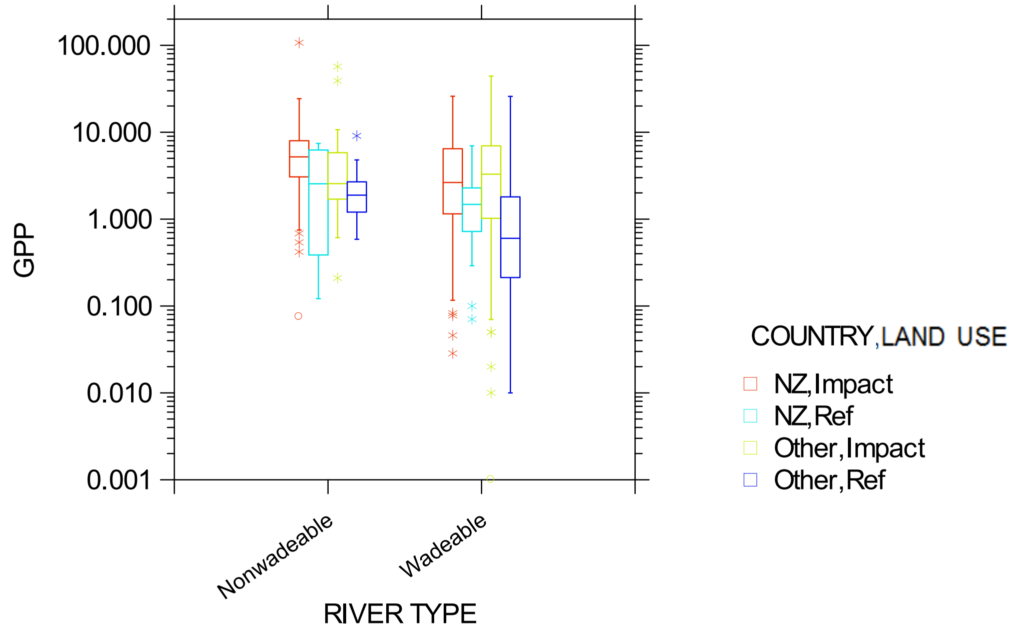

Figure 2. Range in GPP (g O_2 m^{-2} d^{-1}) observed at 682 sites from New Zealand and international studies of river metabolism. Log scale on y-axis.

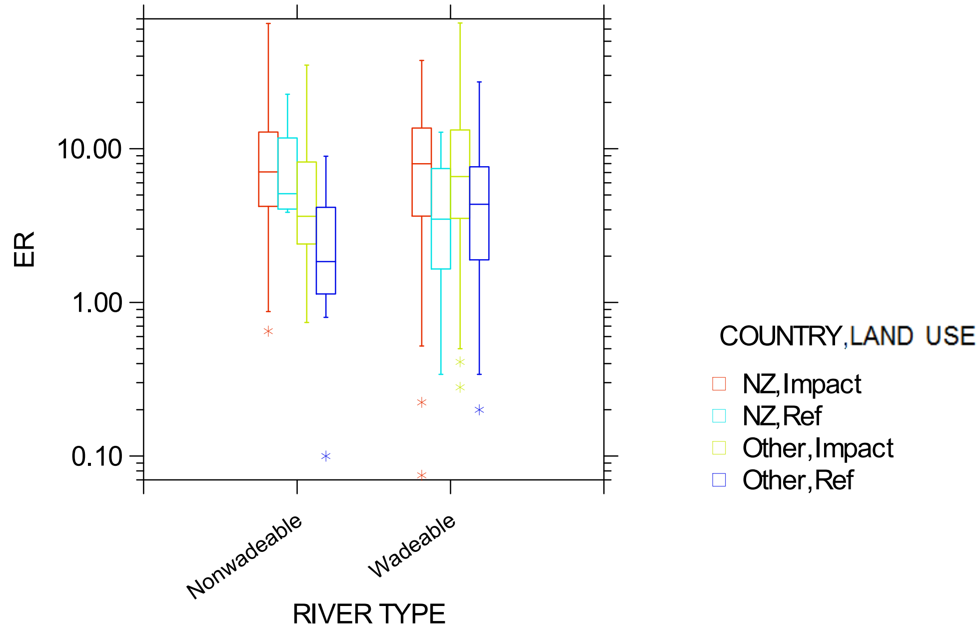

Figure 3. Range in ER (g O_2 m^{-2} d^{-1}) observed at 682 sites from New Zealand and international studies of river metabolism. Log scale on y-axis.

There was a significant effect of land use category (reference vs. impact) and river type (wadeable vs. non-wadeable) on GPP and no effect of country of origin or canopy (Table 2). Greater GPP was associated with human impacts and non-wadeable rivers (Figure 2). However, a Student t-test showed that mean GPP observed at open canopy sites was higher than that observed at closed canopy sites (balanced t = 9.08, n = 342, $P < 0.001$), and that mean GPP was higher in New Zealand compared to overseas rivers (t = 4.11, n = 682, $P < 0.001$).

Similarly for ER, there was a significant land use and canopy cover effect but no effect for country or river type (Figure 3; Table 2). Again, Student t-tests showed that mean ER observed in New Zealand rivers was higher than that observed overseas (t = 4.07, n = 682, $P < 0.001$), but there was no difference between ER rates observed in wadeable versus non-wadeable rivers (t = 2.89, n = 254, $P = 0.77$).

Table 2. General linear model output for GPP and ER in response to categorical variables for all data (n = 682).

Model	Variable	SS	F	*P*
Log (GPP+1)	Land use	8.905	75.105	0.000
	River type	1.653	13.943	0.000
	Canopy	0.666	2.807	0.061
	Country	0.004	0.032	0.858
	(error)	80.155		
Log (ER+1)	Land use	5.259	49.904	0.000
	River type	0.379	3.595	0.058
	Canopy	2.481	11.773	0.000
	Country	0.041	0.390	0.532
	(error)	71.239		

3.1.2. New Zealand data

The lowest and highest rates of GPP and ER were observed in New Zealand rivers (n = 281). There was a significant decrease in GPP associated with increasing percentage of native vegetation in the catchment ($F_{(1, 277)} = 27.84$, $P < 0.001$); however, there was also a significant effect of river type ($F_{(1, 277)} = 19.08$, $P < 0.001$) and canopy cover ($F_{(1, 277)} = 12.05$, $P = 0.001$; Figure 4). In contrast, while there was an overall significant decrease in ER associated with increasing native vegetation cover ($F_{(1, 277)} = 38.95$, $P < 0.001$), there was no significant effect of river type ($F_{(1, 277)} = 2.23$, $P = 0.136$) or canopy categories ($F_{(1, 277)} = 2.38$, $P = 0.124$; Figure 5).

Results suggest that lower metabolic rates occur at reference sites and support the use of reference site distributions for assigning management bands.

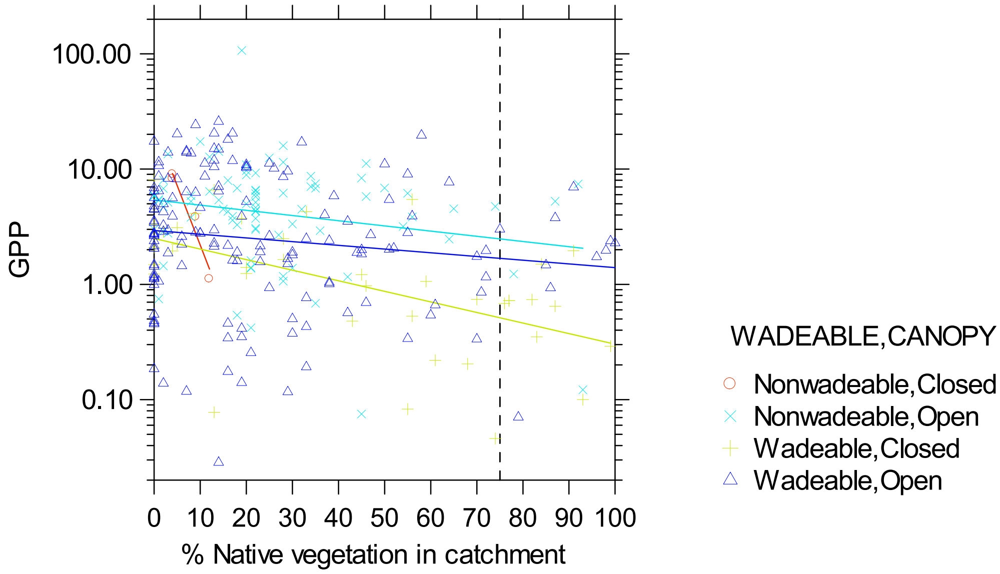

Figure 4. Relationship between GPP and % native vegetation cover in the catchment (n = 281) of New Zealand rivers. The 75% limit used to assign land use type to reference or impact is shown. Log y-axis scale.

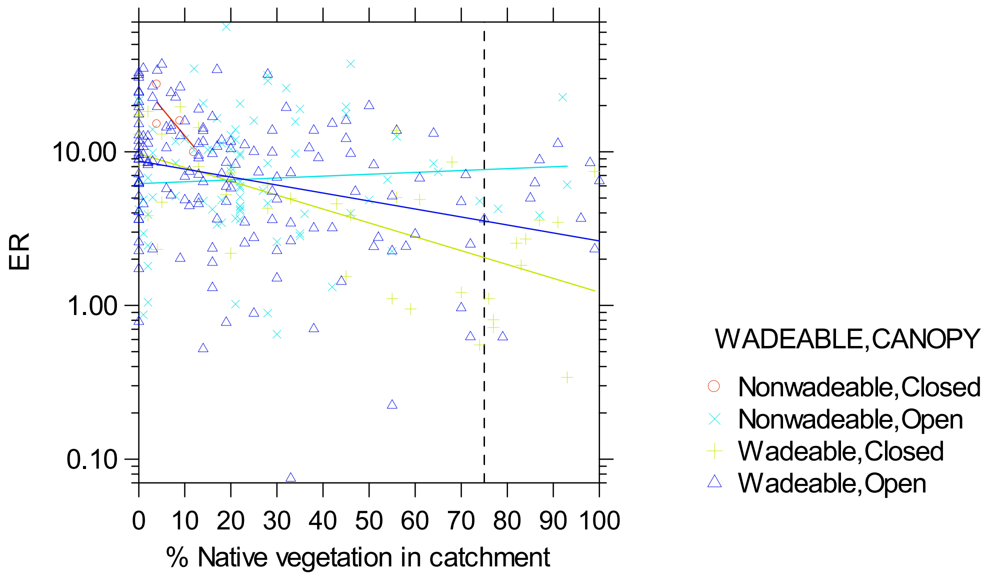

Figure 5. Relationship between ER and % native vegetation cover in the catchment (n = 281) of New Zealand rivers. The 75% limit used to assign land use type to reference or impact is shown. Log y-axis scale.

3.2. Defining management bands

3.2.1. Patterns in ecosystem metabolism data at reference sites

Mean GPP at reference sites was significantly higher at non-wadeable compared to wadeable sites (balanced t = 2.95, n = 48, *P* = 0.005) and significantly higher at open compared to closed canopy sites (t = 7.10, n = 146, $P < 0.001$); there was an absence of closed canopy sites for non-wadeable rivers (Figure 6). There was no significant difference in GPP observed in New Zealand compared to overseas sites (balanced t = 1.14, n = 58, $P = 0.260$).

Mean ER at non-wadeable reference sites was higher than that observed at wadeable reference sites, but the difference was not significant (balanced t = 2.01, n = 48, $P = 0.051$; Figure 7). There was no significant difference between rates of ER observed at open and closed canopy sites (t = 0.01, n = 146, $P = 0.992$), nor between ER observed in New Zealand compared to overseas (balanced t = 0.07, n = 58, $P = 0.941$).

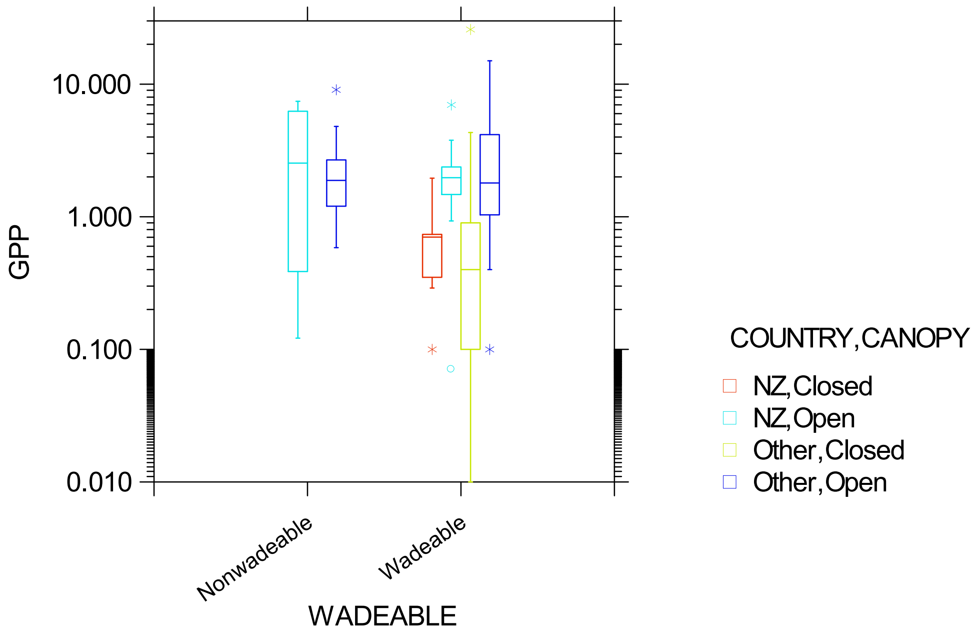

Figure 6. Distribution of GPP at reference sites grouped by country and canopy cover (n = 146). Log y-axis scale.

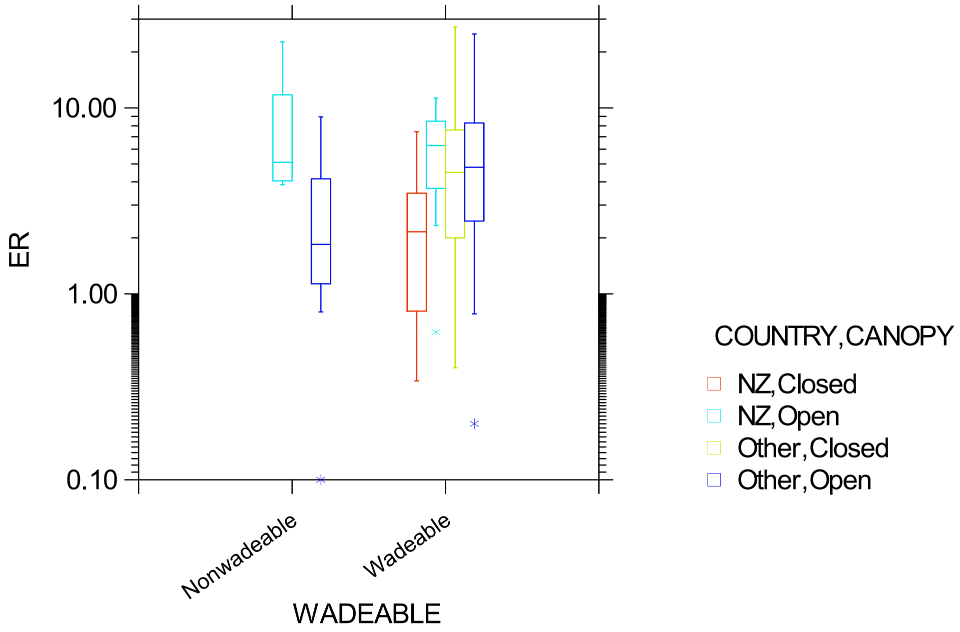

Figure 7. Distribution of ER at reference sites grouped by country and canopy cover (n = 165). Log y-axis scale.

3.2.2. Applying the Young et al. 2008 methodology

For GPP, I used the 75th percentile value from reference sites to establish the upper band indicating 'Good' ecosystem health. Between the 75th and 95th percentile values indicate 'Satisfactory' ecosystem health and values beyond the 95th percentile indicate 'Poor' ecosystem health.

I assessed the resulting criteria using data from all impact sites and non-wadeable river impact sites. The most stringent criteria for GPP were developed using data from reference sites with closed canopies; when applied to impact sites only 19% of sites had 'Good' ecosystem health and 49% of sites had ''Poor' ecosystem health (Table 3). In comparison, application of the Young *et al*. (2008) criteria for GPP results in 52% of sites have good ecosystem health and 24% having 'Poor' ecosystem health (Table 3). When Young *et al*. (2008) tested their criteria on 82 impact sites (a subset from this study) 20% had good ecosystem health.

Criteria for GPP developed based on non-wadeable reference sites are very similar to those already proposed by Young *et al*. (2008). This suggests minor amendment of the current Young *et al*. (2008) criteria for GPP would be suitable for non-wadeable sites. Current analyses also suggest more sensitive criteria could be applied to wadeable streams, particularly those with closed canopies.

Table 3. Management band criterion for GPP (g O_2 m^{-2} d^{-1}) developed using summer or annual mean values from reference sites. Percent proportions shown as **Good**/Satisfactory/**Poor**.

Gross primary production criterion	N	Good (G)	Satisfactory (S)	Poor (P)	Proportion (%) of all impact sites assigned to each band N = 510.	Proportion (%) of non-wadeable impact sites assigned to each band. N = 108.	Proportion (%) of non-wadeable Waikato sites assigned to each band. N = 28.
Young *et al.* 2008	132*	< 3.5	3.5 – 7.0	> 7.0	52 / 23 / 24	36 / 38 / 26	29 / 50 / 21
All data	172	< 2.0	2 – 8.4	> 8.4	35 / 45 / 20	19 / 61 / 19	21 / 61 / 18
Closed canopy	71	< 0.9	0.9 – 3.3	> 3.3	19 / 32 / 49	07 / 28 / 65	07 / 21 / 71
Non-wadeable	24	< 3.1	3.1 – 7.9	> 7.9	na	31 / 45 / 23	25 / 57 / 18

* replicate measures not site averages.

For ER, I used values between the 25th and 75th percentile values from reference sites to indicate 'Good' ecosystem health. Values between the 5th and 25th as well as between the 75th and 95th percentiles indicated 'Satisfactory' ecosystem health. Values less than 5th or greater than the 95th percentile indicated 'Poor' ecosystem health. This approach acknowledges the non-linear nature of the relationship between ER and human impacts, *i.e.* varying impacts can lead to very low or very high rates.

Assessments of ER were very similar for all criteria for wadeable rivers with between 35-42% of all sites classified as 'Good' (Table 4). In contrast, the non-wadeable criteria resulted in a much more sensitive assessment of non-wadeable river health with only 11% of sites classified as 'Good'.

Table 4. Management band criterion for ER (g O_2 m^{-2} d^{-1}) developed using summer or annual mean values from reference sites. Percent proportions shown as **Good**/Satisfactory/**Poor**.

Ecosystem respiration criterion	N	Good (G)	Satisfactory (S)	Poor (P)	Proportion (%) of all impact sites assigned to each band N = 510.	Proportion (%) of non-wadeable impact sites assigned to each band. N = 108.	Proportion (%) of non-wadeable Waikato sites assigned to each band. N = 28.
Young *et al.* 2008	132*	1.6 – 5.8	0.8 – 1.6 or 5.8 – 9.5	< 0.8 > 9.5	35 / 24 / 31	39 / 21 / 40	32 / 21 / 46
All data	172	1.6 – 6.9	0.7 – 1.6 or 6.9 – 13.9	< 0.7 > 13.9	42 / 33 / 25	45 / 31/ 24	39 / 43 / 18
Closed canopy	71	1.8 – 6.8	0.7 – 1.8 or 6.8 – 15.5	< 0.7 >15.5	41 / 38 / 21	44 / 34 / 21	39 / 50 / 11
Non-wadeable	24	1.2 – 2.6	0.6 – 1.2 or 2.6 – 13.0	< 0.6 > 13.0	na	11 / 65/ 24	04 / 75 / 21

* replicate measures, not site averages.

Comparing test sites to local reference sites should result in a more sensitive assessment of ecosystem health than comparison to absolute criteria. In the case of non-wadeable Waikato rivers there is no data from reference sites in the region and data from only four suitable sites in New Zealand are available. Spot metabolism estimates from those four rivers (Motu (North Island), Mokihinui and Karamea (South Island), Freshwater (Stewart Island)) results in a 75th percentile ('Good' threshold) for GPP of 5.8 g O_2 m^{-2} d^{-1}, which is higher than the 3.1 g O_2 m^{-2} d^{-1} threshold based on 24 non-wadeable reference sites globally, or 2.0 g O_2 m^{-2} d^{-1} threshold based on all data (*cf*. 3.5 g O_2 m^{-2} d^{-1} threshold from Young *et al*. 2008). The 'Good' threshold for ER based on four New Zealand sites is between 10.2–20.2 g O_2 m^{-2} d^{-1}. Given the limited number of reference sites available it is recommended that universal data are used to inform management thresholds for non-wadeable rivers, with consideration of the higher values observed locally.

3.2.3. Recommended management bands and application in Waikato rivers

The proposed benchmarks for GPP in non-wadeable rivers are predominantly informed by data from non-wadeable reference sites. The proposed benchmarks for ER in non-wadeable rivers takes into consideration the lack of a significant difference between wadeable and non-wadeable rivers observed in previous analysis and the unlikely influence of closed canopy on non-wadeable rivers. Benchmarks for ER are subsequently informed by non-wadeable and all river datasets.

Table 5. Recommended management band criterion for GPP and ER (g O_2 m^{-2} d^{-1}) developed using summer or annual mean values from reference sites.

Metric	Good/Healthy	Satisfactory	Poor
GPP (g O_2 m^{-2} d^{-1})	< 3.0	3.0 – 8.0	> 8
ER (g O_2 m^{-2} d^{-1})	1.6 – 6	0.6 – 1.6 or 6 – 13.0	< 0.6 or > 13.0

I compared the results of applying the recommended criteria along with alternative criteria for 28 non-wadeable sites in the Waikato region (Table 4, Table 5, Figure 8). The assessments for GPP were very similar with the majority of sites graded as 'Satisfactory' regardless of criteria. Application of the recommended criteria for GPP result in 25% of sites graded as 'Good', 57% of sites graded as 'Satisfactory' and 18% of sites graded as 'Poor'.

The assessments for ER were quite different with only one site graded as 'Good' based on the non-wadeable river criteria. However, the recommended criteria are also informed by all data. Application of the recommended criteria for ER result in 36% of sites graded as 'Good', 43% of sites graded as 'Satisfactory' and 21% of sites graded as 'Poor'.

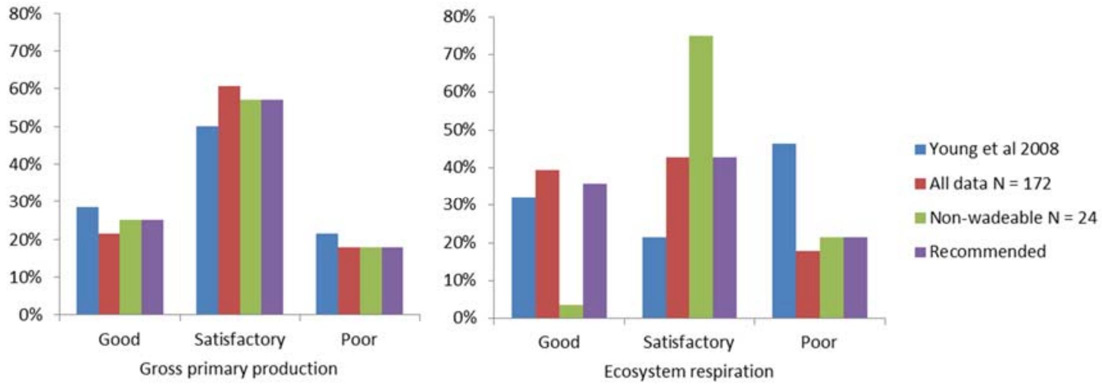

Figure 8. Relative proportion of non-wadeable Waikato river sites (n = 28) that fall within ecosystem metabolism management bands based on the criteria of Young *et al*. (2008), all data criteria, or non-wadeable river criteria from this report.

4. DISCUSSION

A significant effort went into compiling values of gross primary production (GPP) and ecosystem respiration (ER) from the scientific literature spanning 1956 to 2014. An analysis of the data from 682 sites showed that GPP was strongly associated with land use and as such confirmed the appropriateness of using GPP as an indicator of stream health. GPP was also higher at sites with open canopies and in non-wadeable rivers. These two factors are related because 128 of 132 non-wadeable rivers had open canopies.

Results are consistent with ecological theory (Vannote *et al.* 1980) and a recent review of ecosystem metabolism in 218 streams which showed a quantile relationship with larger watersheds having greater GPP (Hoellein *et al.* 2013). Meyer & Edwards (1990) also observed an increase in GPP and ER associated with stream order along a single river continuum.

While ER was also strongly associated with land use there was significant variation among sites occurring in wadeable and non-wadeable rivers and with open and closed canopies. This probably reflects the fact that ER is not limited by light in the same way as GPP is. Water temperature and flow fluctuations have shown to be strong drivers of ER (Uehlinger *et al*. 2003; Roberts *et al.* 2007), and may account for some of the variability observed in the current review. I attempted to minimise the influence of temperature by using predominantly summer data, but there was limited information available to characterise precedent flow.

While not accounting for all factors that can influence ecosystem metabolism, the current review provided a large data set to determine suitable benchmarks for using rates of ecosystem metabolism as functional indicators of river health.

Exploring potential management bands based on the new data set suggests criteria similar to the current Young *et al*. (2008) absolute criteria are suitable for assessing GPP in non-wadeable rivers. Slightly amended criteria are recommended for ER. Application of recommended bands in the Waikato region based on average summer metabolism values from 28 sites suggests the majority of sites have satisfactory ecosystem health.

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6. APPENDIX

Appendix 1. Sources of data used in this study.

Reference	No. sites	Country	Land use	Size	Canopy
Acuña *et al.* 2004	1	EU	Ref	Wadeable	Closed
Alnoee *et al.* 2015	3	EU	Ref	Wadeable	Open
Atkinson *et al.* 2008	1	Australia	Impact	Wadeable	Open
Beaulieu *et al.* 2013	1	US	Impact	Wadeable	Closed
Benson *et al.* 2013	4	US	Ref	Non-wadeable	Open
Bernot *et al.* 2010	62	US	Impact, Ref	Wadeable	Closed
Betts & Jones 2009	3	US	Impact, Ref	Wadeable	Closed, Open
Birkel *et al.* 2013	2	EU	Ref	Wadeable	Closed, Open
Bott & Newbold 2013	3	Peru	Impact, Ref	Wadeable	Closed
Bott *et al.* 2006	36	US	Impact, Ref	Wadeable	Closed, Open
Capblancq & Lavandier 1975	1	EU	Ref	Wadeable	Closed
Chessman 1985	5	Australia	Impact, Ref	Non-wadeable, Wadeable	Closed, Open
Clapcott & Doehring 2014	6	NZ	Impact	Non-wadeable, Wadeable	Closed, Open
Clapcott & Young 2009	24	NZ	Impact	Non-wadeable	Open
Clapcott *et al.* 2010	83	NZ	Impact, Ref	Non-wadeable, Wadeable	Closed, Open
Clapcott unpublished data[1]	11	NZ	Impact, Ref	Non-wadeable, Wadeable	Closed, Open
Colangelo 2007	1	US	Impact	Non-wadeable	Open
Collier *et al.* 2009	9	NZ	Impact, Ref	Non-wadeable	Open
Dodds *et al.* 2013	2	US	Impact	Non-wadeable	Open
Doehring & Young 2010	10	NZ	Impact	Non-wadeable, Wadeable	Closed, Open
Duffer & Dorris 1966	3	US	Impact, Ref	Wadeable	Open
Edwards & Meyer 1987	1	US	Impact	Non-wadeable	Open
Edwards & Owens 1962	1	EU	Impact	Wadeable	Open
Elosegi & Sabater 2013	2	EU	Impact	Wadeable	Open
Fellows *et al.* 2001	2	US	Ref	Wadeable	Open
Fellows *et al.* 2006	4	US	Ref	Wadeable	Closed, Open
Fisher & Carpenter 1976	1	US	Impact	Wadeable	Open
Flemer 1970	3	US	Impact	Wadeable	Closed, Open
Frankforter *et al.* 2010	4	US	Impact	Wadeable	Closed, Open
Griffiths *et al.* 2013	6	US	Impact	Wadeable	Open
Gücker *et al.* 2006	4	EU	Impact	Wadeable	Open
Hall & Tank 2003	11	US	Ref	Wadeable	
Hall 1972	1	US	Ref	Wadeable	Closed
Hall *et al.* 2015	5	US	Ref	Non-wadeable	Open
Hoellein *et al.* 2007	2	US	Ref	Wadeable	Closed
Hoellein *et al.* 2013	1	US	Ref	Wadeable	Closed
Holtgrieve & Schindler 2011	2	US	Ref	Wadeable	Open
Holtgrieve *et al.* 2010	1	US	Impact	Wadeable	Open
Hope *et al.* 2014	1	US	Impact	Wadeable	Open
Hornberger *et al.* 1977	6	US	Impact, Ref	Non-wadeable, Wadeable	Open
Houser *et al.* 2005	8	US	Impact, Ref	Wadeable	Closed
Hunt *et al.* 2012	3	Australia	Impact	Non-wadeable	Open

[1] Sites in Whanganui-Manawatu region, NZ.

Iwata *et al.* 2007	23	Japan	Impact	Wadeable	Open
Izagirre *et al.* 2008	19	EU	Impact, Ref	Non-wadeable, Wadeable	Closed, Open
Kaenel *et al.* 2000	1	EU	Impact	Wadeable	Open
Logue *et al.* 2004	2	EU	Ref	Wadeable	Open
McDiffett *et al.* 1972	1	US	Impact	Wadeable	Open
McTammany *et al.* 2003	4	US	Ref	Non-wadeable, Wadeable	Open
McTammany *et al.* 2007	6	US	Impact, Ref	Wadeable	Open
Meyer & Edwards 1990	1	US	Impact	Wadeable	Closed
Meyer *et al.* 2005	6	US	Impact, Ref	Wadeable	Closed, Open
Molla *et al.* 1996	2	EU	Ref	Wadeable	Open
Mulholland *et al.* 2001	8	US	Ref	Wadeable	Closed, Open
Mulholland *et al.* 2006	2	US	Ref	Wadeable	Open
Naegeli & Uehlinger 1997	1	EU	Impact	Wadeable	Open
Odum 1956	3	US	Impact, Ref	Non-wadeable	Open
Oliver & Merrick 2006	3	Australia	Impact	Non-wadeable	Open
Pennino *et al.* 2014	3	US	Impact	Wadeable	Open
Rasmussen *et al.* 2011	1	EU	Ref	Wadeable	Open
RG Young unpublished data[2]	20	NZ	Impact	Wadeable	Open
Riley & Dodds 2013	6	US	Impact, Ref	Wadeable	Closed, Open
Roberts *et al.* 2007	1	US	Ref	Wadeable	Closed
Roley *et al.* 2014	2	US	Impact	Wadeable	Open
Ruggiero *et al.* 2006	2	EU	Impact	Wadeable	
Sánchez-Pérez *et al.* 2009	4	EU	Impact, Ref	Wadeable	Closed
Snyder & Minshall 2005	3	US	Ref	Non-wadeable	Open
Uehlinger 1993	1	EU	Impact	Non-wadeable	Open
Uehlinger 2000	2	EU	Impact	Non-wadeable, Wadeable	Open
Uehlinger *et al.* 2003	1	EU	Impact	Wadeable	Open
Vink *et al.* 2005	4	Australia	Impact	Non-wadeable	Open
Von Schiller *et al.* 2008	13	EU	Impact, Ref	Wadeable	
Wagenhoff *et al.* in review	41	NZ	Impact, Ref	Non-wadeable, Wadeable	Closed, Open
Webster & Meyer 1997	24	US	Impact, Ref	Non-wadeable, Wadeable	Closed, Open
Webster *et al.* 2003	8	US	Ref	Wadeable	Closed, Open
Webster *et al.* 2005	1	Australia	Ref	Non-wadeable	Open
Wilcock *et al.* 1998	21	NZ	Impact, Ref	Non-wadeable, Wadeable	
Wiley *et al.* 1990	25	US	Impact	Wadeable	Closed, Open
Young & Clapcott 2010	5	NZ	Impact	Non-wadeable, Wadeable	Open
Young & Collier 2009	15	NZ	Impact, Ref	Non-wadeable, Wadeable	Closed, Open
Young & Huryn 1996	12	NZ	Impact	Non-wadeable, Wadeable	Open
Young 1998	17	NZ	Impact, Ref	Non-wadeable, Wadeable	Closed, Open
Young *et al.* 2006	3	NZ	Impact	Wadeable	Closed
Young 2006	5	NZ	Impact	Wadeable	Open
Young *et al.* 2010	20	NZ	Impact, Ref	Wadeable	Closed, Open

[2] Sites in Tukituki catchment in Hawkes Bay region, NZ.