Memorandum

To: Otago Regional Council

Attention: Jason Auspurger

From: Ton Snelder

Date: 4 March 2024

Subject: Aggregate trends for Otago region

Introduction

Otago Regional council (ORC) monitors river water quality at 59 sites across the Otago region. Several water quality variables are measured at each site on a monthly basis and records at some sites are longer than 20 years. Trends in water quality variables at all sites with sufficient data for the 10 and 20 year periods ending June 2022 were analysed and reported by Fraser (2023).

ORC is now interested in making statements about the direction of trends in the monitored variables over scales larger than that represented by individual sites. Inferences about river water quality trends at broader spatial scales such as the region or particular groupings of rivers into management classes can be made by aggregating the trend assessments for multiple individual sites. This is often undertaken by aggregating information about trends at individual sites into tables or graphs (e.g., Larned et al. 2016). In the report to ORC, Fraser (2023) presented summary plots showing the proportions of river sites with improving 10- and 20-year time period trends at different categorical levels of confidence as a way of indicating the aggregate trend at the regional level. There is also an existing method for analysing aggregate trends called the regional Kendall trend test (Helsel and Frans 2006).

Both the simple tabulation of site-scale trend assessments and the regional Kendall test have the limitation that they do not account for spatial correlation that may exist among sites within a monitoring network. Spatial correlation implies a degree of redundancy in the available data because a trend direction at a site is likely to be consistent with nearby sites. From a statistical perspective, this redundancy reduces the effective size of the dataset and results in an overly liberal assessment of confidence in the aggregate trend (Douglas et al. 2000; Yue and Wang 2002).

In the analyses of aggregate river water quality trends in Otago presented below, a more recent procedure for assessing aggregate trends developed by Snelder et al. (2022) was used. The method assesses the modal direction of individual trends at multiple sites (i.e., the aggregate trend direction) and assesses the confidence associated with this determination while taking into account the spatial autocorrelation between sites. The method has been applied to the available

10- and 20-year river water quality trend information at both the regional scale and within management classes of rivers that ORC use to define management objectives and other planning provisions. This memo presents these results and provides some commentary on the conclusions that can be drawn from them.

Methods

The 10- and 20-year trends evaluated by Fraser (2023) for seven river quality variables (shown in Table 1) were obtained along with the individual observations at each site. All trends were not flow-adjusted and had a hi-censor filter applied during the analysis. For each water quality variable and individual site, Fraser (2023) used the Kendall's tau (τ) statistic to evaluate the direction (D^{τ}) and confidence in that assessment (C^{τ}) using the methods described by Snelder et al. (2022).

The first step was to prepare bar plots that showed the proportion of individual 10- and 20-year site trends that were increasing and decreasing with confidence in the assessment of trend direction described by the four categories shown in Table 2.

Table 1. River water quality variables, measurement units and site numbers used in this study.

Variable	**Abbreviation**	**Units**	**Number of monitoring sites**
Ammoniacal Nitrogen	NH4N	g m^{-3}	111
Dissolved Reactive Phosphorus	DRP	g m^{-3}	110
Dissolved Inorganic Nitrogen	DIN	g m^{-3}	105
Total Nitrogen	TN	g m^{-3}	109
Total Phosphorus	TP	g m^{-3}	109
Turbidity	TURB	NTU	110
E. coli	ECOLI	MPN $100mL^{-1}$	110

Table 2. Level of confidence categories used to convey the confidence in the assessed trend direction.

Categorical level of confidence in assessed trend direction	**Value of C**
Highly likely	0.95 - 1.00
Very likely	0.90 – 0.95
Likely	0.67 – 0.90
Uncertain	0.50 – 0.67

The second step used the directions of the individual site trends derived by Fraser (2023) to calculate the aggregate trend direction (D^{T}) to be the modal (i.e., most frequently occurring) direction of the individual site trends and the aggregate trend strength ($\widehat{\mathrm{T}}$)[1] as the proportion of site trends that are in the modal direction. The confidence in the assessed aggregate trend direction (C^{T}) was calculated from the confidence in the direction of the individual site trends and adjusted for spatial autocorrelation between sites using the method described by Snelder et al. (2022). Briefly, the adjustment is necessary if there is spatial correlation among sites within a monitoring network. Spatial correlation means that the information representing the sites is not independent and this results in under-estimation of the variance and over-estimation of confidence in the assessed aggregate trend direction. The method of Snelder et al. (2022) uses the sample cross-correlation coefficient, which is computed from the observation time series for all sites, to “correct ” the variance to account for the spatial correlation.

Both the bar charts and the aggregate site trends were prepared for each water quality variable shown in Table 1, for the 10- and 20-year time periods for the region as a whole and for the management classes adopted by ORC that group rivers into 4 categories: Mountain (M), Hill (H), Lowland (L) and Lake-fed (Lk).

Results

Aggregate 20-year trends at the regional level

Figure 1 is a colour-coded bar chart that represents the proportions of sites across the whole region with increasing and decreasing 20-year trends for the seven water quality variables with confidence expressed by the categories defined in Table 2. Yellow indicates high confidence in the assessed direction and the darker colours indicate lower confidence.

At the regional level and for the 20-year trend period, there were between 33 and 41 sites representing each water quality variable (Figure 1). The majority of individual site trends for NH4N, DRP, and TP were decreasing (Figure 1). In addition, for the decreasing trends, confidence in direction at the majority of sites was high (i.e., a majority of decreasing trends were in the Highly likely category). Figure 1 indicates that the majority of individual site trends for DIN, TN, TURB and ECOLI are increasing. For DIN, TN and ECOLI confidence in direction at the majority of sites was high (i.e., a majority of decreasing trends were in the Highly likely category).

Overall Figure 1 indicates that at the regional level and for the 20-year period trends in NH4N, DRP, and TP were predominantly decreasing and in DIN, TN and ECOLI were predominantly increasing. The dominant direction of trends for TURB was increasing but a smaller proportion of sites had confidence in the Highly likely category than for DIN, TN and ECOLI.

[1] Note that the Greek letter tau is used to trends for both individual site and aggregate trends. When an individual site trend is being referred to the lower-case tau (τ) is used. When an aggregate trend is being referred to the upper-case tau is used (T).

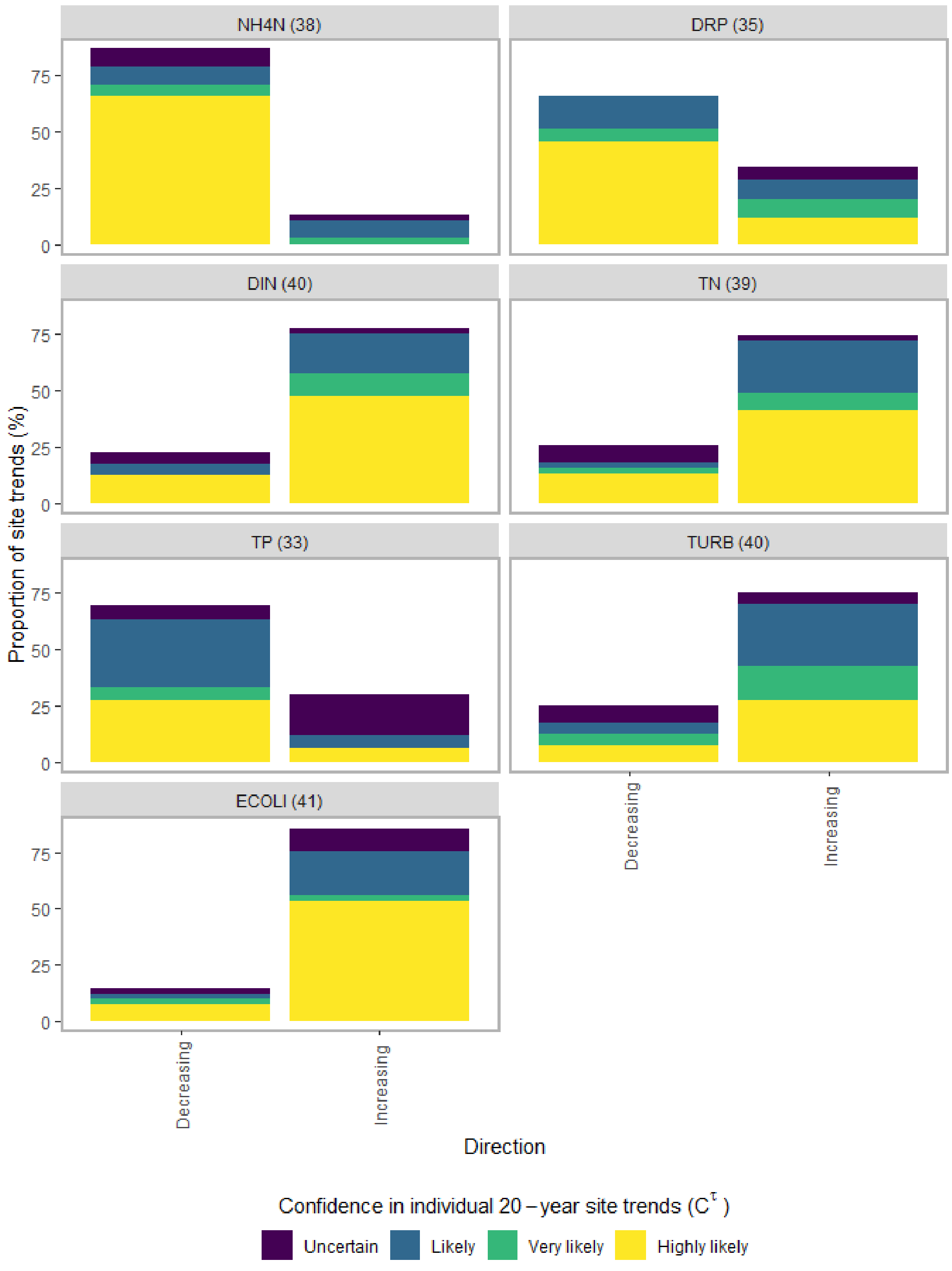

Figure 1. Summary plot showing the proportion of river sites with decreasing and increasing 20-year trends at each categorical level of confidence defined by Table 1. The values in parentheses after the variable names on the x-axis labels indicate the number of sites that were included in the analysis.

For the 20-year period, observations exhibited a degree of cross-correlation between all pairs of sites for all water quality variables (Figure 2). Between site cross-correlation could be both negative and positive but there was a tendency for correlation to be positive. The mean of the cross-correlations was largest (0.33) for DIN and least for TP (0.07).

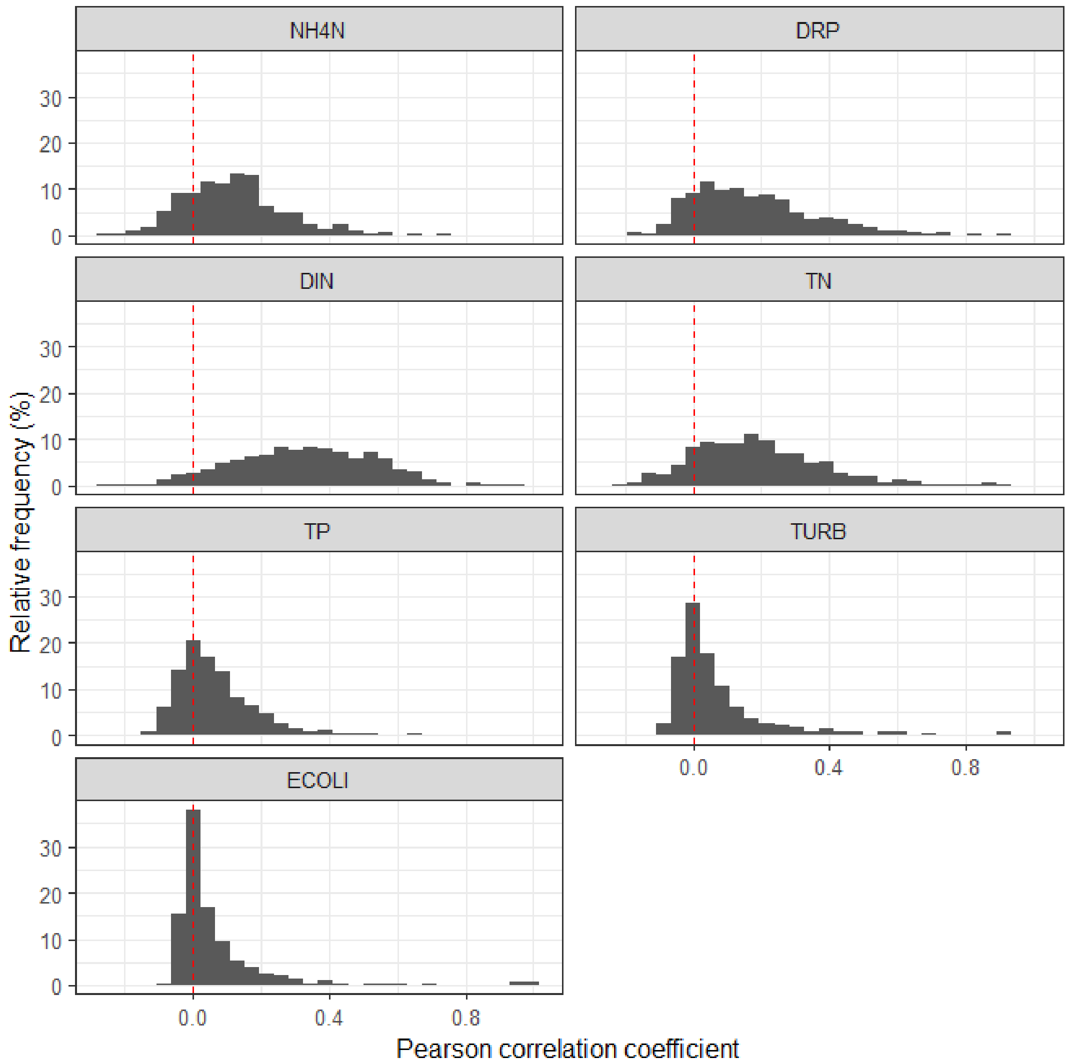

Figure 2. Distributions of cross-correlations between observations for all pairs of sites for each of the seven water quality variables for the 20-year trend period. The red dashed line indicates correlation of zero.

A compact graphical representation of the aggregate 20-year trends at the regional level is shown in Figure 3 and more detail is supplied separately in “TauRegional20Summary.csv". Note that confidence in the modal directions (C^{T}) shown in Figure 3 are a function of the directions and levels of confidence in the individual site trends shown in Figure 1, the number of sites and the degree of cross correlation between sites (Figure 2). In general, confidence in the modal trends was high when a majority of individual site trends were in one direction and having high confidence (C^{τ}). This was the case for all variables except TP, which despite having a majority of decreasing individual site trends (Figure 1) had a large proportion of sites for which confidence in trend direction was less than Highly likely.

The aggregate trend direction (i.e., modal direction, D^T) was decreasing for NH4N and DRP and aggregate trend strength ($\hat{\mathrm{T}}$) was > 0.6 (Figure 3). Confidence in the aggregate trend direction (C^T) for NH4N and DRP was Highly likely (Figure 3). These results are consistent with the dominance of decreasing individual sites trends for these variables (Figure 1). For TP, the aggregate trend direction was decreasing and confidence was Very Likely, (i.e. less than Highly likely), reflecting the large proportion of individual site trends sites for which confidence was less than Highly likely (Figure 1).

For DIN, TN, TURB and ECOLI, the aggregate trend direction was increasing and confidence was Highly likely for all four assessments (Figure 3). Again, these results are consistent with the dominance of decreasing individual sites trends for these variables (Figure 1).

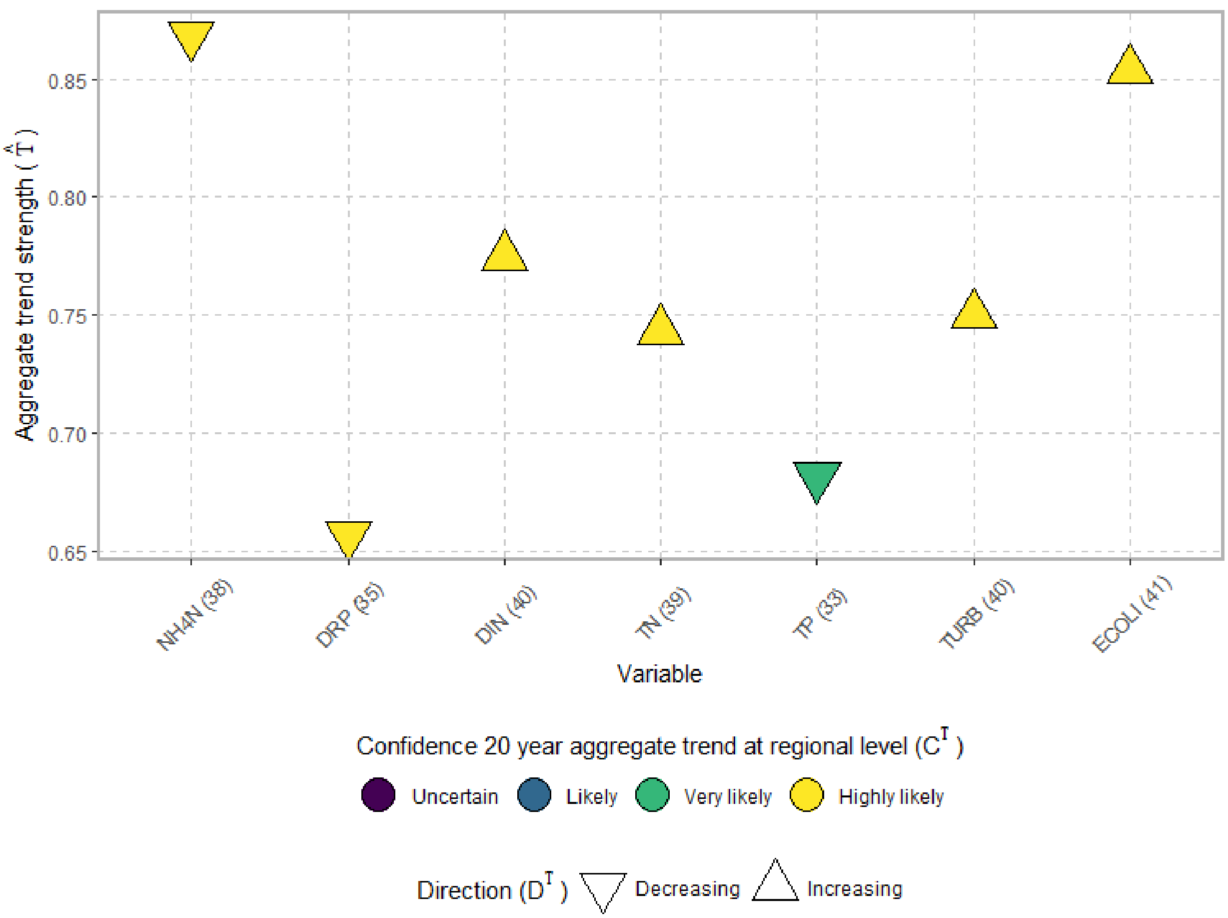

Figure 3. Aggregate trend direction (D^T) and strength ($\hat{T}$) for 20-year trends for seven water quality variables over all sites grouped at regional level. Confidence in the aggregate direction (C^T) is indicated by the four confidence categories (see Table 2 for details). Confidence is shown for calculations that have been corrected for spatial correlation. The values in parentheses after the variable names on the x-axis labels indicate the number of sites that were included in the analysis.

Aggregate 10-year trends at the regional level

At the regional level and for the 10-year trend period, there were between 55 and 59 sites representing each water quality variable (Figure 4). The majority of individual site trends were decreasing for NH4N, DRP, TP and TURB (Figure 4). For DIN, TN and ECOLI there were approximately the same number of sites increasing and decreasing. Figure 4 indicates that, at the regional level and for the 10-year period, trends in NH4N, DRP, TP and TURB were predominantly decreasing but that there was a mix of trend directions for DIN, TN and ECOLI.

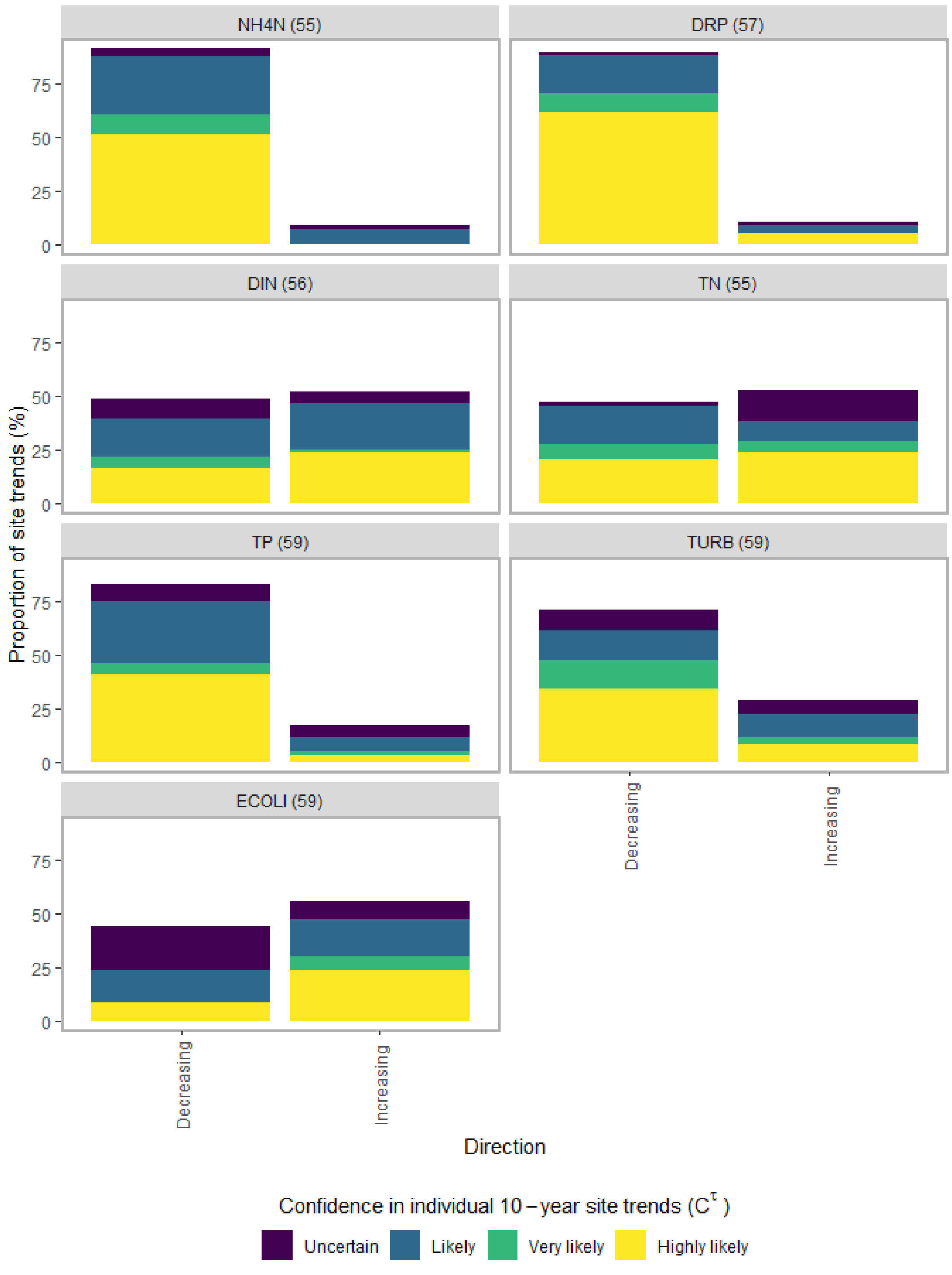

Figure 4. Summary plot showing the proportion of river sites with decreasing and increasing 10-year trends at each categorical level of confidence defined by Table 1. The values in parentheses after the variable names on the x-axis labels indicate the number of sites that were included in the analysis.

For the 10-year period, observations made in each sample interval exhibited a degree of cross-correlation between all pairs of sites for all water quality variables (Figure 5). Between site cross-correlation could be both negative and positive but there was a tendency for correlation to be positive. The mean of the cross-correlations was largest (0.33) for DIN and least for ECOLI (0.07).

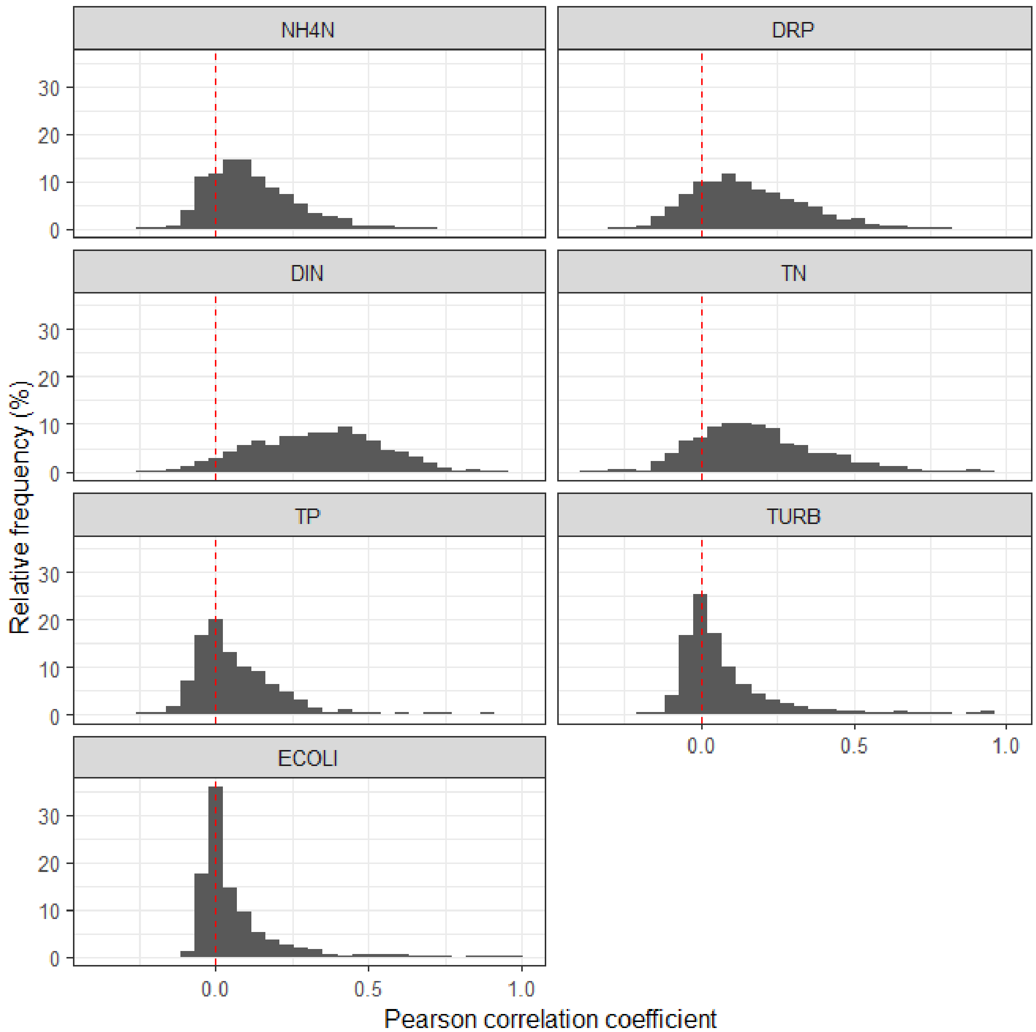

Figure 5. Distributions of cross-correlations between observations for all pairs of sites for each of the seven water quality variables for the 10-year trend period. The red dashed line indicates correlation of zero.

The aggregate 10-year trends at the regional level are shown in Figure 6 and more detail is supplied separately in “TauRegional10Summary.csv". The aggregate trend direction (D^T) was decreasing and confidence was “Highly likely” for NH4N, DRP, TP and TURB and aggregate trend strength ($\widehat{T}$) was > 0.6 (Figure 6Figure 3). This is consistent with the dominance of decreasing individual sites trends for these variables (Figure 4). The aggregate 10-year trend direction (D^T) was increasing for DIN, TN and ECOLI but aggregate trend strength ($\widehat{T}$) was < 0.6 and confidence in this direction for DIN and TN was “Uncertain” and for ECOLI was Likely (Figure 6Figure 3). This is consistent with the was a mix of individual site trend directions for DIN, TN and ECOLI shown in Figure 4.

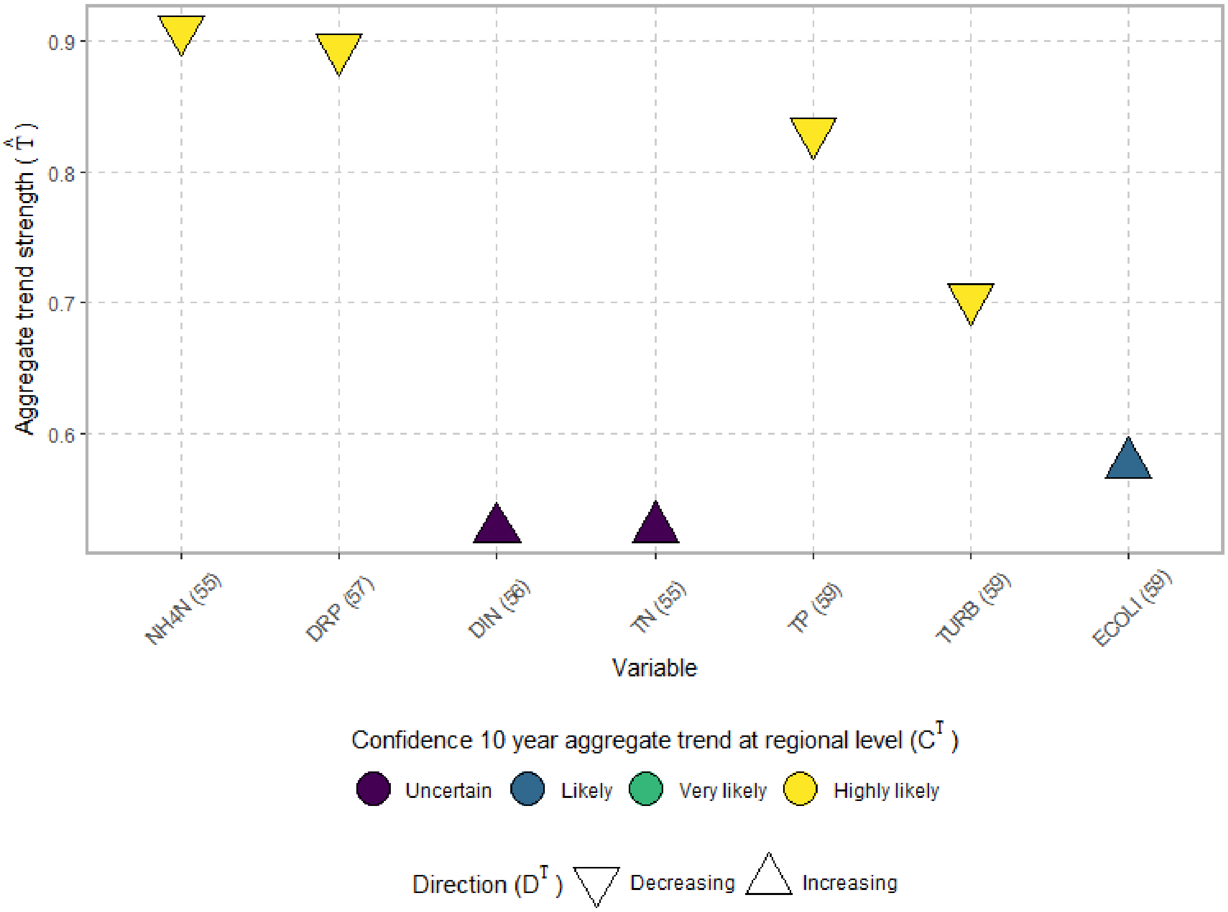

Figure 6. Aggregate trend direction ($\boldsymbol{D^T}$) and strength ($\hat{\boldsymbol{T}}$) for 10-year trends for seven water quality variables over all sites grouped at regional level. Confidence in the aggregate direction ($\boldsymbol{C^T}$) is indicated by the four confidence categories (see Table 2 for details). Confidence is shown for calculations that have been corrected for spatial correlation. The values in parentheses after the variable names on the x-axis labels indicate the number of sites that were included in the analysis.

Aggregate 20-year trends at the management class level

At the management class level for the 20-year trend period, site numbers were low (i.e., ≤5) for the Lake fed and Mountain classes but were at least 13 for the Lowland and Hill classes (Table 3). Within water quality variables, the aggregate trend direction varied by management class (Figure 7). For example, DRP predominantly decreased at sites in the Hill class but increased for sites in the Lowland class, whereas DIN and TN predominantly increased at sites in both the Hill and Lowland class.

Table 3. Number of sites included in the analysis of 20-year trends at the management class level.

Variable	Management class			
	H	L	Lk	M
NH4N	13	16	5	4
DRP	16	14	3	2
DIN	16	16	5	3
TN	16	16	4	3
TP	12	14	4	3
TURB	16	15	5	4
ECOLI	17	15	5	4

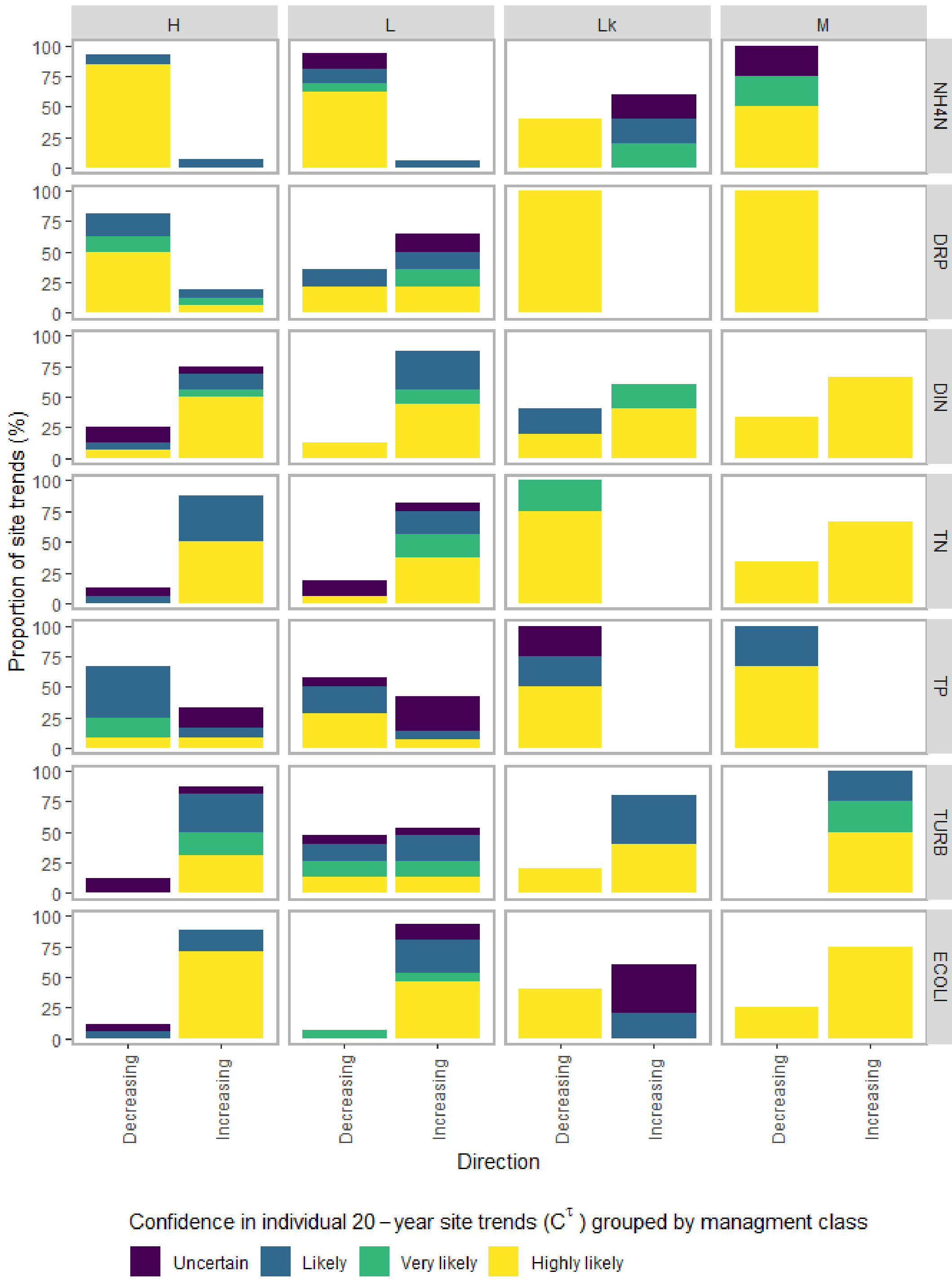

Figure 7. Summary plot showing the proportion of river sites with decreasing and increasing 20-year trends at each categorical level of confidence defined by Table 1 for sites grouped by river management classes.

A compact graphical representation of the results of the aggregate 20-year trends at the management class level is shown in Figure 8 and more detail is supplied separately in “TauRegional20Summary_SRC_OF_FLW.csv". Aggregate 20-year trends at the management class level exhibited a variety of directions for some variables. For example, for the Lowland class, the aggregate DRP trend direction was increasing ($C^{\mathrm{T}} = Likely$, $\widehat{\mathrm{T}} = 0.64$) whereas the aggregate trend direction for the Hill class was decreasing ($C^{\mathrm{T}} = Highly\ likey$, $\widehat{\mathrm{T}} = 0.81$) (Figure 8). More generally, aggregate trend directions for NH4N, DRP and TP were decreasing and for DIN, TN, TURB and ECOLI were increasing in most management classes. This is consistent with the aggregate trend directions for these variables at the regional level (Figure 3).

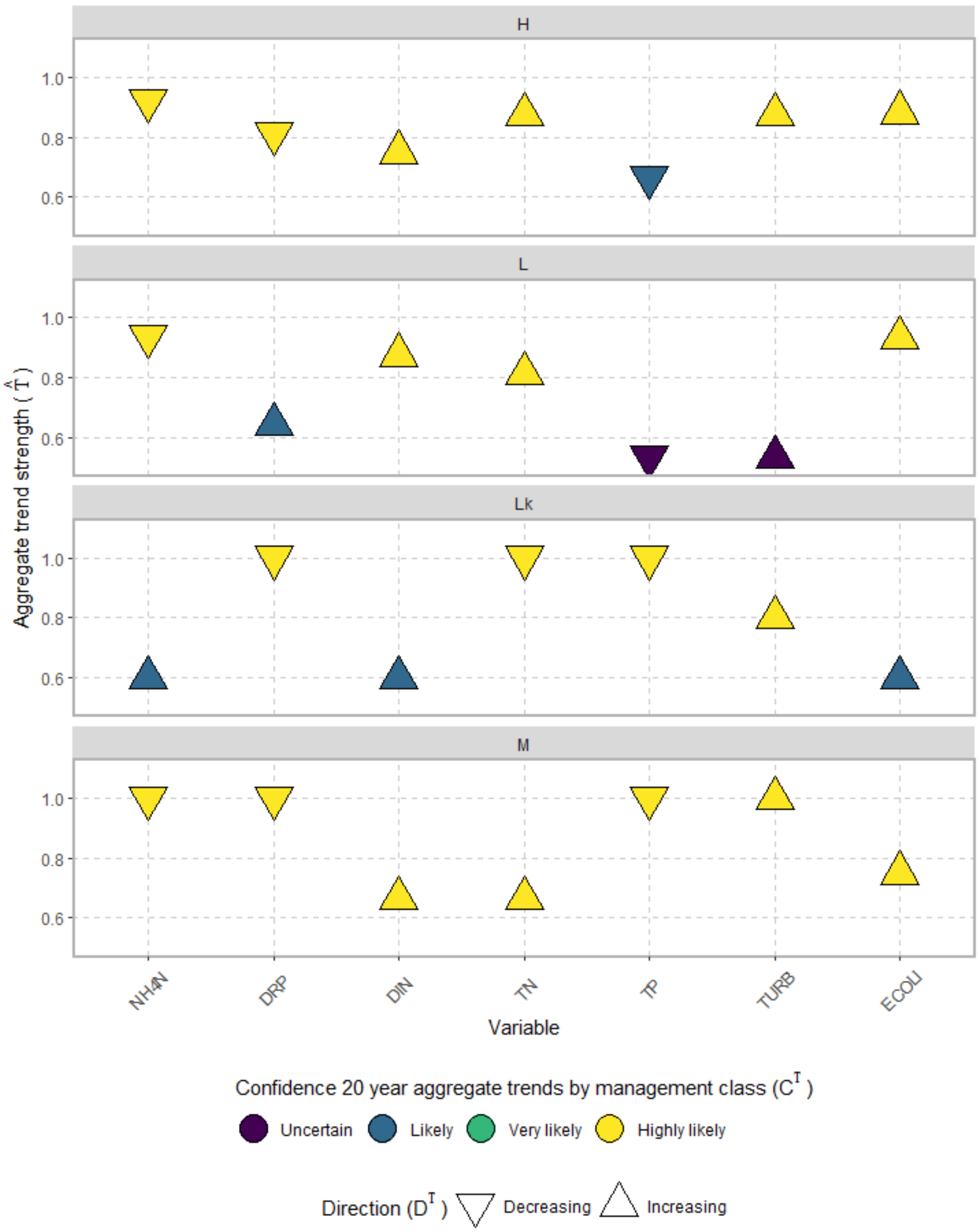

Figure 8. Aggregate trend strength ($\widehat{\boldsymbol{T}}$) and direction ($\boldsymbol{D^T}$) for 20-year trends for the seven water quality variables at the management class level. Confidence in the aggregate direction ($\boldsymbol{C^T}$) is indicated by the four confidence categories (see Table 1 for details). Confidence is shown for calculations that have been corrected for spatial correlation.

Aggregate 10-year trends at the management class level

At the management class level for the 10-year trend period, site numbers were low (i.e., ≤5) for the Lake fed and Mountain classes but were at least 21 for the Lowland and Hill classes (Table 4). Within water quality variables, the direction of the aggregate trend direction varied by management class (Figure 9). For example, DIN predominantly increased at sites in the Hill class but decreased for sites in the Lowland class, whereas TP predominantly decreased at sites in both the Hill and Lowland class.

Table 4. Number of sites included in the analysis of 10-year trends at the management class level.

Variable	Management class			
	H	L	Lk	M
NH4N	21	24	5	5
DRP	25	24	3	5
DIN	22	24	5	5
TN	24	24	4	3
TP	25	24	5	5
TURB	25	24	5	5
ECOLI	25	24	5	5

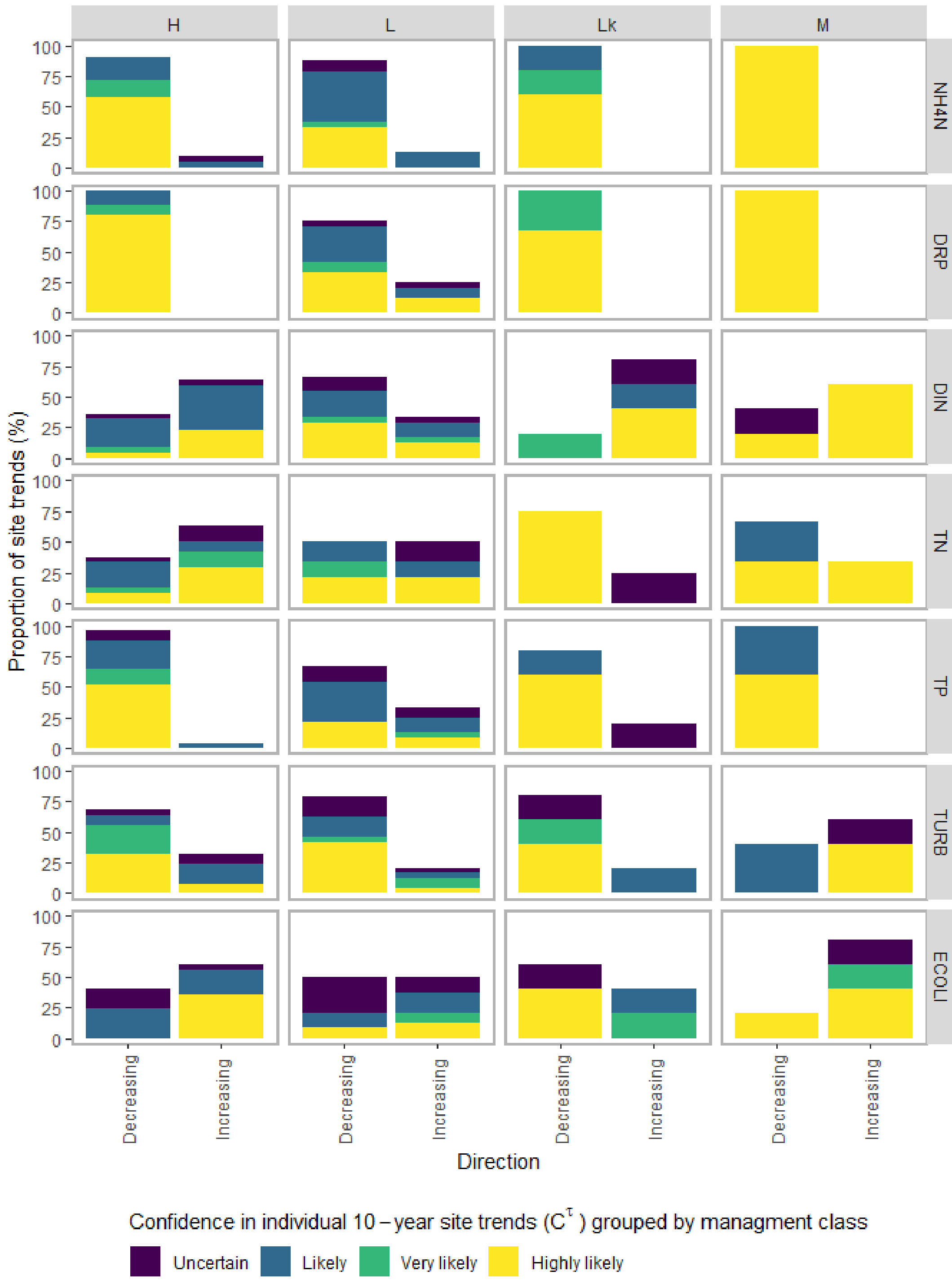

Figure 9. Summary plot showing the proportion of river sites with decreasing and increasing 10-year trends at each categorical level of confidence defined by Table 1 for sites grouped by river management classes.

A compact graphical representation of the results of the aggregate 10-year trends at the management class level is shown in Figure 10 and more detail is supplied separately in “TauRegional10Summary_SRC_OF_FLW.csv". Aggregate 10-year trends at the management class level management class exhibited a variety of directions for some variables. For example, for the Lowland class, the aggregate DIN trend was decreasing ($C^{\mathrm{T}} = Likely$, $\widehat{\mathrm{T}} = 0.65$) whereas the aggregate trend for the Hill class was increasing ($C^{\mathrm{T}} = Likey$, $\widehat{\mathrm{T}} = 0.78$) (Figure 10). More generally, aggregate trends for NH4N, DRP, TP and TURB were decreasing and DIN and ECOLI were increasing in most management classes. This is consistent with the aggregate trend directions for these variables at the regional level (Figure 3).

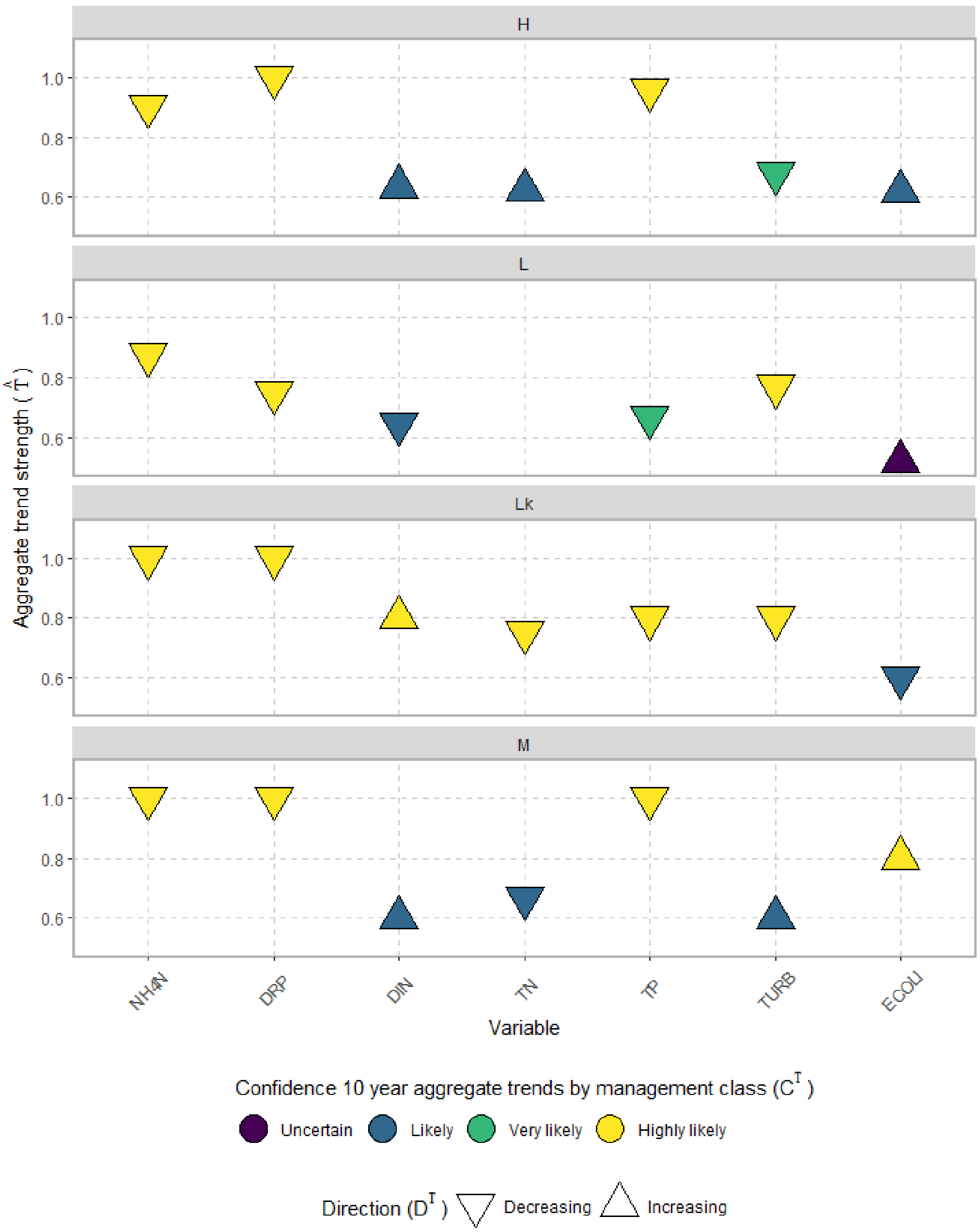

Figure 10. Aggregate trend strength ($\widehat{\boldsymbol{T}}$) and direction ($\boldsymbol{D^T}$) for 20-year trends for 10 water quality variables over all sites. Confidence in the aggregate direction ($\boldsymbol{C^T}$) is indicated by the four confidence categories (see Table 1 for details). Confidence is shown for calculations that have been corrected for spatial correlation.

Discussion

This study has assessed aggregate trend directions, strength and the confidence in the assessed aggregate trend direction in Otago for the 10- and 20-year periods ending June 2022. These analyses are focused on the direction of the aggregate trend as the primary question is whether water quality has improved or degraded. It should be kept in mind that analyses may be very confident about the aggregate trend direction, but the rates of change of most or all of the contributing sites may be small. This study has not taken the extra step of considering rates of change and it is possible that this information is also relevant when making management decisions about taking action to maintain or improve water quality. Information about rates of change at all sites is contained in the outputs of Fraser (2023).

At the regional level, the 20-year river water quality trends indicate appreciable variation in trend direction between sites for all variables but also some general patterns in aggregate trend direction, which differed between variables. A striking aggregate pattern at the regional scale is increasing nitrogen but decreasing phosphorus. These patterns have been identified in New Zealand's river water quality data by previous studies (McDowell et al. 2019; Snelder, Fraser, et al. 2021). Attributing these changes to specific causes is difficult and uncertain. McDowell et al. (2019) suggest that decreasing trends in river DRP and TP concentrations over the last 20 years is attributable to the growing use of mitigation measures to reduce the loss of phosphorus from agricultural land (e.g., shifting from high to low solubility fertilizers). In contrast, increasing trends in NNN and TN are consistent with limitations in the ability to mitigate nitrogen loss from farms (Monaghan et al. 2021) and increasing nitrogen fertilizer use on agricultural land, which is driven by replacement of the formerly dominant sheep industry by dairy farming (Dymond et al. 2013; MFE & StatsNZ 2019).

In a national scale data-driven analysis, Snelder et al. (2021) found that increasing NO3N trends were associated with catchments in which stocking intensity associated with dairy cows and sheep had increased and decreased, respectively. This supports the explanation that replacement of the sheep industry by dairy farming is the cause of increasing riverine nitrogen concentrations. In addition, Snelder et al. (2021) found that decreasing trends in DRP and TP is associated with catchments in which stocking intensity by dairy cows and sheep is high and low, respectively. A plausible explanation for this may be that the implementation of mitigation measures to reduce phosphorus loss has been growing rapidly on dairy farms, which have had the greatest pressure to improve land use management practices under the Dairying and Clean Streams Accord and its successors (Bewsell et al. 2007; Scarsbrook and Melland 2015; Monaghan et al. 2021).

Snelder et al. (2021) also found that at the national level, NH4N has been decreasing over the last three decades and this pattern was evident in the Otago region (Figure 3). Snelder et al. (2021) found that decreasing trends in NH4N was associated with catchments with increasing dairy cow stocking intensity A plausible explanation is the improved management of farm dairy effluent, particularly as dairy farms have intensified and have often been required to upgrade their infrastructure. Over the past 25 years, there has been a widespread shift from discharging dairy effluent directly to streams and drains to land application. This management change may have reduced effluent-derived inputs of NH4N to rivers (Monaghan et al. 2010) and may be the reason for the decreasing aggregate 20-year trend in NH4N at the region level shown in this study.

At the 10-year time scale, this study found that aggregate trends at the regional level were generally consistent with the 20-year counterparts. For example, 10-year aggregate trends at the regional level for NH4N, DRP and TP were decreasing and for DIN, TN and ECOLI were increasing, which is consistent with the 20-year trends. However, this study found that aggregate 10-year TURB was decreasing whereas at the 20-year times scale TURB was increasing. It is known that trends at the 10-year time scale are more strongly influenced by climatic variation within the time period than 20-year trends (Snelder, Larned, et al. 2021). This means that water quality trends, particularly at shorter times scales, should not be interpreted as purely the signal of human activities. The effect of human activity on water quality is confounded by climatically driven variation in catchment processes that influence water quality outcomes such as contaminant mobilisation and biogeochemical transformation. For this reason, caution is advised in attribution of trends of all durations to causes but particularly the 10-year trends presented here.

At the management class level, aggregate 20-year trends were generally decreasing for NH4N, DRP and TP and were generally increasing for DIN, TN, TURB and ECOLI (Figure 8). This is consistent with the aggregate trend directions for these variables at the regional level (Figure 3). This study has no robust basis for attributing deviations in the aggregate trends at the management class level from the more general patterns at the regional level. The directions of the aggregate trends at the management class level are established with high confidence. However, the numbers of sites in each class is relatively low and, coupled with the locations of these sites, the aggregate trends may not be representative of classes. Caution is therefore urged in inferring water quality changes in management classes as a whole, based on the aggregate management class level trends presented here.

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Attachments:

- TauRegional20Summary.csv,
- TauRegional10Summary.csv,
- TauRegional20Summary_SRC_OF_FLW.csv,
- TauRegional10Summary_SRC_OF_FLW.csv]