

Light attenuation in Pelorus Sound in relation to foraging by King Shag

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Executive summary

During the ongoing hearings related to the Marlborough Salmon Farm Relocation Proposal, Mr Rob Schuckard presented evidence in which he argued that the maximum depth to which King Shag could successfully forage by vision falls from about 52 m to about 37 m as chlorophyll concentrations rise from 1 mg m^{-3} to 2 mg m^{-3} . He used those calculations together with results drawn from biophysical modelling (that we have undertaken as part of the Assessment of Environmental Effects for the salmon farm relocation proposal) to suggest that the foraging depths for King Shag might become substantially reduced if the relocated farms were to be developed to the extent implied by some of the scenarios that we examined.

The Ministry for Primary Industries asked us to review Mr Schuckard's evidence – focussing upon evaluating the validity of his assumptions regarding the influence that chlorophyll has upon light attenuation within Pelorus Sound.

As part of the review, I have:

- Given consideration to the coefficients adopted by Mr Schuckard. As a part of that, I have:
 - Examined the relationship between light attenuation inferred from measurements of depth-specific Photosynthetically Active Radiation (PAR) at seven stations within Pelorus Sound.
 - Examined the relationship between light attenuation inferred from measurements of Secchi Disk depth at the same seven stations within Pelorus Sound.
- Given consideration to the manner in which Mr Schuckard has interpreted the results of the biophysical modelling that we undertook for the Salmon Farm Relocation AEE.

My conclusions are as follows:

- Mr Schuckard assumed that the light intensity immediately below the sea surface is 100 lux (R. Schuckard, by email). Unless King Shag preferentially feed around dawn and/or dusk, this figure seems very low. The light intensity under a summer, overcast sky is around 1000 lux. Under a clear sky it can exceed 30,000 lux. Wikipedia suggests that 100 lux would be associated with a 'very dark, overcast day'.
- The estimates of light attenuation derived from direct measurements of depth-specific light intensities in Pelorus Sound and light attenuation derived from Secchi depth in Pelorus Sound corroborate one another.
- Both indicate that light attenuation does increase as chlorophyll concentrations rise, however:
 - Within Pelorus Sound, the slope of this relationship is much shallower (half or less) than Mr Schuckard assumed.
 - The chlorophyll-independent component of light attenuation within Pelorus Sound is around 2.5 times larger than Mr Schuckard assumed.

- Chlorophyll is not the dominant driver of spatial and temporal variability of the light attenuation within Pelorus Sound. (I speculate that fluctuating concentrations of suspended sediment are).
- In consequence, I believe that it is likely that Mr Schuckard has over-estimated the putative light-limited (100 lux) foraging depths of King Shag when chlorophyll concentrations are low, and over-estimated the rate at which this foraging depth declines as chlorophyll concentrations rise.
- Whilst our modelling does indicate that time-averaged chlorophyll concentrations will rise during the mid-spring to mid-summer period, even the largest rise ($<0.1 \text{ mg Chl m}^{-3}$) is small relative to the Sounds-wide median chlorophyll (approx. 1 mg m^{-3}).
- More importantly, it is also small relative to the range of chlorophyll concentrations that have been measured ($0.18 - 5 \text{ mg m}^{-3}$) in the MDC data; the highest chlorophyll concentration that I am aware of from Pelorus Sound region is 25 mg m^{-3} (in Kenepuru Sound).
- Whilst Mr Schuckard is right that farm-feed induced rises in chlorophyll concentrations would result in increased attenuation and decreased putative maximum foraging depths if they were to occur in the regions where the Shag forage:
 - Calculations based upon the Pelorus Sound PAR and Secchi data suggest that the foraging depth loss will be much smaller (in an absolute sense) than Mr Schuckard calculates (but larger in a relative sense – if his sea-surface-level lux value is adopted).
 - The areas where the birds do forage are not the areas where the biggest chlorophyll increases are observed in our AEE biophysical modelling.

Our biophysical modelling indicates that time-averaged spring/summer chlorophylls will rise a little if fish-feed inputs rise. Scenario 13 (which modelled the discharge of 57726 t of feed over an 18 month period) induced a summertime time-averaged chlorophyll increase of $<5\%$ (around 2%) relative to the baseline (24080 t) within the inner-most parts of Pelorus Sound. In absolute concentration terms, this chlorophyll increase amounts to less than $0.1 \text{ mg Chl m}^{-3}$. Elsewhere in the Sound, our modelling suggests that the chlorophyll increments will be smaller. In those parts of the Sound where King Shag are commonly seen, the modelling suggests a time-averaged summer increment of less than 0.04 mg m^{-3} .

There have been suggestions that a reduced baseline ought to have been used. Had we done so, I estimate that the resulting time-averaged summer increment within the innermost parts of Pelorus would be (less than) approximately $0.105 \text{ mg Chl m}^{-3}$ (rounding upwards). Given the uncertainties in the modelling (biophysical and shag-foraging) and the large fluctuations evident in the field measurements of chlorophyll (and other determinants of light attenuations), it is my opinion that (less than) $0.105 \text{ mg Chl m}^{-3}$ is not meaningfully greater than the figure of (less than) 0.1 mg m^{-3} that stems from the baseline that we did use.

Our biophysical modelling indicates that time-averaged spring/summer chlorophylls will rise a little if fish-feed inputs rise. Like the data from the field, the modelling also indicates that chlorophyll concentrations can vary by a factor of two or more across space and time. The additional fish farm inputs change the nature of the spatial variation a little by inducing greater chlorophyll increases in the inner Sound than elsewhere. On the other hand, the increased farm inputs do not materially change the frequency, duration or amplitude of seasonal-scale or weather-scale temporal chlorophyll oscillations. Even in the main channels and central parts of larger bays within Pelorus Sound, chlorophyll concentrations have briefly climbed above 3.5 (and even 5) mg Chl m⁻³ in the past and they are likely to do so again in the future. Our modelling to date indicates that the salmon farms are unlikely to be the primary drivers of such events.

1 Introduction

I am Dr Niall Broekhuizen. I am employed by NIWA as an ecological modeller. I hold a First Class B.Sc. (Hons) in Biology and a Ph.D. in population biology. I am programme leader for NIWA's CORE-funded program *Aquaculture/Environment interactions*. I have worked for NIWA since 1995. I was lead-author for the water-quality modelling reports prepared for the AEE associated with this salmon farm relocation proposal. I also co-authored the aquaculture-related code components within the ROMS-based biophysical models of Queen Charlotte and Pelorus Sounds that were delivered in 2015 and 2016.

I confirm that I have read and am familiar with section 7 of the Environment Court Practice Note 2014 which relates to expert witnesses. I agree to be bound by that Code of Conduct and confirm that I have not omitted to consider material facts known to me that might alter or detract from the opinions that I express in the following evidence. The evidence I give is within my expertise, save where the context indicates otherwise.

The Friends of Nelson Haven and Tasman Bay and Kenepuru & Central Sounds have submitted written comments during the hearings related to the MPI salmon farm relocation proposal for Pelorus Sound. In particular, Mr R. Schuckard presented evidence (Schuckard 2017) concerning the impacts of possible chlorophyll concentration increases upon the foraging of King Shag (*Leucocarbo carunculatus*). In that evidence, Mr Schuckard suggested that:

- The maximum foraging depth will shallow as chlorophyll concentrations rise (from circa 52 m at 1 mg Chl-a m⁻³ to circa 37 m at 2 mg Chl-a m⁻³).

In making those calculations, he relied upon two key assumptions:

- the maximum depth to which King Shag (*Leucocarbo carunculatus*) forage is constrained by light intensity – i.e., that the birds cannot successfully forage for prey in those parts of the water-column where light intensities fall below a critical threshold,
- data concerning dive-depths and corresponding light-intensities gathered for another species of shag (Blue Shag) inhabiting a very different location may be used to infer a plausible threshold light intensity for King Shag. The Blue Shag data are reported in Wanless, Finney et al. (1999).

Having read Wanless, Finney et al. (1999) briefly, it is my impression that they too rely upon an assumption that the maximum dive depths attained by their birds were constrained by light-levels.

Mr Schuckard's evidence seeks to imply that, because the feed loads associated with the proposed farm relocations are higher (in some cases, substantially so), chlorophyll concentrations within Pelorus Sound will rise sufficiently that the depth to which Shags can forage may become materially reduced.

The Ministry for Primary Industries has asked us to review that part of Mr Schuckard's evidence that relates to light attenuation within the water-column of Pelorus Sound.

In this report, I use the term *light attenuation* to refer to the tendency for the intensity of light to decline with depth. In this context, the focus should be upon light that is within the visible spectrum of *L. carunculatus*. Mr Schuckard's evidence appears to implicitly assume that that visible spectrum is identical to the spectrum spanned by so-called photosynthetically active radiation (PAR). In turn, that is not materially different from the spectrum that is visible to humans. Dr David Thompson (NIWA), advises me that he knows of no specific information regarding the visual spectrum of *L. carunculatus*, but he noted that many seabirds may be able to perceive parts of the ultra-violet spectrum that are invisible to us. Nonetheless, I will adopt the implicit assumption that Mr Schuckard made.

1.1 Causes of light attenuation

In water, two processes determine the pattern of light attenuation: (a) absorption and (b) reflection (scattering). The absorbance and scattering properties of a water-body are determined by the nature of the solutes and particulates suspended within the water. A water-body's absorption and scattering properties are termed 'inherent optical properties'. In contrast, light attenuation is an emergent property (dictated by the more fundamental, inherent optical properties).

Even 'pure' water absorbs light-photons, but in most coastal water bodies there are other solutes and particulates that also absorb photons. These include: coloured solutes such as tannins, photosynthetic pigments (such as chlorophyll), the breakdown products of those pigments (e.g., phaeophytins) and (to a lesser extent) many non-photosynthetic particulates.

Particulates within the water-column (particularly fine ones such as clays) are the dominant causes of scattering. Scattering serves to increase the realized path length that an individual particle is likely to have to travel whilst traversing one linear, vertical metre. In a well-mixed water-body, a photon's probability of encountering an absorbing agent is linearly related to the path-length that the photon has accrued. By path-length travelled per vertical metre to increase, scattering increases the probability that a particle will be absorbed before successfully traversing the vertical metre.

The attenuation coefficient is an empirically determined number that has only an indirect relationship to the inherent optical properties. It is usually estimated by measuring light intensities at each of several different depths along a vertical profile, and then fitting an exponential curve to the intensity x depth data.

Pure water absorbs light from the 'red' end of the visible spectrum more strongly than it absorbs light from the 'green' part of the spectrum. Similarly, the majority of other absorbing materials will be more absorptive in some parts of the spectrum than in others. This has two important consequences. Firstly, the spectral characteristics of the light field change as one passes deeper into the water-column (all colours become less abundant/intense, but red light is lost more rapidly than green/blue light). Secondly, the attenuation coefficient for PAR tends to decline as one passes deeper into the water-column (because, at depth, strongly absorbed wavelengths are no longer present to be absorbed!)

2 Key Points from the evidence of Mr Schuckard

For this review, I will focus upon evaluating the calculations which led to Mr Schuckard's statement that maximum shag foraging depths could fall from 52 m to 37 m if chlorophyll levels were to rise from (circa) 1 mg m⁻³ to 2 mg m⁻³ (paragraph 14 of his evidence).

Mr Schuckard presents a graph illustrating the relationship between maximum foraging depth¹ and chlorophyll. Mr Schuckard's evidence does not fully explain how he constructed this graph. I believe that construction of this graph would have required that Mr Schuckard used four coefficients. This was confirmed in a subsequent email from Mr Schuckard (provided to Mr Ben Knight by Mr Rob Schuckard). Specifically, he used the following equations to calculate the light at any given depth:

$$K_{PAR} = K_{bk} + K_{chl}[Chl] \quad \text{equation 1}$$

$$L(z) = L_0 \exp\{-K_{PAR}z\} \quad \text{equation 2}$$

K_{PAR} denotes the overall attenuation coefficient (m⁻¹) for the relevant part of the light spectrum, K_{bk} (m⁻¹) denotes a 'background' light attenuation coefficient, K_{chl} (m² mg Chl⁻¹) determines the manner in which chlorophyll influences total attenuation, and $[Chl]$ denotes the chlorophyll concentration (mg Chl m⁻³). $L(z)$ denotes the light intensity (lux) at depth z below the surface, L_0 (lux) denotes the light intensity immediately below the sea-surface. Note that this equation implicitly assumes that K_{bk} , K_{chl} and $[Chl]$ are constant throughout the depth-range. In reality, these assumptions will often be invalid.

Equation 2 can be used to calculate a putative maximum foraging depth by setting $L(z)$ to a nominated value (L_{thresh} (lux, the chosen threshold minimum light intensity for foraging)) and re-arranging the equation so that it can be solved for the depth (z_{thresh}) at which the light intensity is equal to L_{thresh} :

$$z_{thresh} = \frac{-\ln\left(\frac{L_0}{L_{thresh}}\right)}{K_{PAR}} \quad \text{equation 3}$$

Mr Schuckard's evidence makes clear that he chose to set $L_{thresh}=0.5$ Lux but he provides no information regarding the values of the other coefficients. I am not an expert in bird vision or Shag foraging, so I cannot evaluate the merit of his choice. I will however note that there is scope for confusion within the paper that he cites (Wanless, Finney et al. 1999). The figure of 0.5 lux derives from the figure -0.3 log₁₀ lux (appearing in the abstract and in first paragraph of page 222). Elsewhere in the same paper, a figure of -1.3 log₁₀ lux (0.05 lux) is used (third paragraph of Results and first paragraph of Discussion). In all cases the values appear to be for Blue-eyed shag (cf European shag – which also appears in the paper). Figure 2a of the Wanless paper indicates that some Blue-eyed shag did forage at light levels of <0.1 lux, but in Figure 3a, the lowest light intensity illustrated is > 0.3 lux. Thus, I cannot determine whether 0.5 lux or 0.05 lux was the value that Wanless, Finney et al. (1999) deduced for Blue Eyed Shag.

Mr Ben Knight asked Mr Schuckard what values he had adopted for the remaining three coefficients. Mr Schuckard responded in an email to Ben Knight dated 14/5/2017. Mr Schuckard replied to the effect that he adopted:

$$L_0=100 \text{ lux}$$

¹ The title of the graph refers to diving depth but the context implies that he is referring to foraging depth

$$K_{bk}=0.06 \text{ m}^{-1}$$

$$K_{chl}=0.042 \text{ m}^2 (\text{mg Chl})^{-1}$$

The value for L_0 is surprisingly low. Wikipedia (<https://en.wikipedia.org/wiki/Lux>; see also <http://skyeinstruments.com/wp-content/uploads/LightGuidanceNotes.pdf>) suggests that light intensity can reach 30,000-100,000 lux on a clear-sky, summer day. Even under over-cast conditions, the light intensity can reach 1000 lux (Wikipedia). Even after accounting for some reflection at the sea-surface (up to 20% (Kirk 1983)), Mr Schuckard's figure seems very low – unless the shags feed preferentially around dawn and dusk? By adopting $L_0=100$ lux, I have successfully duplicated Mr Schuckard's two critical foraging depths (52 m and 37 m at 1 and 2 mg Chl m^{-3} respectively). Thus, I am satisfied that that is the figure he used. Accordingly, I will also adopt that figure.

In a later section of this report, I will address the coefficients K_{bk} and K_{chl} but first I will discuss what relevant data exist for Pelorus Sound.

3 Analysis of field data concerning light attenuation in Pelorus Sound

Marlborough District Council have sampled water-quality (including chlorophyll concentrations and concentrations of total suspended sediment) at seven stations in Pelorus Sound (Figure 3-1). Most of the stations are in the centres of the main channels or larger bays of the Sound and none are within small side-bays. Sampling has been at (roughly) monthly intervals since July 2012.

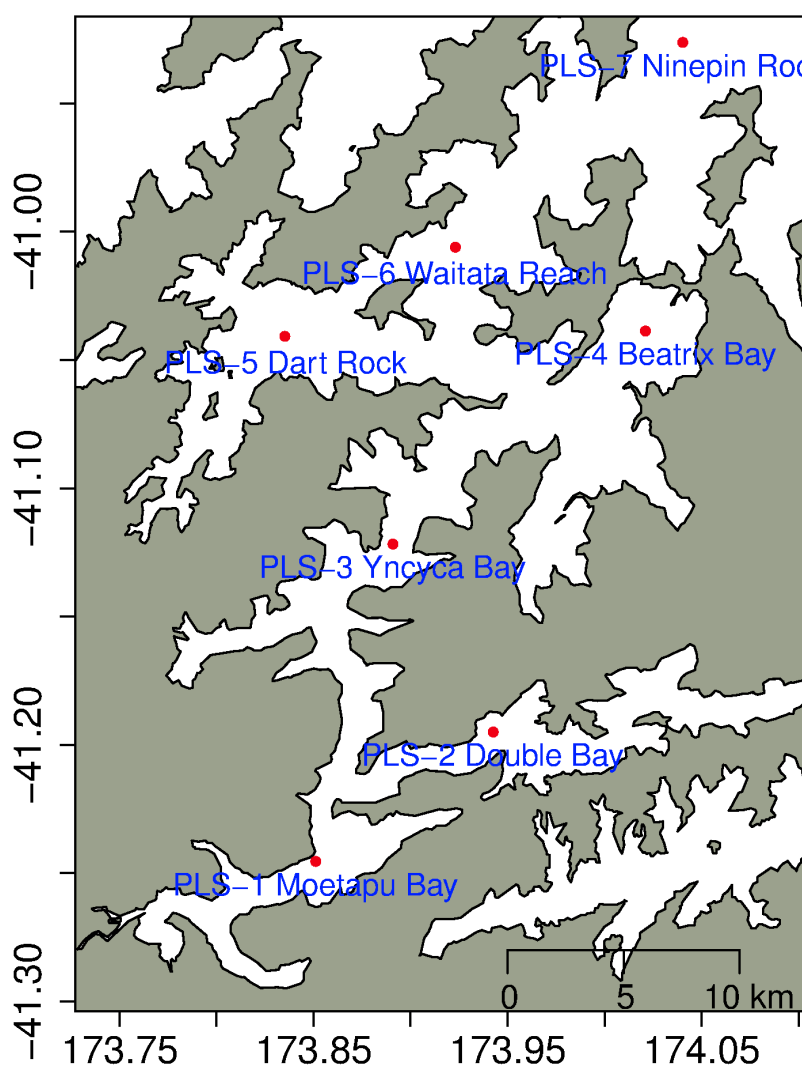


Figure 3-1: Map illustrating the locations of the Marlborough District Council sampling stations.

At each station, they take a surface water sample. At most stations, they have also taken a near-bed water sample. From July 2012-June 2014, they used a Van Dorn bottle to take both the near-surface and near-bed samples. Those near-surface samples were taken at approximately one metre below sea-surface, and the near-bed one approximately one-four meters above the bed. From July 2014, the pattern of near-surface sampling changed. Instead of using a Van Dorn, a 'hose-sampler' was adopted. This extends to approximately 15 m below the surface and takes an integrated sample of water from that entire depth range. Sites PLS-1 (Mahau Sound) and PLS-2 (Kenepuru) are in water <

15 m deep. At these sites, the hose sampler was lowered to within approximately 1 m of the bed. The near-bed sampling at these sites was stopped when hose-sampling was begun.

Several water-quality variables are measured within each water sample. These include: concentrations of major nutrients, suspended solids (surface samples only), turbidity, chlorophyll, organic detritus etc.). At each station, Marlborough District Council also:

- measure the Secchi disk depth,
- make a vertical case through the water-column using a probe that measures conductivity, temperature and pressure (conductivity provides a measure of salinity, pressure provides a measure of instrument depth; thus, the instrument is known as CTD-probe). The CTD frame was also fitted with a sensor to measure photosynthetically active radiation (PAR, $\mu\text{E m}^{-2} \text{s}^{-1}$).

3.1 Chlorophyll

Figure 3-2 illustrates the probability distributions for the chlorophyll concentrations which have been measured at each of the seven water-quality monitoring stations within Pelorus Sound.

Concentrations have ranged from 0.18 – 5.1 mg Chl-a m^{-3} . They tend to be greater at the two inner-most stations (PLS-1 and PLS-2). At all sites, the majority of records have been less than 2 mg m^{-3} . The Sounds-wide median is around 1 mg m^{-3} .

There have been many other chlorophyll measurements within Pelorus Sound on earlier dates in other sampling programmes. I will not review those data for this report, but I will note that, to the best of my knowledge, (by far) the highest chlorophyll concentration recorded within Pelorus Sound was circa 25 mg Chl m^{-3} (Kenepuru Sound, 1983. MacKenzie, Kaspar et al. 1986). Clearly, chlorophyll concentrations are very variable in both space and time within Pelorus Sound.

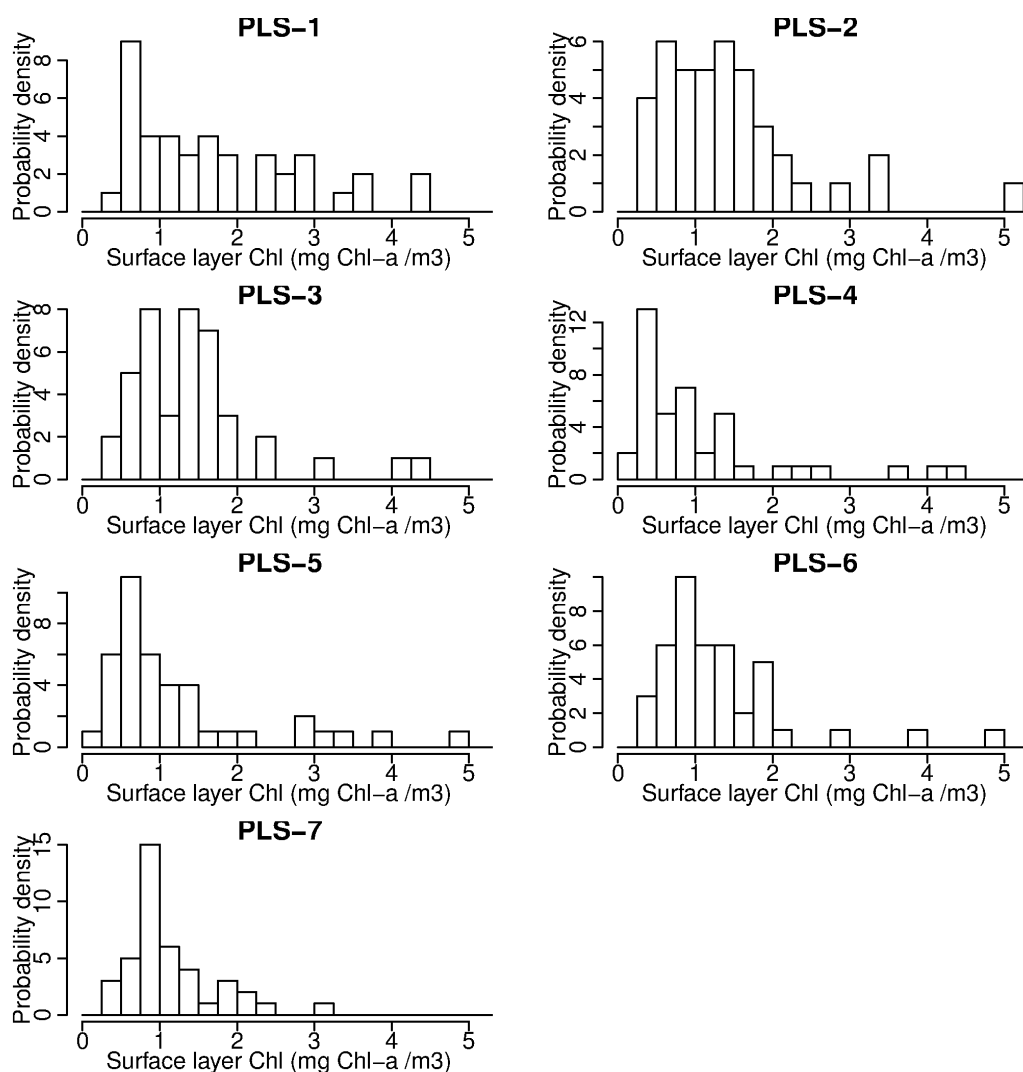


Figure 3-2: Probability density histograms illustrating the distribution of chlorophyll concentrations measured within Pelorus Sound by Marlborough District Council. The histograms include measurements made in the upper 15 m of the water-column and measurements made close to the seabed.

3.2 Analysis of the CTD & PAR sensor data

The CTD and PAR sensors the Marlborough District Council use make measurements at regular time intervals (every few seconds). Depths can be inferred from the pressure records. Thus, it is possible to pair each PAR measurement with a depth measurement.

Some time ago, my colleague Dr David Plew (NIWA) derived estimates of the diffuse-light attenuation coefficient (K_{PAR}) at each station on each sampling occasion for the months July 2012–July 2013 inclusive. PAR-sensor data collected from Aug 2013 onwards have not yet been analysed and there was insufficient time to process them for inclusion within this report.

Data from the upper five metres were excluded – because wave-induced ‘flecking’ tends to cause near-surface PAR values to fluctuate wildly. Similarly, in cases where the data were clearly anomalous (e.g., PAR rose abruptly at some depth rather than continuing to decline, or remained stable across several depths) were also discarded. Anomalies of this sort are not necessarily

indicative of instrument failures – ship shadows etc., can induce these sorts of artefact. A total of 28 casts were deleted. 13 of these came from the inner-most site (site PLS-1 within Mahau Sound). Indeed, there were no useable casts made at PLS-1.

Linear regression was used to relate the natural logarithm of measured light intensity to the natural logarithm of depth (expressed in metres). The slope of the regression line is the value of K_{PAR} at the station on the given date. Time-series of the inferred values for K_{PAR} are presented in Figure 3-5. The inferred values range between 0.11 and 0.40 m^{-1} . The values at site PLS-2 tend to be higher than those further out into the Sound, but the values at all the sites are temporally variable. Vincent, Howard-Williams et al. (1989) report measurements of light attenuation at three stations within Pelorus Sound. They recorded values of about 0.2 m^{-1} close to Yncyc Bay, around 0.25 m^{-1} within Kenepuru and around 0.5 m^{-1} within Mahau Sound. Those values are broadly consistent with the ones inferred from the MDC data.

It is possible to use linear regression to fit equation 1 to the K_{PAR} and chlorophyll data (for this purpose, I use the average of near-surface and near-bed chlorophyll measurements (where both exist) rather than only the near-surface ones). The best-fit equation proves to be:

$$K_{PAR(Plw)} = 0.16 + 0.012[Chl] \quad \text{equation 4}$$

Four points are worth noting:

- a) The best fit value for K_{chl} (0.12) is about one quarter of that adopted by Mr Schuckard.
- b) The 95% confidence limits for this slope include zero (0.06 – 0.30). It is significantly smaller than Mr Schuckard's chosen value (indeed, it does not differ significantly from zero).
- c) The best fit value for K_{bk} (0.16) is almost three times larger than the value adopted by Mr Schuckard.
- d) This equation was derived from the measurements made at depths greater than 5 m below the sea-surface. In the shallower water, the apparent K_{PAR} would be higher because the light would still contain photons from some of the more strongly absorbed parts of the visible spectrum.

The second and third of these three points suggest that factors other than chlorophyll play a large role in determining K_{PAR} . In the next section, I will present evidence that demonstrates suspended sediment is one such factor.

I have not undertaken a formal literature survey, but it is my impression that the fitted value for K_{chl} is towards the lower end of values that would be found in the literature. Conversely, I believe that Mr Schuckard's value is towards the upper end. It is my informal impression that values around 0.02 to 0.03 $m^2 (mg chl)^{-1}$ are most common in the literature. Given that the coefficient K_{chl} is not significantly different from zero, it is not clear that it is appropriate to use equation 4 to predict K_{PAR} or infer a putative maximum foraging depth. Nonetheless, I have done so (see section 4).

The key conclusions from this analysis are (estimated at depths > 5 m):

- Factors other than chlorophyll appear to be the dominant determinant of spatio-temporal variations in K_{PAR} across the range of chlorophyll concentrations that has been observed to date in The MDC sampling.

- There is evidence that the light attenuation coefficient (measured at depths >5 m) is positively correlated with chlorophyll concentrations – but the slope of the relationship appears to be substantially shallower than the one adopted by Mr Schuckard.

3.3 Analysis of Secchi depth

A Secchi disk is a circular disk (usually about 30 cm diameter) in which alternating quadrants are painted black or white. The disk is lowered into the water and the ‘Secchi disk depth’ is the depth at which a human observer determines that the disk is no longer visible. Secchi disk depths are imprecise. Different observers may determine that they have lost sight of the disk at different depths. Wave conditions, the angle of elevation of the sun in the sky and cloud cover are other factors that have been shown to influence the Secchi disk depth. Despite the imprecise nature of Secchi disk measurements, they are widely used and have been shown to be correlated with other measures of water clarity – including the light attenuation coefficient. In particular, Kirk (1983) (citing Poole, Atkins (1929)) suggests that the relationship:

$$K_{PAR,Secchi} = 1.44/SecchiDepth \quad \text{equation 5}$$

is often useful.

The raw time-series of Secchi disk data are presented in Figure 3-3. Secchi disk-depths tend to rise as one progresses from the inner-most stations (PLS-1 & PLS-2) to the outer-most ones (PLS-6 & PLS-7). The shallowest Secchi depths (<2 m) have been recorded at the two inner-most stations (PLS-1 and PLS-2). Elsewhere, most records have been in the range 6-10 m. The maximum recorded values are around 15 m. Secchi disk depth is very variable at all stations.

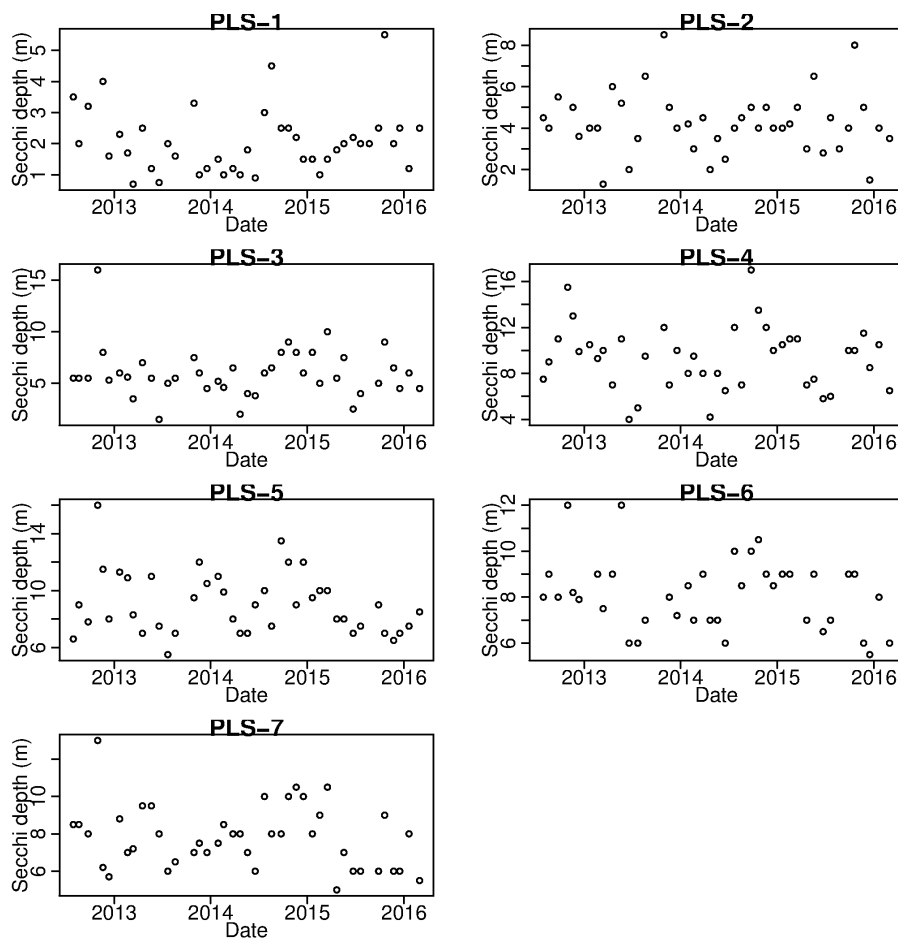


Figure 3-3: Secchi disk depths recorded at seven stations within Pelorus Sound.

Figure 3-4 presents scatter plots that illustrate the manners in which Secchi depth is correlated with measures of suspended sediment abundance (turbidity, total suspended solids, volatile suspended sediment) and chlorophyll.

It transpires that:

- Secchi disk depth declines with increasing concentrations of total suspended solids² (TSS, turbidity).
- Secchi disk depth declines (weakly) with rising concentrations of volatile suspended solids (a measure of total organic matter).
- Secchi disk depth also declines with increasing concentrations of chlorophyll.
- The inverse relationship between Secchi disk depth and TSS (or turbidity) is stronger than that with chlorophyll.

² The mass of total suspended solids are dominated by inorganic particulates, however TSS also includes organic material such as living and dead algae.

Whilst I have not made a detailed analysis, I believe that much of the variation in TSS is driven by factors unrelated to aquaculture (e.g., rainfall driving sediment inputs from the catchment and winds causing resuspension of sediments in some parts of the Sound).

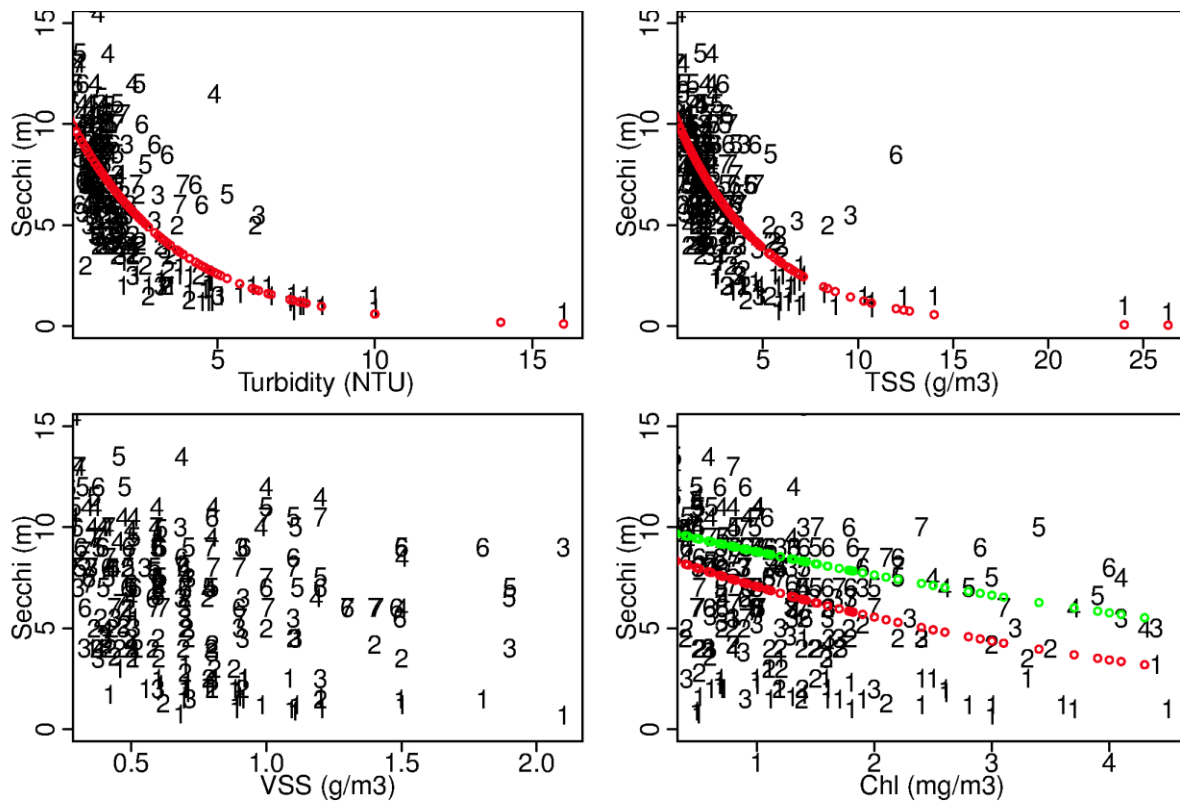


Figure 3-4: Scatter plots illustrating the manners in which Secchi disk depth is related to a variety of water-quality parameters. Black numerals are the raw data (the numeral denotes the sampling station). Red symbols illustrate least-squares exponential regression curves through all of the data. The green symbols illustrate the best fit regression through the data stemming from only stations PLS-3 to PLS-7 (inclusive).

I have used equation 5 to infer values of $K_{PAR,Secchi}$. The resultant time-series of inferred values are illustrated in Figure 3-5. The $K_{PAR,Secchi}$ values inferred from Secchi disk depths are broadly similar to those inferred from light profiles ($K_{PAR,Plew}$) - but the Secchi disk depth values do tend to be a bit higher. The slope of the linear regression curve that relates $K_{PAR,Secchi}$ to $K_{PAR,Plew}$ is approximately 2.1 – indicating that factors which tend to drive $K_{PAR,Plew}$ upwards have an even greater impact upon $K_{PAR,Secchi}$.

The finding that $K_{PAR,Secchi}$ tends to exceed $K_{PAR,Plew}$ is not unexpected. Firstly, Kirk (1983) cautions that equation 5 will tend to over-estimate K_{PAR} in waters that contain a lot of suspended sediments. He does not specify what ‘a lot’ means in this context, but it is not unreasonable to believe that sites PLS-1 and PLS-2 (and perhaps, even the other sites) fall into that class. Secondly, $K_{PAR,Secchi}$ is calculated from measurements made across the upper-most few metres of the water-column. In contrast $K_{PAR,Plew}$ relies upon measurements made at depths \geq five metres below the

surface. Given that we know that the most-strongly absorbed wavelengths will have been removed before the light reaches five metres, it is reasonable that $K_{PAR,Secchi}$ exceeds $K_{PAR,Plow}$. Indeed, one might argue that two estimates of K_{PAR} corroborate one another.

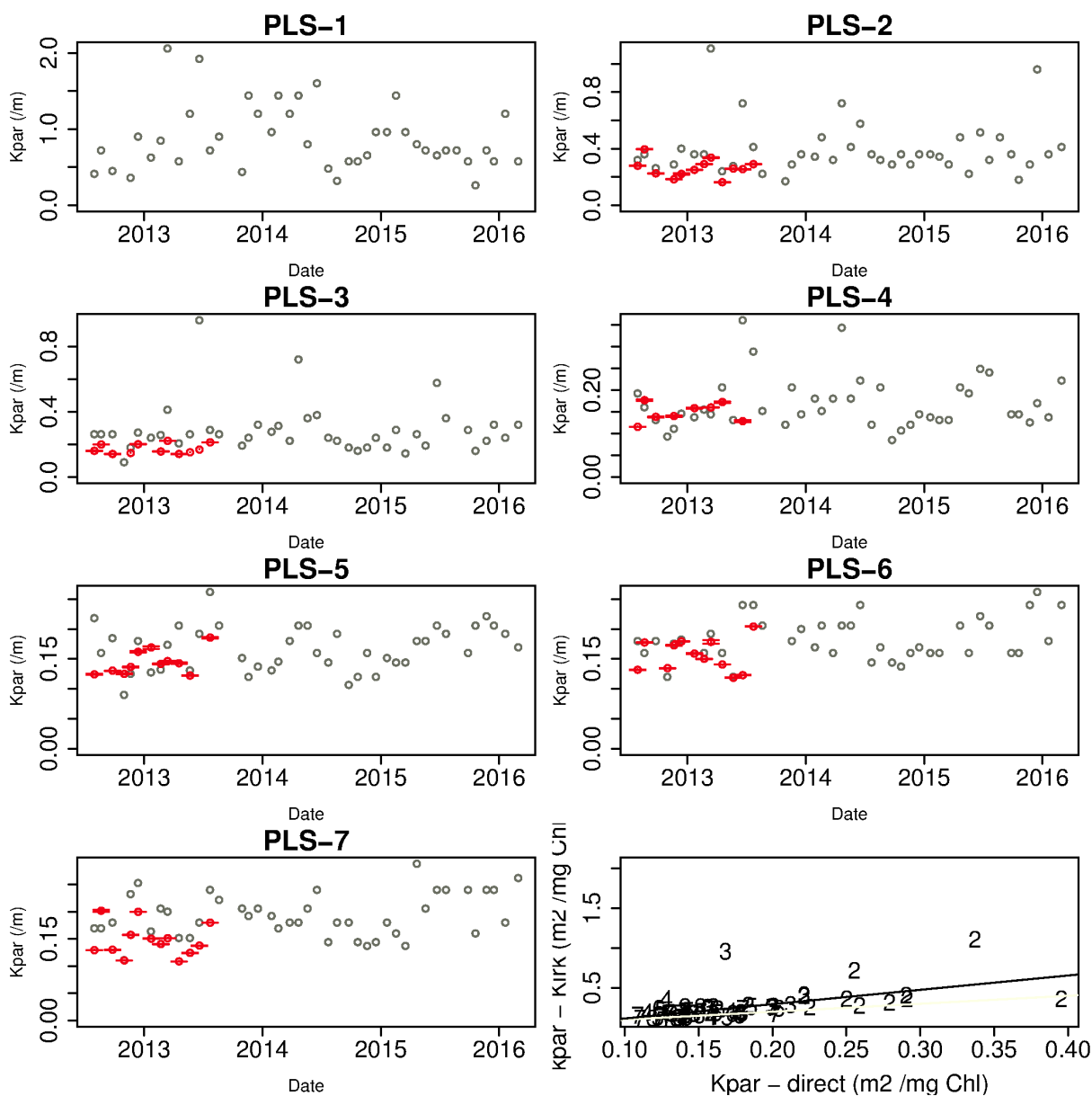


Figure 3-5: Time-series of K_{par} inferred from Secchi depth (black symbols) and from measurements of depth-specific light intensities (red symbols). The correlation between the two measures of K_{par} is shown in the bottom left plot. Numerals indicate station numbers. The black line is the least-squares linear fit through the data. The grey line is the 1:1 line.

The relationship between $K_{PAR,Secchi}$ and near-surface chlorophyll is illustrated in Figure 3-6. Stations PLS-1 & PLS-2 stand out as having unusually high attenuation coefficients (in an absolute sense and relative to values inferred from the corresponding chlorophyll concentrations). These high values are probably induced by the high suspended sediment concentrations that are found at these two sites.

I have used least-squares linear regression to determine how chlorophyll influences $K_{PAR,Secchi}$. Two different regressions were undertaken (red and green symbols in Figure 3-6). In the first (red symbols), I used the data from all stations. In the second (green symbols), I excluded data from stations PLS-1 & PLS-2. Given that: (a) Mr Schuckard's evidence indicates that King shag do not forage in the vicinities of stations PLS-1 & PLS-2, (b) the attenuation coefficients at those two stations are markedly greater than those measured in the regions where the shags do forage, it appears more appropriate to adopt the regression line corresponding to the green symbols when discussing possible implications for King Shag foraging. This best fit line through the data from stations PLS-3 to PLS-7 (green symbols) is:

$$K_{PAR,Secchi} = 0.15 + 0.019[Chl] \quad \text{equation 6.}$$

Both coefficients are significantly greater than zero. The slope of the relationship (0.019; 0.09-0.19 95% confidence intervals) is greater than that calculated for the relationship between $K_{PAR,Plew}$ but remains well below (about half of) the slope adopted by Mr Schuckard.

The key conclusions from this section are similar to those from the preceding section:

- Secchi depths (and, by inference, light attenuation) are spatially and temporally variable.
- Chlorophyll is not the dominant driver of this variability.
- Nonetheless, Secchi disk depths do tend to fall as chlorophyll concentration rises. A plausible inference is that the light attenuation will rise in consequence.
- Data from Pelorus Sound indicate that Mr Schuckard's calculations adopt an over-estimate of the influence that chlorophyll has upon light attenuation.

By also taking into account the findings from the analysis of the PAR data (3.2), a further important conclusion can be reached:

- Two (almost) entirely independent means of estimating the relationship between K_{PAR} and chlorophyll within Pelorus Sound have both yielded slopes which are substantially smaller (closer to zero; half or less) than the slope adopted by Mr Schuckard.

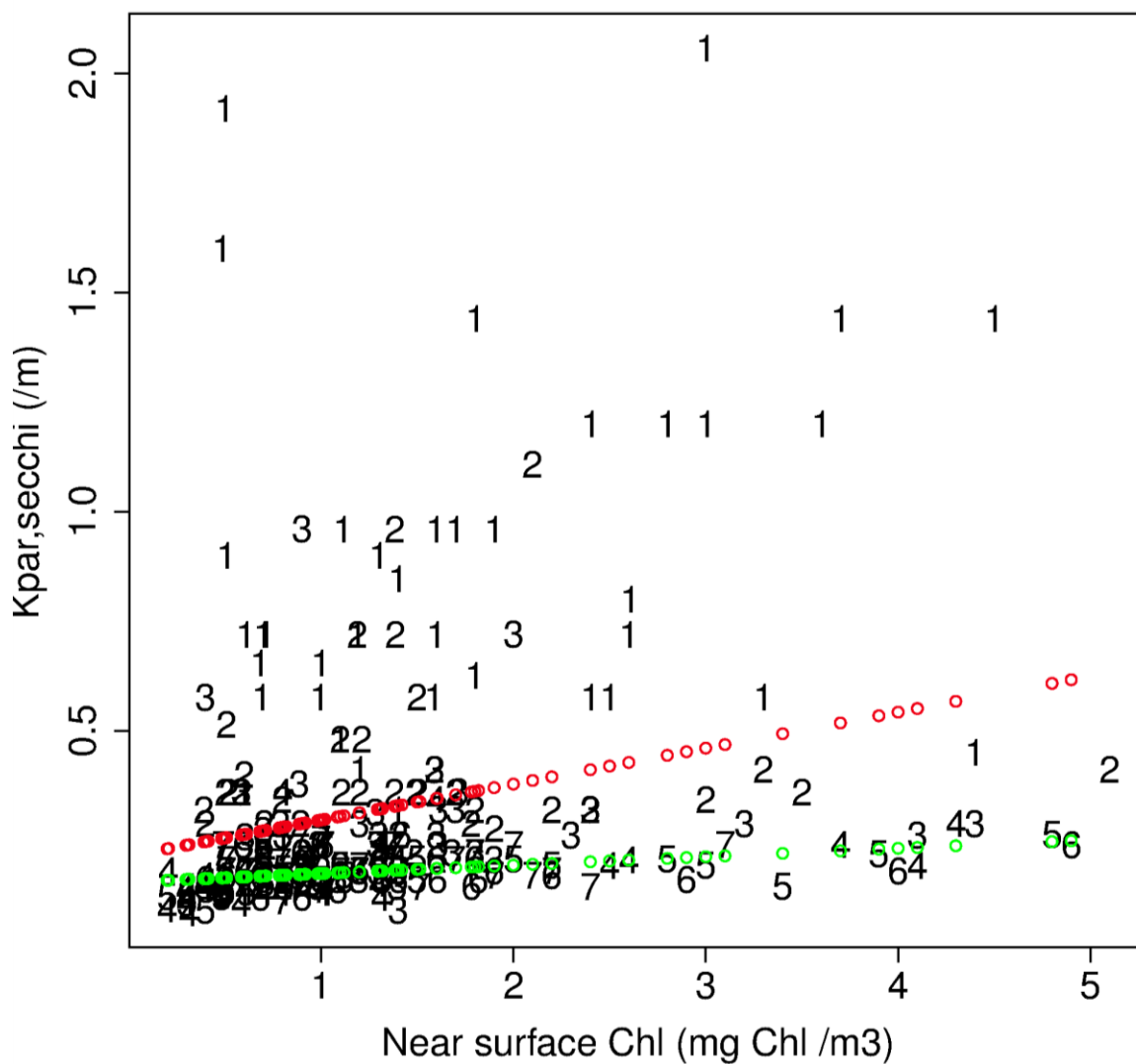


Figure 3-6: Scatter-plot illustrating the relationship between $K_{PAR,Secchi}$ and near-surface chlorophyll concentration. Numerals indicate the station. The red symbols illustrate the best fit linear regression - using all of data. The green symbols illustrate the least-squares linear regression fitted thorough the data from stations 3-7.

4 Light attenuation, chlorophyll and putative foraging depths

In this section, I use Mr Schuckard's methods to determine the relationship between chlorophyll concentration and putative maximal foraging depths of King Shag. I repeat the calculations three times. First, I adopt his K_{PAR} -Chl relationship (equation 1 with $K_{bk}=0.06 \text{ m}^{-1}$.

$K_{chl}=0.042 \text{ m}^2$). Second, I adopt the $K_{PAR,plew}$ -Chl relationship (equation 4). Third, I adopt the $K_{PAR,Secchi}$ -Chl relationship (equation 6).

Figure 4-1a illustrates the K_{PAR} -Chl relationships for each of the comparisons. Figure 4-1b illustrates the resultant putative Shag maximal foraging depths.

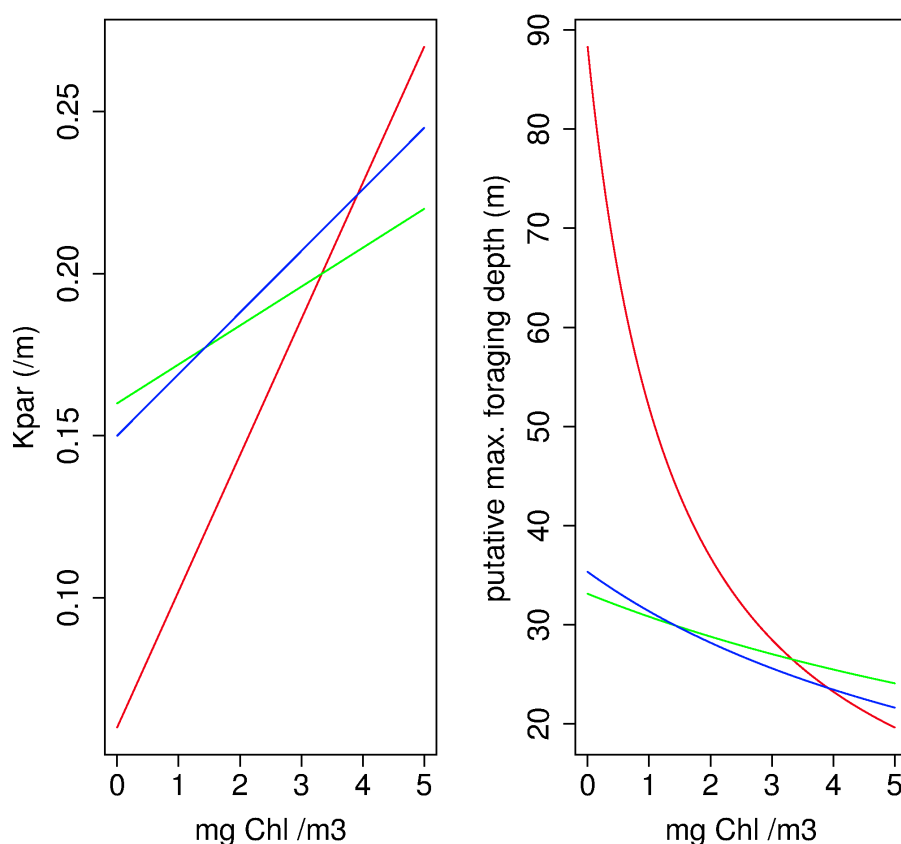


Figure 4-1: K_{par} : Chl relationships adopted by Schuckard and implied by field data from Pelorus Sound (left) and corresponding putative maximum foraging depths (right). The red lines indicate Schuckard's relationships. The green ones indicate the relationships derived from $K_{PAR,plew}$ and blue ones indicate the relationship stemming from $K_{PAR,Secchi}$. When calculating the foraging depths, I have followed Mr Schuckard's practice and assumed that the light intensity immediately below the sea-surface is 100 lux. In section 2 I cautioned that this value seems very low (10 times or more) – unless the shags preferentially forage around dawn and dusk.

The $K_{PAR,Plow}$ -Chl and $K_{PAR,Secchi}$ -Chl are more similar to one-another than either is to Mr Schuckard's K_{PAR} -Chl relationship. As has already been noted, the influence that chlorophyll has upon K_{PAR} is much stronger in Mr Schuckard's calculations than appears to be the case for Pelorus Sound (Figure 4-1a). Consequently, the putative foraging depths calculated using Mr Schuckard's relationship decline much more rapidly than those calculated using $K_{PAR,Plow}$ -Chl or $K_{PAR,Secchi}$ -Chl relationships. At chlorophyll concentrations lower than approximately $3.5 \text{ mg Chl m}^{-3}$, Mr Schuckard's relationship yields deeper putative foraging depths than the two other relationship do. For chlorophyll concentrations greater than approximately 3.5 mg m^{-3} , Mr Schuckard's relationship yields shallower foraging depths.

A corollary of the fact that the slopes of the $K_{PAR,Plow}$ -Chl and $K_{PAR,Secchi}$ -Chl relationships are much shallower than the slope adopted by Mr Schuckard is that they yield a smaller foraging depth decrement per unit chlorophyll increment than Mr Schuckard's relationship yields. Mr Schuckard calculated that the foraging depth drops from approximately 52 m at 1 mg Chl m^{-3} to approximately 37 m at 2 mg Chl m^{-3} (a decline of about 15 m). Using the $K_{PAR,Secchi}$ -Chl and $K_{PAR,Plow}$ -Chl relationships the corresponding critical depths are around 31 m and 28 m (a decline of about 3 m).

It is worth noting that even the deepest putative foraging depths stemming from the $K_{PAR,Plow}$ -Chl and $K_{PAR,Secchi}$ -Chl relationships are less than about 40 m. King Shag are known to dive to depths greater than 40 m. There are at least three possible explanations for this discrepancy:

- The dives in question were made under conditions of unusually high water clarity.
- King Shag are able to perceive prey at light intensities lower than that assumed by Mr Schuckard (either because they have better-than-assumed low-light vision, or because they are not reliant upon vision to locate prey).
- King Shag hunt at times of the day when the surface light intensity is somewhat greater than Mr Schuckard's chosen value of 100 lux (i.e., not around dawn and dusk). Even under over-cast conditions, the surface light intensity can reach 1000 lux (<https://en.wikipedia.org/wiki/Lux>). At that light intensity the respective maximum putative foraging depths would be more than two times greater than I (or Mr Schuckard) have calculated!
- The approximations inherent in all three sets of calculations are such that deep-water light intensities cannot be accurately reproduced. Recall that the calculations rely upon assuming that K_{bk} , K_{Chl} and $[Chl]$ are constant throughout the depth of the water-column. These assumptions are often violated in the real-world.

The key conclusions are:

- Data from Pelorus Sound indicate that chlorophyll has a much weaker influence upon light attenuation than Mr Schuckard has assumed.
- Consequently, whilst the putative foraging depths are still predicted to shallow as chlorophyll concentrations rise, the rate of shallowing is smaller and the quantum of foraging-depth-loss is likely to be substantially less than Mr Schuckard calculated (around 3 m rather than 15 m for the transition from $1\text{-}2 \text{ mg Chl m}^{-3}$).

- Unless King Shag forage preferentially at dawn and dusk, I believe that the sea-surface light intensity adopted by Mr Schuckard is likely to be unrealistically low – such that foraging depths are under-estimated – in his calculations and mine.

5 Comments in relation to our biophysical modelling and shag foraging

Mr Schuckard correctly states that our modelling indicates that time-averaged summertime chlorophyll concentrations will rise in response to increased feed inputs. Even under the largest feed-input scenario, the time-averaged summertime (strictly speaking, mid-spring to mid-summer) is predicted to be less than $0.1 \text{ mg Chl m}^{-3}$ relative to the baseline that we used. Table 5-1 illustrates the magnitudes of foraging depth decrement (loss) associated with a 0.1 mg m^{-3} concentration rise for nominal summer chlorophyll concentrations of 1 and 2 mg chl m^{-3} . The foraging depth losses range from about 2 m (about 4% of the initial foraging depth) using Mr Schuckard's relationship to 0.3 m (about 10% of the initial foraging depth) using the relationships that I have derived.

Table 5-1: Putative foraging depths and magnitudes of foraging depth loss at a chlorophyll increment of 0.1 mg m^{-3} .

Chlorophyll change (mg m^{-3})	Slope of Kpar:Chl relation	Foraging depth at lesser chlorophyll (m)	Foraging depth at greater chlorophyll (m)	Difference (m)
1.0 -> 1.1	0.042 (Schuckard's)	51.9	49.9	2.05
1.0 -> 1.1	0.012 (from CTD/PAR profiles)	30.4	30.2	0.21
1.0 -> 1.1	0.019 (from Secchi data)	31.3	31.0	0.34
2.0->2.1	0.042 (Schuckard's)	36.79	35.75	1.04
2.0->2.1	0.012 (from CTD/PAR profiles)	28.47	28.29	0.18
2.0->2.1	0.019 (from Secchi data)	28.17	27.88	0.28

The calculations in Table 5-1 assume that the chlorophyll increments arising from additional fish feed will develop in areas where the shags forage. Our modelling suggests that the biggest increments will arise within inner Pelorus (Kenepuru and Mahau Sounds). Mr Schuckard's evidence suggests that King Shag are not often seen in those areas. Our modelling suggests that the chlorophyll increments will be much smaller in those parts of Pelorus when the shags are commonly seen.

It has been suggested that the baseline which was adopted for our biophysical modelling was inappropriate because it included inputs from farms which have not been operated in recent years (the Crail Bay farms). Had we adopted that 'reduced baseline', the total 'reduced baseline' feed inputs would have been about 1660 tonne (<10%) lower than those used in our baseline. The simulations presented in our modelling report indicate that there is a near linear positive relationship between summer time-average chlorophyll and feed inputs. A 2.4 fold increase in feed inputs (scenario 13 relative to baseline) induced a summertime time-averaged chlorophyll increase of <5% (around 2%) relative to baseline. Were scenario 13 to have been compared against this 'reduced baseline', the summertime chlorophyll increment (scenario13 vs 'reduced baseline') would certainly have been larger, but I do not believe they would have been meaningfully larger. The summertime chlorophyll increment associated with moving from our baseline to scenario 13 is less than $0.1 \text{ mg Chl m}^{-3}$ (<5% of baseline) – yet scenario 13 had feed inputs which were 2.4 times greater than those

of our baseline. This implies that a 10% increase in feed inputs yields a chlorophyll increase of less than $0.004 \text{ mg Chl m}^{-3}$. Thus, a 10% feed decrease (which exceeds what is required to achieve the 'reduced' baseline) will yield a decrement (relative to the present baseline) of about $0.004 \text{ mg Chl m}^{-3}$. We can add that figure onto the baseline:scenario13-increment figure ($<0.1 \text{ mg m}^{-3}$) to derive an estimate of the possible increment relative to the 'reduced baseline'. Rounding upwards, the resulting figure is approximately $0.105 \text{ mg Chl m}^{-3}$. In my opinion that is not a meaningfully larger number than 0.1 mg m^{-3} given the uncertainties in the modelling (biophysical and shag-foraging) and the large fluctuations evident in the field measurements of chlorophyll.

Our biophysical modelling indicates that time-averaged spring/summer chlorophylls will rise a little if fish-feed inputs rise. Like the data from the field, the modelling also indicates that chlorophyll concentrations can vary by a factor of two or more across space and time. The additional fish farm inputs change the nature of the spatial variation a little by inducing greater chlorophyll increases in the inner Sound than elsewhere. On the other hand, the increased farm inputs do not materially change the frequency, duration of amplitude of seasonal-scale or weather-scale temporal chlorophyll oscillations. Even in the main channels and central parts of larger bays within Pelorus Sound, chlorophyll concentrations have briefly climbed about 3.5 (and even 5) mg Chl m^{-3} in the past and they will do so again. To date, our modelling has indicated that the farms are unlikely to be the primary drivers of such events.

6 Acknowledgements

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