THE INFLUENCE OF WEATHER AND SOLAR ELEVATION ON PERCEIVED COLOUR OF BLUE LAKE, MOUNT GAMBIER, SOUTH AUSTRALIA.

J. EMENY1, G. TURNER2, N. J. TUROCZY1* & F. STAGNITTI1

1School of Life and Environmental Sciences, Deakin University, Warrnambool VIC 3280, Australia.
2Aquifer Tours, PO Box 1199, Mt Gambier SA 5290, Australia.
*Corresponding author

Summary

Previous studies of the remarkable seasonal colour changes of Blue Lake, Mount Gambier, South Australia have speculated on the roles of weather and solar elevation in this phenomenon. In this study the influence of weather and solar elevation on apparent colour is examined. Solar elevation and some weather variables were found to have a statistically significant influence, particularly when Blue Lake is undergoing transition from its blue to grey stage. However, the proportion of the overall variation in colour explained by solar elevation and weather was only 16%, so it is concluded that in-lake properties are probably the main determinants of colour.

KEY WORDS: Blue Lake, colour, weather

Introduction

The perceived colour of a water body is the result of selective absorption and scattering of the incident light (Wetzel 2001). Variations in the apparent colour of a water body may therefore arise from changes in the physicochemical properties of the water body (changes in the concentration and nature of dissolved and suspended matter), or from changes in the incident light field and light transmission through the atmosphere due to changes in solar elevation and weather.

The Blue Lake at Mount Gambier, South Australia, systematically changes colour each year, from extremes of ‘steel grey’ in winter to ‘bright blue’ in summer (Telfer 2000). A number of studies have investigated possible mechanisms for this remarkable colour change phenomenon (Tamuly 1970; Turner 1979; Telfer 2000; Turoczy 2002). Typically, these studies have focussed on physical and chemical processes occurring within the lake, and despite speculation about the possible influence of variations in the incident light field and weather these factors have not been investigated in detail.

This study therefore tests the hypothesis that the apparent colour of Blue Lake is influenced by solar elevation and weather conditions.

Materials and Methods

Field Observations

The Blue Lake is a volcanic crater lake surrounded by cliffs 50-100 m high. Access to the lake surface by the general public is restricted, as water from the lake is used to supply the city of Mt Gambier. The observations reported here were therefore conducted from a point along the north cliff of the lake and represent the colour observed by a typical visitor to the lake. Davis-Colley et al. (1997) and Telfer (2000) have both described the use of an underwater viewer to facilitate comparisons of water colour with standard colour plates. However, the use of an underwater viewer near water level would eliminate some of the variations caused by weather (eg reflections, the effects of wind, and the presence of rain between the observer and the lake) and was therefore not considered appropriate for this study.
Telfer (2000) used Australian Standard colour plates to describe the colours of Blue Lake in its various stages. In this study, lake colour was matched to Methuen colour charts (Kornerup & Wanscher 1963) which contain approximately 200 shades of blue, and which allow colour to be coded in terms of the three variables hue, brightness and saturation.

A total of 744 observations of the colour of Blue Lake were conducted during the two-year period from August 2000 to August 2002. Observations were usually performed on a daily basis, with the time of day being pseudo-random. All observations were performed by a single observer, who also recorded the time, the cloud cover on a scale of 0 to 8 where 0 represents no cloud and 8 represents 100% cloud cover, the presence or absence of rain, whether the lake was illuminated by direct sun, and whether the lake surface was rippled or calm.

Data Analysis

For each observation, the solar elevation at the time of the observation was calculated using the equations presented in Kirk (1994). For some analyses, solar elevation was categorized into intervals of 10 degrees.

Given the large number of blue colours available in the charts, the colour observations were classified as being either blackish blue, dull/greyish blue, or bright blue. The colour codes corresponding to these colour names are provided in the Methuen colour charts (Kornerup & Wanscher 1963).

Bivariate associations between weather variables and colour measures were explored using a chi-square test of association. The associations were investigated for each season separately and also for all seasons combined. Chi-squared analysis was used to investigate the dependence of solar elevation with colour variables. Possible autocorrelations between independent weather variables were calculated and checked prior to inclusion in a multiple discriminant analysis (MDA). The strengths of associations were estimated using Cramer’s V. The standard $\chi^2$ test of association and Cramer’s V were used in most analyses, with the exception of double dichotomous variables, which used Yate’s corrected $\chi^2$, and phi as a measure of association. The Kruskal-Wallis, a non-parametric test (free from the assumption of data normality) was used to investigate differences between brightness/saturation and solar elevation with colour.

Multiple discriminant analysis (MDA) was used to determine the discriminatory power of weather and solar elevation on different measures of colour (brightness, saturation and overall colour), and thus determine the percentage of variation in colour observations that can be explained by these variables. The relative importance of the predictor variables was assessed by examination of canonical correlation coefficients, Wilks’s Lambda and Huberty’s (1994) “leave one out” method. Huberty’s (1994) “leave one out” method involves running multiple MDAs, systematically removing an independent variable and examining the reduction in classification success. Before the MDAs were conducted, all the usual assumptions associated with parametric multivariate analyses (eg independence of residuals, multivariate normality, homogeneity of variances etc) were tested.

Results

Figs 1a to 1c show the pattern of variation in each of the three colour variables over the entire two year study period. Saturation and brightness vary systematically with time of year, but hue displays no apparent trend with time. It is therefore variations in saturation and brightness that characterize the seasonal colour changes of Blue Lake. Based on spectroradiometer readings (one in summer and one in winter) Telfer (2000) concluded that small changes in the spectral pattern of emergent light (i.e. hue) reflected the seasonal colour changes, but the data reported in Fig. 1a suggest that the day-to-day variability in hue masks any seasonal variability.
Figure 1. Observations of Blue Lake colour from August 2000 to August 2002: (a) hue (b) saturation and (c) brightness, according to Methuen Codes. • = observed colour, ♦ = monthly average
Although distinct seasonal patterns are evident in both the brightness and the saturation, there is also considerable within-season variability present in these variables. Statistical analysis has therefore been applied to determine whether either the between-season variability or the within-season variability is attributable to weather or solar elevation. When the entire data set was analysed for associations between colour and weather variables (Table 1), observations of brightness were found to be weakly but significantly (p<0.001) associated with cloud cover and the presence of rain. Lake stillness and the presence or absence of direct sun were not statistically significantly when associated with brightness. Saturation was significantly associated with cloud cover and the presence of direct sun, although again these associations were weak.

Table 1. Associations between lake colour attributes and weather/solar elevation variables for the entire two year study period.

| Colour attribute | Explanatory variable | p ($\chi^2$) | n  | Cramer’s V |
|------------------|----------------------|-------------|----|------------|
| Brightness       | Lake stillness       | 0.572       | 4  | 0.061      |
|                  | Direct sun           | 0.046       | 4  | 0.112      |
|                  | Cloud cover          | 0.000       | 32 | 0.150      |
|                  | Rain                 | 0.000       | 4  | 0.163      |
|                  | Solar elevation (10° intervals) | 0.000 | 28 | 0.240 |
| Saturation       | Lake stillness       | 0.597       | 6  | 0.077      |
|                  | Direct sun           | 0.011       | 6  | 0.146      |
|                  | Cloud cover          | 0.000       | 48 | 0.165      |
|                  | Rain                 | 0.729       | 6  | 0.068      |
|                  | Solar elevation (10° intervals) | 0.000 | 42 | 0.183 |
| Overall colour   | Lake stillness       | 0.280       | 2  | 0.057      |
|                  | Direct sun           | 0.010       | 2  | 0.109      |
|                  | Cloud cover          | 0.000       | 16 | 0.187      |
|                  | Rain                 | 0.000       | 2  | 0.161      |
|                  | Solar elevation (10° intervals) | 0.000 | 14 | 0.325 |

n = degrees of freedom

Lake colour according to the three-colour categorization was found to be significantly associated with the presence/absence of direct sun, the presence/absence of rain, and cloud cover (Table 1). Again, associations were rather weak (Cramer’s V<0.2), with cloud cover having the strongest association (Cramer’s V=0.187). Lake stillness appeared to have no significant association with lake colour.

Solar elevation was significantly associated with brightness, saturation and overall colour. When expressed in categories of 10°, solar elevation had a stronger association than weather variables for observations of brightness, saturation and overall lake colour (Table 1).

Associations among the ‘independent’ predictors were weak (Cramer’s V or phi <0.3), except, not surprisingly, for cloud cover and direct sun, which showed strong association (Cramer’s V= 806). Lake stillness was not significantly related to any other variables.

Investigation of bivariate relationships, between lake colour variables and solar elevation/weather parameters within individual seasons, revealed that significant correlations occurred mainly in the
THE INFLUENCE OF WEATHER ON PERCEIVED COLOUR OF BLUE LAKE

‘transition’ seasons for lake colour, i.e. in spring and autumn, when the perceived colour changes from grey to blue or vice versa (Table 2). The only exception was a significant association between saturation and direct sun in winter. All colour attributes of the lake appear to be significantly associated with direct sun, cloud cover and rain in spring, during the transition from grey to blue. In autumn, solar elevation was found to be significantly associated with all colour variables during the transition from blue to grey.

Table 2. Associations between lake colour attributes and weather/solar elevation variables according to season.

| Colour attribute | Explanatory variable | all year | winter | spring | summer | autumn |
|------------------|----------------------|---------|--------|--------|--------|--------|
| Brightness       | direct sun           | 0.112   | 0.084  | 0.307* | 0.131  | 0.179  |
|                  | cloud cover          | 0.150*  | 0.280  | 0.299* | 0.190  | 0.180  |
|                  | rain                 | 0.163*  | 0.158  | 0.286* | 0.134  | 0.070  |
|                  | solar elevation      | 0.240*  | 0.117  | 0.219  | NS     | 0.286* |
| Saturation       | direct sun           | 0.146*  | 0.341* | 0.233  | 0.078  | 0.226  |
|                  | cloud cover          | 0.165*  | 0.266  | 0.205  | 0.240  | 0.226  |
|                  | rain                 | 0.068   | 0.140  | 0.147  | 0.027  | 0.190  |
|                  | solar elevation      | 0.183*  | 0.187  | 0.196  | 0.187  | 0.206* |
| Overall colour   | direct sun           | 0.109*  | 0.088  | 0.275* | 0.094  | 0.079  |
|                  | cloud cover          | 0.187*  | 0.287  | 0.334* | 0.161  | 0.186  |
|                  | rain                 | 0.161*  | 0.160  | 0.286* | 0.128  | 0.050  |
|                  | solar elevation      | 0.325*  | 0.118  | 0.232  | 0.177  | 0.346* |

* p<0.01

Univariate analysis for outliers detected no extreme values in the solar elevation. The distribution of this variable closely matched a normal distribution, only slightly skewed to the right (skewness=0.145). Box’s M test was found to be significant (p=0.000) for all three dependent colour variables, indicating that the assumption of equal covariance matrices was violated. However this test has been found to be overly sensitive when n is large (Hair et al. 1998), and on inspection of the log determinants, the covariances were sufficiently similar. Therefore the results may be accepted cautiously.

Computation of Wilks’s Lambda revealed that weather variables had little or no discriminatory power for the colour variables of saturation and brightness (see Table 3). Only rain and cloud cover had a small but significant discriminatory power for brightness. Solar elevation had slightly better discriminatory power for both brightness and saturation. Based on these results, solar elevation, rain and cloud cover were included as variables for the MDA with brightness as the dependent variable. Only solar elevation was included as an independent variable for the discriminant analysis with saturation as a dependent variable.
Table 3. Discriminatory power of independent variables to predict lake colour, using Wilks’s Lambda to test significance.

| Colour attribute | explanatory variable | Wilks’s Lambda | F     |
|------------------|----------------------|----------------|-------|
| brightness       | rain                 | 0.974          | 5.22* |
|                  | solar elevation      | 0.875          | 27.38*|
|                  | cloud cover          | 0.969          | 6.08* |
|                  | direct sun           | 0.988          | NS    |
|                  | lake stillness       | 0.991          | NS    |
| saturation       | rain                 | 0.995          | NS    |
|                  | solar elevation      | 0.964          | 4.81* |
|                  | cloud cover          | 0.988          | NS    |
|                  | direct sun           | 0.979          | NS    |
|                  | lake stillness       | 0.994          | NS    |
| overall colour   | rain                 | 0.974          | 10.20*|
|                  | solar elevation      | 0.880          | 52.45*|
|                  | cloud cover          | 0.970          | 12.13*|
|                  | direct sun           | 0.988          | 4.62* |
|                  | lake stillness       | 0.997          | NS    |

* p < 0.01

Solar elevation and all weather variables except lake stillness had significant discriminatory power for overall colour (Table 3). Therefore lake stillness was excluded from further analysis. Direct sun was also excluded from the multiple discriminant analysis due to its strong correlation with cloud cover.

Table 4. MDA classification success using weather variables and solar elevation as independent variables to discriminate colour classes.

| Colour measure | Hit ratio | Cross-validated hit ratio | Cmax | Press’s Q |
|----------------|-----------|---------------------------|------|-----------|
| Brightness     | 29%       | 27%                       | 39%  | 38.67*    |
| Saturation     | 18%       | 16%                       | 57%  | 7.30*     |
| Colour         | 50%       | 49%                       | 45%  | 96.75*    |

*p<0.01.

The MDA using cloud cover, rain and solar elevation as independent variables gave only a low to moderate classification success against all three dependent colour variables (Table 4). Overall colour had the best classification rate, with a hit ratio (i.e., correct prediction of colour, based on weather parameters and solar elevation) of 50% (49% after cross validation). The percentages of cases correctly classified for both saturation and brightness were lower than the $C_{max}$ values in Table 4, a measure of the minimum expected correct classification (Morrison 1969). Press’s Q statistic, which determines if the overall classification is significantly better than chance (Hair et al. 1998), was found to be significant in all cases. However, caution must be taken as this statistic is particularly sensitive to large sample sizes (Hair et al. 1998).

The MDA used to predict the overall colour created two discriminant functions (Table 5). Only the first was found to be statistically significant (Wilks’s Lambda = 0.836, p<0.01). This function explained 99% of variation in the colour. The canonical coefficient for this function was 0.405, indicating that only 16% of variance in colour observations can be explained by weather and solar elevation. Solar elevation was found to be the most important variable in the discriminant function,
The Influence of Weather on Perceived Colour of Blue Lake

with the highest canonical correlation coefficient of -0.870, the smallest Wilks’s Lambda and the greatest reduction in classification accuracy if removed (Table 5). Cloud cover was the next most important variable in the model according to its canonical correlation coefficient. Rain was the least important predictor but removing it from the analysis reduced the hit ratio by a factor of 2, and so it was retained.

Table 5. Importance of independent variables in predicting colour.

| Independent variable | Canonical correlation coefficient (standardized) | Wilks’s Lambda | Hit ratio after removal (cross validation hit ratio) | Rank |
|----------------------|-------------------------------------------------|----------------|-----------------------------------------------------|------|
| Solar elevation      | 0.869                                           | 0.880*         | 39(39)*                                             | 1    |
| Cloud cover          | -0.394                                          | 0.970*         | 49(48)*                                             | 2    |
| Rain                 | -0.325                                          | 0.974*         | 48(47)*                                             | 3    |

*p<0.01

Discussion

Detailed observations of the colour of Blue Lake confirm the systematic seasonal variations documented by Telfer (2000), but the results here indicate that it is the intensity-related properties of colour (saturation and brightness) rather than the spectral distribution (as it influences hue) that change between summer and winter. In summer, the colour is brighter and more saturated than in winter, but there appears to be no seasonal trend in hue.

The results indicate that, on a yearly basis, brightness is significantly associated with the solar elevation and the absence of rain, and that saturation is significantly associated with solar elevation, the presence of direct sun, and the amount of cloud cover. However these observations seem to be linked by both being dependent on season. When the seasons are analysed individually, it is found that in summer and winter, lake colour is essentially independent of weather and solar elevation. However in spring and autumn, the transition seasons, the colour is significantly associated with weather and solar elevation.

Whilst the individual components of colour (brightness and saturation) were unable to be predicted with any great accuracy from solar elevation and weather conditions, a significantly better classification rate was obtained when the observed colour was reduced to just three meaningful groups. This is expected as classification accuracy improves with a reduced number of groups. However, the MDA results indicated that classification accuracy (50%, or 49% after cross-validation) was better than the maximum hit ratio than could be achieved by chance alone (C_max = 45%, Press’s Q = 96.75).

Solar elevation was found to be the most important variable in distinguishing colour, but its association only appears to be important in autumn, during the transition period of lake colour from blue back to grey. Of the weather variables, cloud cover and rain were also found to provide some discrimination. Lake stillness (i.e. no or little wind) had apparently no influence on lake colour. This result is somewhat surprising, because a blue-coloured lake should, in principle, appear more clearly blue under conditions of rough and choppy water than under calm conditions (Kirk 1994). However this effect appears to have been masked by other factors operating at Blue Lake.

Although significant discriminant functions were obtained for classifying colour based on weather and solar elevation, the classification success rate was not particularly good (49% after cross validation). The best discriminant function revealed that weather and solar elevation could only account for 16% of variation in colour observations. This indicates that, whilst weather and solar elevation do influence lake colour, there are more important factors. Furthermore, they are only important at certain times of the year consistent with earlier suggestions that physico-chemical
properties may be more important overall in explaining the perceived colour variations at Blue Lake.

Conclusion

The hitherto speculated role of solar elevation and weather in causing colour variations in Blue Lake has been studied. A relatively weak, but statistically significant, association between solar elevation, some weather parameters and the observed colour of the lake has been demonstrated. Specifically, (1) solar elevation, cloud cover and presence or absence of rain had a small effect on colour variation,

(2) solar elevation was more important in discriminating between lake colour classes than weather variables,

(3) weather variables were only significant in partially explaining lake colour variation in spring, during the transition of lake colour from grey to blue,

(4) solar elevation was only significant in partially explaining lake colour variation in autumn, during the transition of lake colour from blue to grey, and

(5) lake stillness is not an important predictor of lake colour.

Whilst variations in solar elevation and weather conditions may explain a small fraction of the variation in lake colour, as asserted by earlier studies, within-lake factors (chemical or physical) are likely to be the main cause for colour changes in the lake. As these physico-chemical properties in turn may also be affected by changes in solar elevation and weather properties, the explained colour variation of the lake reported in this paper may simply reflect changes in the physico-chemical status of the lake. Therefore in future studies exploring lake colour, observations of weather conditions and solar elevation should be recorded as well as physico-chemical parameters to explore variation in lake colour.

References

Davies-Colley, R.J., Smith, D.G., Speed, D.J. & Nagels, J.W. (1997) Matching natural water colors to Munsell Standards. Journal of the American Water Research association 33, 1351-1361.

Hair, J.F., Anderson, R.E., Tatham, R.L. & Black, WC. (1998) Multivariate data analysis. (Prentice Hall, Upper Saddle River).

Huberty, C. (1994) Applied Discriminant Analysis. (John Wiley & Sons Inc, New York).

Kirk, J.T.O. (1994) Light and Photosynthesis in Aquatic Ecosystems. (Cambridge University Press, Cambridge).

Kornerup, A. & Wanscher, J.H. (1963) Methuen handbook of colour. (Methuen, London).

Tabachnick, B.G. & Fidell, L.S. (1996) Using multivariate statistics, 2nd ed. (Harper and Row, New York).

Tamuly, A. (1970) Physical and chemical limnology of the Blue Lake of Mt Gambier, South Australia. Transactions of the Royal Society of South Australia 94, 71-96.

Telfer, A.L. (2000) Identification of processes regulating the colour and colour change in an oligotrophic, hardwater, groundwater-fed lake, Blue Lake, Mount Gambier, South Australia. Lakes & Reservations: Resource Management 5, 161-176.

Turner, J.V. (1979) The hydrologic regime of Blue Lake, South Eastern Australia. Unpubl. Ph.D. Thesis Flinders University, South Australia.

Turoczy, N.J. (2002) Calcium chemistry of Blue Lake, Mt Gambier, Australia, and relevance to remarkable seasonal colour changes. Archives of Hydrobiology 156, 1-9.

Wetzel, R.G. (2001) Limnology. Lake and River Ecosystems, 3rd ed. (Academic Press, San Diego).