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Optically pure waters in Waikoropupu ('Pupu') Springs, Nelson, New Zealand

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Abstract We have made *in situ* observations of the optical properties of Waikoropupu ("Pupu") Springs, Nelson, New Zealand. Visual clarity was measured in the horizontal direction over a sight path "folded" using a plane mirror so as to accommodate the sighting range within the 35 m wide main springs basin. An average black-body visibility of 63 m was obtained, the highest yet reported for any fresh water, and close to the theoretical maximum for optically pure water. Measurements with a beam transmissometer were consistent with the visibility observations. As well as ranking among the very clearest waters in the world, these spring waters are virtually indistinguishable from pure water as regards their spectral irradiance attenuation in the ultraviolet and beam attenuation in the green region of the spectrum, undetectably low content of yellow-coloured organic material, and remarkable blue-violet colour.

Keywords optical water quality; clarity; colour; Waikoropupu Springs

INTRODUCTION

Many springs around the world are notable for their high-quality water, including very high *optical* quality. However, few optical measurements have been made in spring waters, which is somewhat surprising given that their clarity is a feature often remarked on. Waikoropupu Springs, generally called Pupu Springs, near Takaka, Nelson, are New Zealand's largest springs (ranked 24th in the world among Karst—carbonate rock aquifer—springs, with an average flow of 15 $m^3\ s^{-1}$: Ford & Williams 1989; Williams 1992). These springs have long been renowned for their beauty and water clarity (Williams 1992). Although the general ecology (Michaelis 1977), hydrology (Williams 1977; Stewart & Downes 1982; Stewart & Williams 1981) and chemistry (Michaelis 1976) of the springs have been reasonably well studied, there have been only a few simple measurements of their optical properties (Michaelis 1976). These measurements, made with a filter radiometer, suggested that the spring waters are optically very pure. Here we report more comprehensive optical measurements, including visual clarity, carried out on the spring waters emanating from the main vent (which discharges about 80% of the total mean flow).

METHODS

Visual range was measured on 11 February 1993 in the main saucer-shaped spring basin using two modifications of the black disc method (Davies-Colley 1988). The first modification relates to the limited visual range (only 35 m) in the spring basin and involved positioning a vertical 1.5 m × 1.5 m plane glass mirror in the springs diametrically opposite the black target, thereby doubling the available path length to about 70 m (Fig. 1). A necessary condition of the black body visibility method is that the path of sight behind the target be unrestricted so that the target is seen silhouetted against the water spacelight (Davies-Colley 1988). As a rule of thumb, the total unrestricted light path in the water should be about 50% greater than the visual range at target extinction. Again, because of the limited physical size of the spring basin, this could not be achieved directly. Instead, acrylic mirror sheet (0.75 m wide by 1.2 m deep) was

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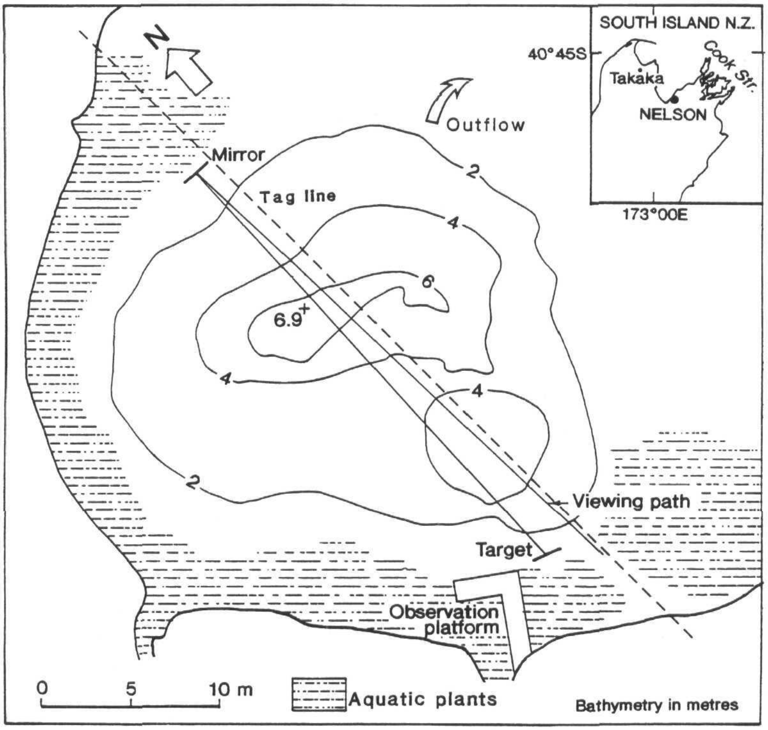

Fig. 1 Map of the main spring basin of Waikoropupu Springs, South Island, New Zealand, showing bathymetry after Michaelis (1974). The position of the target, mirror, and tag line for visibility observations are indicated.

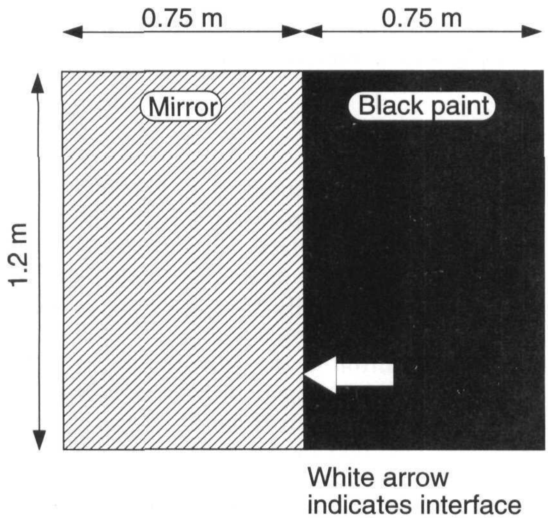

Fig. 2 Design of the visiblity target. Observers viewed the vertical interface between the black-painted area of the target and the mirrored area which reflected the water background lighting. The position of this interface was indicated by the white arrow which, being highly contrasting with the black background, was visible at a greater distance than the interface.

placed adjacent to the black target (of the same size) and used to simulate background spacelight by reflecting the *foreground* water luminance (Fig. 2). The black target was marked with a white arrow to guide observers to the position of the interface. This high contrast "accessory" target could be seen at a greater distance than the interface which was used for black body range assessment.

Observations of the target (the interface) were made by snorkel divers who viewed the image in the mirror opposite the target, otherwise visibility measurements followed standard procedures (Davies-Colley et al. 1993).

Ideally, these visibility measurements would have been supported with instrumental measurements using a beam transmissometer of the type designed for clear ocean waters (Petzold & Austin 1968) but a suitable sensor was not available at the time.

However, on the morning of 10 March, 1995, 2 years after the visibility observations, we again visited the Springs with a 1 m path Martek XMS beam transmissometer. Transmittance measurements were made in the main spring vent at 493 nm in the blue region of the spectrum, and again, about

1 h later, at 528 nm in the green, following a filter change (which required opening of the instrument's pressure housing) and careful recalibration in air. On consideration of the errors involved in both air calibration and *in situ* readings, we expect our transmittance data to be within ± 0.8% (2 times standard error).

Spectral scans were made at 5 nm intervals from 300 to 750 nm with a Li-Cor 1800UW spectroradiometer under clear sky at a solar altitude of 47°.

The spectral light attenuation coefficients were calculated from measurements of downwelling sunlight (spectral irradiance) in the springwater:

$$K_d = \ln(E_z/E_0) / z,$$

where E_0 is the spectral irradiance just below the water surface and E_z is that at depth z. The deepest down-welling spectral scans possible were made at $z = 5.5$ m.

The water spacelight (spectral radiance) was scanned horizontally in the direction of the largest unrestricted path in the springs basin at about 0.3 m depth with a 15° field-of-view restrictor fitted to the spectroradiometer. This spectrum is divided by the incident sunlight (downwelling spectral irradiance) at the same depth to give the so-called "Output/input" spectrum (Tyler 1965).

Water samples were taken from the two main spring vents (located within the 4 m contours) for laboratory measurements with a Pye-Unicam PU8800 spectrophotometer of the absorption coefficient at 440 nm of membrane filtrates, using methods suitable for very clear sea water (Davies-Colley 1992).

RESULTS AND DISCUSSION

Clarity

The average of four independent visibility observations was 63 m, an extremely high value for natural waters. This can be compared with the theoretical black body visibility of pure water, estimated using the values reported for the optical properties of water itself at 550 nm (Smith & Baker 1981), being near the peak sensitivity of the human eye. The absorption coefficient $a_w(550) = 0.0638$ m^{-1} and the scattering coefficient $b_w(550) = 0.0015$ m^{-1}, so that the attenuation coefficient $c_w(550)$ (= $b_w(550) + a_w(550)$) = 0.0653 m^{-1}, and the irradiance attenuation coefficient, $K_w(550)$ (= $0.5b_w(550) + a_w(550)$: Smith & Baker 1981) = 0.0646 m^{-1}. Using the formula for the black body

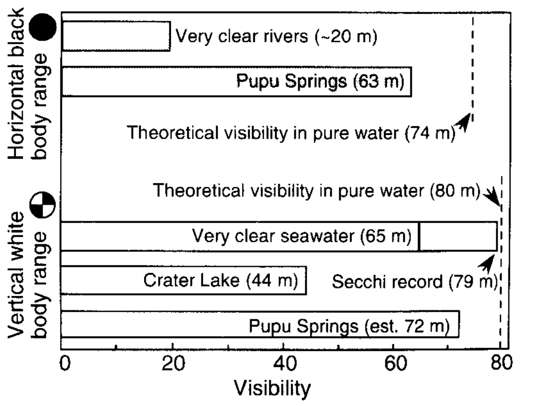

Fig. 3 Comparison of horizontal black body and vertical white body (Secchi disc) visibilities in clear natural waters and optically pure water.

visibility (y_{BD}) (Davies-Colley 1988), we obtain $y_{BD} = 4.8/c_w(550) = 74$ m (Fig. 3). That is, the visibility in Pupu water is about 85% of the theoretical maximum. The measurement of an average visibility of 63 m in Pupu Springs shows that this water, with a corresponding beam attenuation coefficient of 4.8/63 = 0.076 m^{-1}, is a very close natural approximation to optically pure water.

[The 1995 readings made with the Martek beam transmissometer can be compared with the visibility observations. At 493 nm in the blue region, the 1 m transmittance was 97.8 ± 0.8%, corresponding to $c(493) = 0.022$ m^{-1} (0.014–0.030 m^{-1}). At 528 nm in the green, the transmittance was 92.8 ± 0.8%, corresponding to $c(528) = 0.075$ m^{-1} (0.066–0.083 m^{-1}). Beam attenuation coefficients for optically pure water at these wavelengths, interpolated from the data in Smith & Baker (1981), are 0.024 m^{-1} and 0.052 m^{-1}, respectively. The difference between our measured $c(528)$ value and that of pure water can be attributed to the very small concentration of suspensoids in the spring water. The measured beam attenuation at 528 nm is consistent with the measured visibility (corresponding beam attenuation coefficient at 550 nm = 0.076 m^{-1}), taking into account measurement errors and likely spectral trend of suspensoid attenuation.]

Black body visibilities have apparently not been reported for other, very clear, natural waters. However, indirect comparisons can be made with vertical sighting ranges of the traditional Secchi disc. The theoretical Secchi disc depth of optically

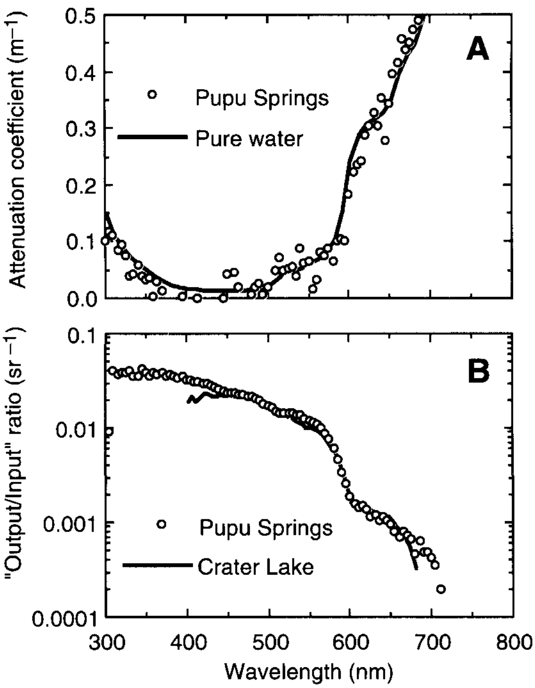

Fig. 4 Spectral characteristics of the waters of Waikoropupu Springs measured with a Li-Cor 1800UW spectroradiometer. **A**, Light penetration (downwelling spectral irradiance coefficients measured over 5.5 m). The Pupu Springs data overlay the spectral attenuation reported by Smith & Baker (1981) for pure water as inferred from spectroradiometry on the clearest natural waters. **B**, Spectral quality of the underwater light field, the "Output/input" ratio of Tyler (1965), i.e., the ratio of spectral radiance viewed horizontally to downwelling spectral irradiance. The Pupu Springs data overlay the curve reported by Tyler (1965) for Crater Lake, Oregon.

pure water can be estimated (Tyler 1968) using published optical coefficients (Smith & Baker 1981). This yields a value of about 80 m (Fig. 3). A record Secchi depth of 79 m in a coastal Polynya of the Eastern Weddell Sea, Antarctica, has been reported (Gieskes et al. 1987) together with several other Secchi depths around 70 m elsewhere in the Weddell Sea. In other sea waters, maximum Secchi depths in the 50 to 70 m range have been recorded (Fig. 3). A 1985 observation of 53 m in the Eastern Mediterranean was claimed as a record (Berman et al. 1985), but clearer waters (up to 62 m in the tropical Pacific Ocean) had earlier been reported (Man'kovskiy 1978). These visual clarities are seldom, if ever, approached in surface freshwaters. Even in Crater Lake, Oregon, a water often cited for its clarity, the maximum recorded Secchi depth (using a 2 m disc) is a comparatively modest 44 m (Larson 1972). Evidently the visual clarity of Crater Lake is not as outstanding as its spectral light penetration and colour (Smith et al. 1973).

Comparison of Secchi observations with our observations in Pupu Springs is not straightforward because there is no unique relationship between vertical visibility of a white target and horizontal black body range. However, again using Tyler's (1968) equation, but with $c(550) = 0.076\ m^{-1}$, the 63 m black body visibility is expected to correspond to a Secchi depth of about 72 m (Fig. 3). Thus, the waters of Pupu Springs exceed the visual clarity of all but the very clearest sea water. It seems unlikely that any *surface* freshwater could rival these springs in clarity, but other spring waters might be comparably clear.

Colour

Figure 4A shows the downwelling spectral irradiance coefficients which quantify light penetration into water. The data scatter arises from the very restricted depth (6.5 m) of the springs basin. Measurements would need to be taken down to many tens of metres depth for precise estimation of spectral attenuation of blue and green light in water of this clarity which was not possible.

The spectral attenuation coefficients compare well with the spectral attenuation of optically pure water (Smith & Baker 1981) (line in Fig. 4A). Evidently the attenuation of light in the spring water is consistent with that of optically pure water. In the ultra-violet range (< 400 nm), natural coloured organic matter ("yellow substance") (Davies-Colley 1993) would be expected to increase the attenuation above the line for pure water. However, even in this region of the spectrum, light penetration into Pupu Springs is consistent with that for optically pure water. Indeed, yellow substance was optically undetectable in water samples; absorption coefficient at 440 nm (g_{440}) < $0.01\ m^{-1}$.

Figure 4B indicates the spectral quality of the underwater light field in Pupu Springs. The spectrum in Fig. 4B is very similar in magnitude and shape to that for Crater Lake, Oregon (Tyler 1965) (also shown) with violet to blue-green light dominating the spectrum of water spacelight. Analysis of the spectrum by the CIE chromaticity method (Anonymous 1966) gave Munsell hue code 1.5PB (1.5 units of the purple-blue range), an unusual blue-violet colour only seen in the very clearest of natural waters.

This hue of the spring water, as calculated using the spectrum in Fig 4B, agreed closely to that matched visually to standards in the Munsell system of colour (Anonymous 1966). Three observers, including one of the authors, matched the apparent hue of the spring water, as observed against patches of white marble sand, to Munsell hue 2.5PB (2.5 units of the purple-blue range). The other author chose 0PB (= 10B), at the boundary between blue and purple-blue. The colour of the spring water is consistent with the undetectably low yellow substance content, since modelling of colour as a function of yellow substance (Bukata et al. 1983) suggests that any detectable amount of yellow substance ($g_{440} > 0.02$ m^{-1}) would shift the colour noticeably towards longer wavelengths. Were the spring basin sufficiently deep for vertical observation of water colour, unaffected by the colour of bottom features, even more hue shift towards violet would be expected. For example, the intrinsic colour of upwelling light in Crater Lake, Oregon, is 5.5PB (Smith et al. 1973).

General

Both the clarity and the colour of Pupu Springs indicate that its water closely approximates optically pure water. The extreme optical purity probably has to do with the long residence time between aquifer recharge by the Takaka River and re-emergence in the springs (roughly 3 to 8 years: Williams 1992). Apparently, filtration within the aquifer removes virtually all the particulate material from the water. The yellow substance that is produced by microbial degradation of organic matter in the recharge water may also be efficiently removed by chemical adsorption on the calcite mineral surfaces of the rock (Mount Arthur marble) comprising the aquifer; calcite is known to chemically adsorb humic material (Suess 1970).

It would be interesting to know how the waters of Pupu Springs compare, optically, with other very clear spring waters, such as those in Florida (Odum 1957; Whitford 1957) and other karstic systems (Ford & Williams 1989). Such spring waters may provide a valuable laboratory for the measurement of the optical properties of pure water, and a source of optically purer water than may be easily achieved in the laboratory—useful, for example, for calibration of certain optical instruments, including transmissometers. We encourage visibility observations, as well as instrumental measurements, in other clear-water springs.

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REFERENCES

Anonymous, 1966: The science of color. The Committee on Colorimetry of the Optical Society of America. Optical Society of America, Washington D.C, 385 p.

Berman, T.; Walline, P. D.; Schneller, A.; Rothenberg, J.; Townsend, D. W. 1985: Secchi disk depth record: a claim for the Eastern Mediterranean. *Limnology and oceanography 30*: 447.

Bukata, R. P.; Bruton, J. E.; Jerome, J. H. 1983: Use of chromaticity in remote measurements of water quality. *Remote sensing of environment 13*: 161–177.

Davies-Colley, R. J. 1988: Measuring water clarity with a black disk. *Limnology and oceanography 33*: 616–623.

Davies-Colley, R. J. 1992: Yellow substance in coastal and marine waters round the South Island, New Zealand. *New Zealand journal of marine and freshwater research 26*: 311–322.

Davies-Colley, R. J.; Vant, W. N; Smith, D. G. 1993: Colour and clarity of natural waters. Ellis Horwood, New York, 310 p.

Ford, D. C.; Williams, P. W. 1989: Karst geomorphology and hydrology. London, Chapman & Hall.

Gieskes, W. W. C.; Veth, C.; Woehrmann, A.; Graefe, M. 1987: Secchi disk visibility world record shattered. *Transactions of the American. Geophysical Union 68*: 123.

Larson, D. W. 1972: Temperature, transparency, and phytoplankton productivity in Crater Lake, Oregon. *Limnology and oceanography 17*: 410–417.

Man'kovskiy, V. I. 1978:. Empirical formula for estimating the light attenuation coefficient in sea water from Secchi disk readings. *Oceanology 18*: 493–494.

Michaelis, F. B. 1976: Physico-chemical features of

Pupu Springs. *New Zealand journal of marine and freshwater research 10*: 613–628.

Michaelis, F. B. 1977: Biological features of Pupu Springs. *New Zealand journal of marine and freshwater research 11*: 357–373.

Odum, H. T. 1957: Primary production measurements in eleven Florida Springs and a marine turtle grass community. *Limnology and oceanography 2*: 85–97.

Petzold, T. J.; Austin, R. W. 1968: An underwater transmissometer for ocean survey work. *Scripps Institution of Oceanography Reference 68–9*, 5 p.

Smith, R. C.; Baker, K. S. 1981: Optical properties of the clearest natural waters (200–800 nm). *Applied optics 20*: 177–184.

Smith, R. C.; Tyler, J. C.; Goldman, C. R. 1973: Optical properties and color of Lake Tahoe and Crater Lake. *Limnology and oceanography 18*: 189–199.

Stewart, M. K.; Williams, P. W. 1981: Environmental isotopes in New Zealand hydrology: isotope hydrology of the Waikoropupu Springs and Takaka River, northwest Nelson. *New Zealand journal of science 24*: 323–337.

Stewart, M. K.; Downes C. J. 1982: Isotope hydrology of Waikoropupu Springs, New Zealand. *In*: Perry, E. C.; Montgomery, C. W. *ed.* Isotope studies of hydrologic processes. Northern Illinois University Press, DeKalb, pp. 15–23.

Suess, 1970, E. Interaction of organic compounds with calcium carbonate. 1. Association phenomena and geochemical implications. *Geochimica and cosmochimica acta 34*: 157–168.

Tyler, J. E. 1965: *In situ* spectroscopy of ocean and lake waters. *Journal of the Optical Society of America 55*: 800–805.

Tyler, J. E. 1968: The Secchi disc. *Limnology and oceanography 13*: 1–6.

Whitford, L. A. 1957: The communities of algae in the springs and spring streams of Florida. *Ecology 37*: 433–442.

Williams, P. W. 1977: Hydrology of the Waikoropupu Springs: a major tidal karst resurgence in northwest Nelson (New Zealand). *Journal of hydrology (Netherlands) 35*: 73–92.

Williams, P. W. 1992: Karst hydrology. *In*: Mosley M.P. *ed.* Waters of New Zealand. New Zealand Hydrological Society, Wellington, New Zealand, pp. 187–206.