

The Effect of Solar Radiation on the Treatability of Reservoir Water and its Subsequent Quality

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Abstract

Solar radiation wavelengths including UVB (280-320 nm), UVA (320-400 nm), and PAR (Photosynthetically Active Radiation; 400-720 nm) are capable of altering the chemical structure of natural organic matter (NOM) in surface waters. Water from Myponga Reservoir, South Australia, was irradiated with UVB, UVA or PAR for 20 days. Jar tests were conducted on non-irradiated and irradiated raw water to determine any changes in the treatability of NOM by alum. Maximum removal of dissolved organic carbon (DOC) was about the same regardless of irradiation type applied. Biodegradable organic carbon (BDOC) concentrations and chlorine demand of treated waters from jar tests were determined to characterize the residual NOM. Photooxidation of NOM was found to increase its biodegradability, but did not affect disinfectant by-product (DBP) formation. Recognizing that NOM is involved in complex inter-relationships with micro-flora in aquatic ecosystems, the effects of exposure to reservoir biota was investigated under laboratory conditions. Reservoir water was incubated in the presence of biologically active sand under UVB irradiation for 20 days. Following exposure to photochemical and microbiological processes, the treatability of the reservoir water improved slightly. However, this slight improvement in DOC removal did not result in a detectable change in BDOC and chlorine demand.

Keywords: solar radiation, natural organic matter, alum coagulation, biodegradable organic carbon, chlorine demand

1. Introduction

In recent decades, the depletion of ozone in the stratosphere has led to an increase in solar UV radiation, potentially causing adverse effects to human health, terrestrial and aquatic ecosystems, and air quality (McKenzie 2003). Another environmental problem, climate change, is expected to cause an increase in temperature, precipitation, evaporation and runoff, and hydrologic extremes such as floods and droughts will probably be more common and more intense (Schindler 1996). Both phenomena have the potential to alter the characteristics of natural organic matter (NOM) in reservoirs, influencing the quality and treatability of water.

The absorption of solar UV radiation by NOM results in photochemical processes that lead to the partial photolysis of humic macromolecules, with the generation of simple compounds that serve as substrates for bacterial degradation (Frimmel 1998). The presence of NOM in source water can be problematic for the treatment of drinking water. It affects water quality by increasing the coagulant and disinfectant demand in conventional treatment, providing precursor material for disinfection by-products (DBPs), and enhancing biofilm growth in the distribution system. Any reduction in the concentration of NOM in our water resources should allow water authorities to reduce water treatment costs, to improve the effectiveness of treatment processes, and to meet any future limits on both disinfectant dose and DBP formation (Drikas 2003).

2. Materials and Methods

2.1 Water Source and Quality

The water used in this study was collected from Myponga Reservoir, South Australia, in February 2005. The sampling point was at the dam wall before chlorination. The water was stored at 4°C prior to experiments. Details of water characteristics are given in Table 1.

Table 1. Characteristics of Myponga Reservoir Water

DOC (mg L ⁻¹)	A ₂₅₄ (cm ⁻¹)	SUVA (L m ⁻¹ mg ⁻¹)	pH	Alkalinity (mgCaCO ₃ L ⁻¹)	Colour (HU)	Turbidity (NTU)
13.1	0.493	3.76	7.76	62	79	2.05

2.2 Experimental Methodology

The effects of three solar radiation wavelength ranges (UVB, UVA and PAR) on the character of NOM in Myponga Reservoir water were studied. Water was subjected to five different experimental conditions as follows: a) Non-irradiated b) UVB-irradiated c) UVA-irradiated d) PAR-irradiated and e) UVB-irradiated in the presence of biologically activated sand (BAS). Following this, the water samples were tested using a jar test procedure to determine the treatability of NOM under conventional water treatment conditions. Biodegradable organic carbon (BDOC) concentrations and chlorine demand of treated waters were then determined.

A 25 L tank and a single 15 W lamp batten were used for irradiation experiments, where 15 W UVB (Sanyo Denki 15T8, Japan), UVA (NEC Blacklight, Japan) and PAR (ExoTerra Reptiglo 5.0, Japan) lamps were used. The three lamps had polychromatic Gaussian-type spectral output with maxima at 310 nm, 340 nm and 430 nm respectively. Raw reservoir water (20 L) was irradiated for 20 days, and the tank was covered by aluminum foil to prevent any effects of ambient light. Air was bubbled through the water to maintain aerobic conditions and to keep it well-mixed. Water temperature was maintained at an ambient level (20 ± 2 °C). Lamp intensities and solar UV radiation were measured using a radiometer (International Light model IL1400BL) with a SEL005/WBS320/W detector.

Dissolved organic carbon (DOC) measurements were made using a Sievers 820 TOC analyser. Water samples were filtered through a 0.45 μm hydrophilic membrane (Durapore PVDF) before DOC analysis. A double beam UV/Vis spectrophotometer (Unicam UV2) was used for all spectrophotometric readings. A 1 cm quartz cell was used for absorbance readings at 254 nm (A_{254}) and a 4 cm glass cell was used to measure colour, in Hazen units (HU) at 446 nm (A_{446}). Specific UV absorbance (SUVA), a measure of the aromaticity of organic compounds, was determined as the ratio of A_{254} to DOC concentration, multiplied by 100 [$(A_{254} / \text{DOC}) \times 100$]. A Hach Sension 156 pH meter was used for pH measurements. Alkalinity was determined using sodium carbonate and sulphuric acid titration (Standard Methods 2320 B) (APHA 1998). Turbidity was measured using a Hach spectrophotometer (DR/4000) and a formazin standard.

2.3 Jar Test Procedure

Alum (aluminium sulphate, $\text{Al}_2(\text{SO}_4)_3 \cdot 18\text{H}_2\text{O}$) was used in jar test experiments. A range of alum concentrations (80, 90, 100, 110 mg L^{-1}) and coagulation pH conditions (4, 5, 6, 7) were used to test each water sample, giving a total of 16 samples (Table 2) for each experimental condition. A Phipps and Bird PB-700 jar tester equipped with 6 paddle stirrers and 6 x 2 L BKer jars were used. Water samples (1 L) were flash mixed at 150 rpm for 1 minute, then slow mixed at 30 rpm for 15 minutes. Floccs were allowed to settle for 60 minutes before filtration (Whatman No.1). The pH of treated water was finally adjusted to 7 before proceeding to subsequent experimental stages.

Table 2. Alum doses and pH levels applied in jar tests from the five experimental conditions.

pH	80 mg L^{-1} alum	90 mg L^{-1} alum	100 mg L^{-1} alum	110 mg L^{-1} alum
4	80-4	90-4	100-4	110-4
5	80-5	90-5	100-5	110-5
6	80-6	90-6	100-6	110-6
7	80-7	90-7	100-7	110-7

2.4 Measurement of Biodegradable Organic Carbon (BDOC)

The BDOC method applied in this study is based on the use of biologically active sand (Joret 1989) collected from the Yarra River, Lilydale, Victoria. Sand-attached bacteria utilise the biodegradable fraction of organic matter remaining in a water sample following treatment and can give an indication of the potential of that water for microbial regrowth in a distribution system. Water samples from the five experimental conditions were each incubated with the BAS for a period of 10 days under aerobic conditions. A control consisting of a 10 ppm sodium acetate solution was prepared and incubated in the same way as the test samples.

2.5 Measurement of Chlorine Demand

Water samples were dosed with chlorine solution made up from 12.5% w/v NaOCl to a final concentration of $25 \text{ mg Cl}_2 \text{ L}^{-1}$ in sealed 40 mL vials before storing in the dark at ambient laboratory temperatures ($20 \pm 2 \text{ }^\circ\text{C}$). Samples spiked with chlorine were tested for chlorine concentration after 3 days of incubation by the DPD Colorimetric method (Standard Methods 4500-Cl G) (APHA 1998). Chlorine concentration for the stock hypochlorite solution was determined by iodometric titration (Standard Methods 4500-Cl B) (APHA 1998). High purity Milli-Q water dosed with the same concentration of chlorine was used as a control to estimate losses of chlorine to atmosphere and wall reactions.

3. Results and Discussion

3.1 Simulation of Solar Radiation

The duration chosen for the irradiation of reservoir water in this study (20 days – 24 hours operation) was to ensure that the effects of exposure to the solar radiation wavelengths could be measured. The UVB, UVA and PAR lamps used produced lower radiation intensities compared with actual solar radiation recorded on the 20/9/2005 (Table 3). Consequently these levels need to be taken into account in the interpretation of the results.

Table 3. Summary of radiation intensity and radiation duration of various sources

Radiation Source	Radiation intensity (mW/cm^2)	Experimental radiation duration (days)	Ratio of radiation intensities with reference to nature	Equivalent* solar radiation (days)
UVB Lamp	0.751	20	0.276	11.04
UVA Lamp	0.961	20	0.353	14.12
PAR Lamp	0.257	20	0.095	3.80
Solar UV (20/09/2005, 1200 hrs)	2.72	-	1	-

* assuming 12 hours of solar radiation at $2.72 \text{ mW}/\text{cm}^2$ per day.

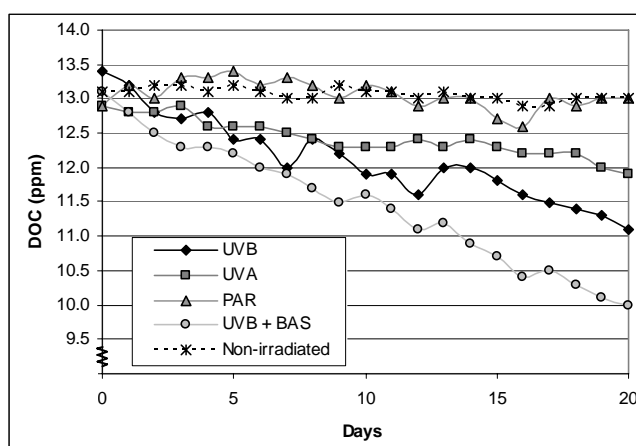


Figure 1. Comparison of DOC over 20 days of irradiation

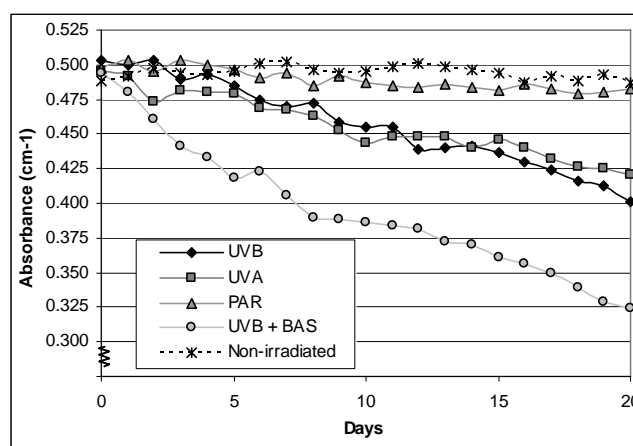


Figure 2. Comparison of A_{254} over 20 days of irradiation

After irradiation for 20 days, DOC mineralization was found to occur as follows: UVB (2.0 ppm) > UVA (1.2 ppm) > PAR (0.1 ppm) (Figure 1). UVB irradiation of water in the presence of BAS was performed to simulate the effects of biota found in the reservoir. Bacteria present in the sand were responsible for the degradation of DOC to the lowest level of 10.0 ppm recorded (a reduction of 3.1 ppm). A_{254} is widely considered as a measure of aromatic and conjugated double bonds of organics in water. The results showed UV absorbance reductions as follows: UVB (0.091 cm^{-1}) > UVA (0.072 cm^{-1}) > PAR (0.010 cm^{-1}), (Figure 2). The sample with UVB + BAS showed a marked decrease in A_{254} (0.168 cm^{-1}), indicating that bacteria in the sand significantly degraded the reservoir NOM.

3.2 Jar Testing

Figure 3 shows the comparison of NOM removal by irradiation and coagulation. Only UVB and UVA irradiation reduced the DOC concentration via photomineralization, with the UVB + BAS sample showing the highest reduction. The removal of NOM by alum coagulation was greater than removal by photomineralization. Comparing all the water samples, the lowest DOC concentration achieved was approximately 4.7 ppm. For most of the treated water samples, the final DOC concentration fell in the 4.7 to 6.3 ppm range, with the exception of samples treated at low alum concentration (80 mg/L) and high pH (pH 7). These results show that irradiation of the raw water reduced its treatability; and can be explained by the formation of smaller NOM being harder to remove by conventional treatment with alum. However, the combination of UVB irradiation with BAS improved the treatability of water across all treatment conditions, as microbial degradation of NOM could have removed the smaller NOM produced from irradiation.

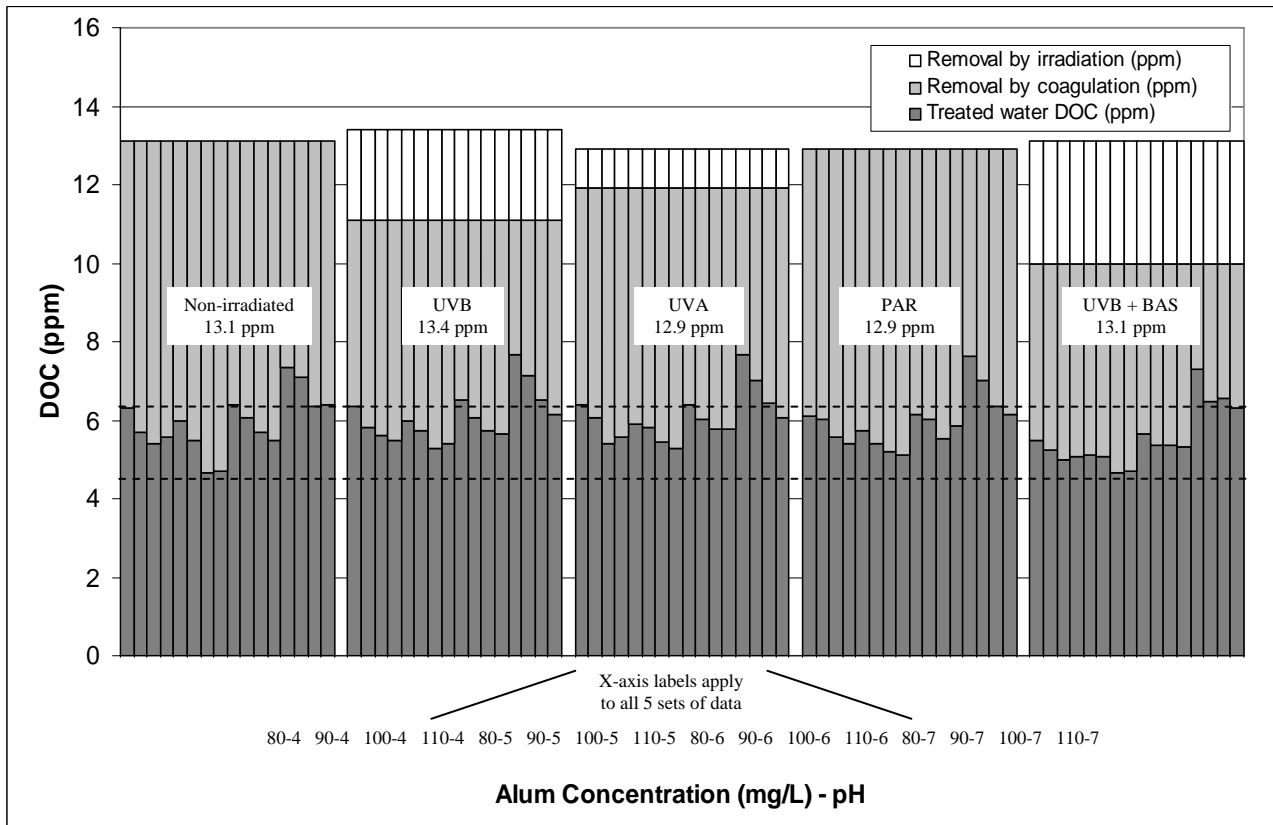


Figure 3. The effects of solar irradiation and alum coagulation on DOC in Myponga Reservoir water.

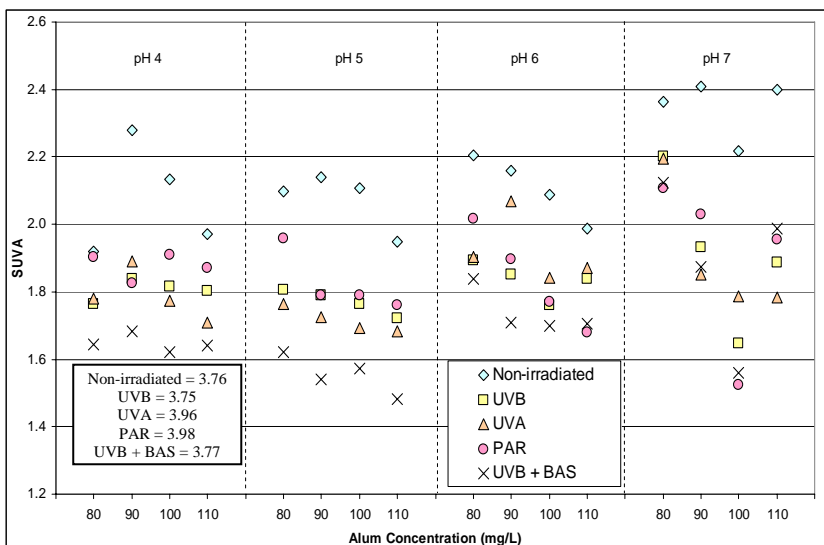


Figure 4. SUVA values of all water samples after alum coagulation.

SUVA values were highest in non-irradiated water (Figure 4) and were similar for samples that had undergone UVB, UVA and PAR irradiation. The lowest SUVA values were obtained from the UVB + BAS samples, attributable to the combination of photodegradation and bacterial effects on NOM. It was expected that the change in SUVA of organics in the treated water samples would have an impact on their biodegradability and chlorine demand.

3.3 Biodegradable Organic Carbon

The BDOC concentrations of the initial and irradiated water samples were compared (Figure 5). The BDOC of the irradiated water samples (UVB, UVA, PAR and UVB + BAS) was not dependent on the treated water DOC concentration and ranged between 0.8 and 1.2 ppm. These BDOC concentrations have the potential to support bacterial growth in distribution systems. From the figure it can be seen that refractory (to microbial degradation) DOC for all water samples (with the exception of the UVB + BAS) remained at approximately 4.5ppm for optimum treatment conditions (pH = 5, alum concentration = 100 mg/L). For the UVB + BAS samples, refractory DOC was lower at 4.0 ppm. This may be due to the organics remaining after coagulation being more assimilable through breakdown by micro-organisms in the BAS.

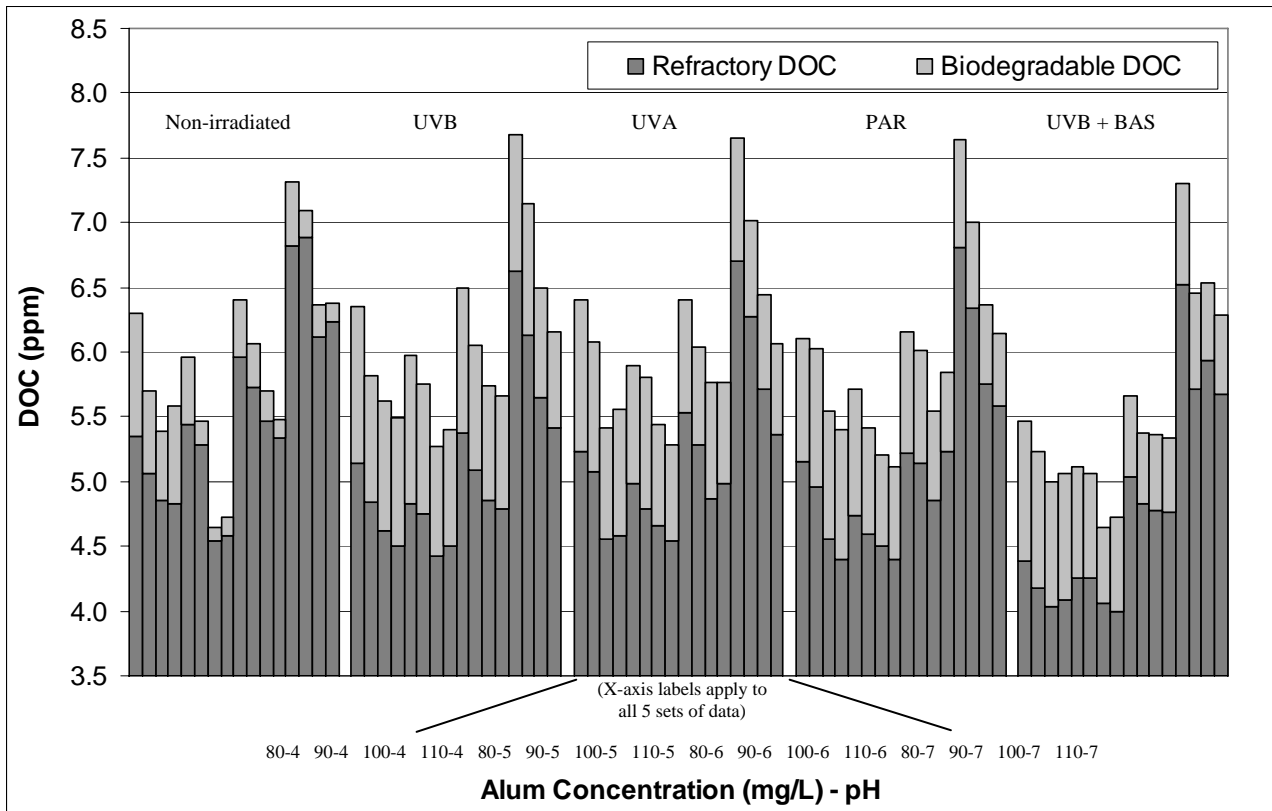


Figure 5. Biodegradable and refractory DOC of all water samples after alum coagulation.

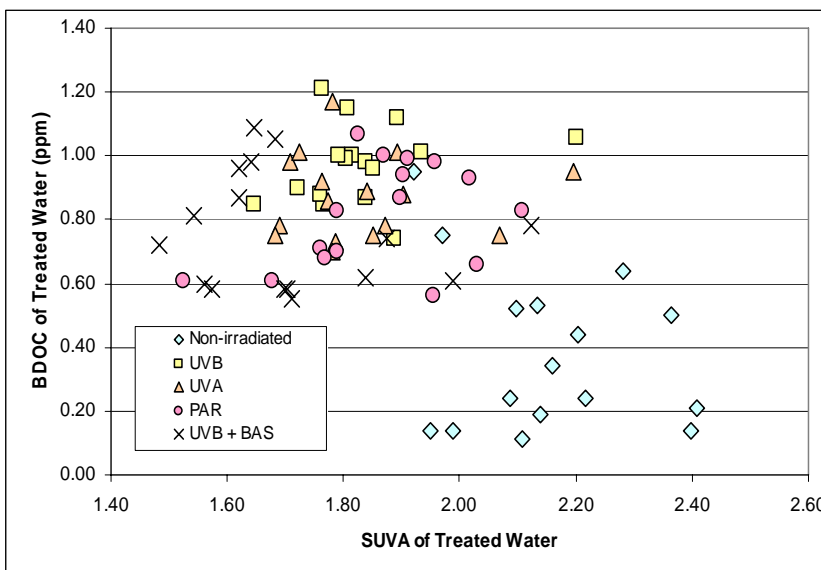


Figure 6. Relationship between BDOC and SUVA of treated water samples.

BDOC was not correlated to the final DOC concentration of treated water, but may be related to other characteristics of the organic matter. By plotting BDOC against the SUVA of treated water (Figure 6), a general inverse trend can be observed. Non-irradiated water had higher SUVA and a lower BDOC while irradiated water had lower SUVA but a higher BDOC. The UVB + BAS samples had the lowest SUVA values, where the predominantly less aromatic NOM would be more labile for bacterial growth in distribution systems.

3.4 Chlorine Residual

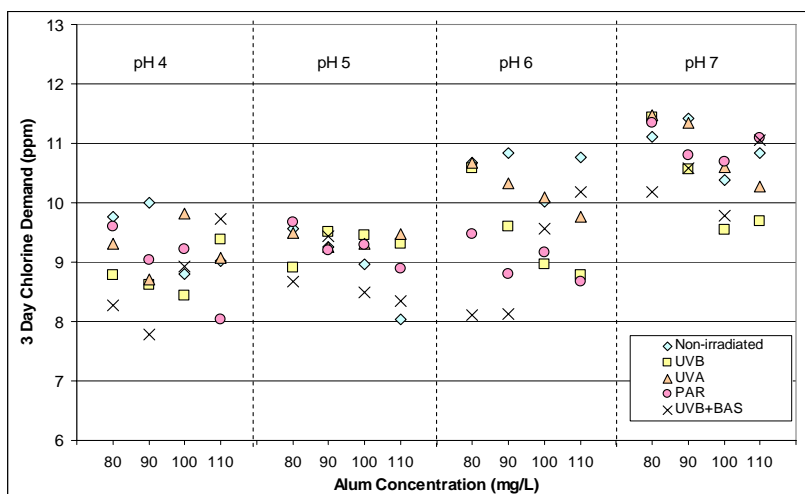


Figure 7. 3 Day chlorine demand of all water samples after alum coagulation.

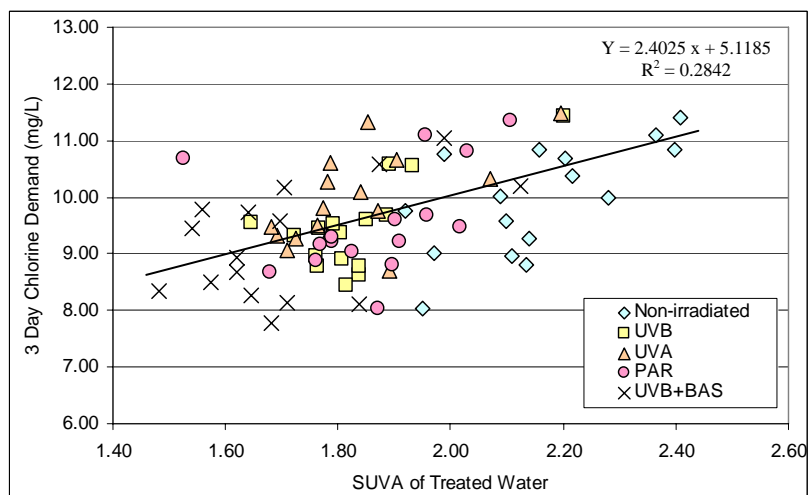


Figure 8. Relationship between 3 Day chlorine demand and SUVA of treated water samples.

There was no clear correlation between chlorine demand and irradiation conditions, with the exception of pH used during coagulation (Figure 7). It is known that slightly acidic conditions are favoured in alum coagulation, consequently, higher DOC concentrations occur for water samples treated at pH 7. Chlorine demand of water after coagulation is also linked to the chemical characteristics of organic matter found in water. The plot of 3-Day Chlorine demand vs SUVA shows that water samples with NOM of higher aromaticity led to a higher chlorine demand, and vice versa (Figure 8). The non-irradiated treated water samples had higher SUVA values compared with the other irradiated samples. Chlorine demand data are scattered (7.8 mg/L to 11.5 mg/L) and the correlation between it and SUVA is weak. It can be assumed that treated water with low SUVA (<2) has a higher BDOC concentration while treated water with high SUVA (>2) has higher chlorine demand and likely higher DBP formation potential.

4. Conclusions

This work has shown that solar radiation has the potential to affect the quality and treatability of reservoir water. Hence, there may be benefits from catchment and water storage management strategies that minimize NOM levels in reservoirs and the subsequent need for conventional water treatment. Artificial destratification is a reservoir management option used by water managers for the control of algae and mobilisation of metals from sediments. Destratification will be studied for its impact on altering the exposure of UV light in reservoir water and the consequential impact on the character and treatability of NOM present in the water in further work.

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