International Conference on Hydroinformatics

2014

Numerical Study On Climate Variation And Population Growth Impacts On An Australian Subtropical Water Supply Reservoir

Edoardo Bertone

Rodney Stewart

Hong Zhang

Kelvin O'Halloran

11^{th} International Conference on Hydroinformatics
HIC 2014, New York City, USA

NUMERICAL STUDY ON CLIMATE VARIATION AND POPULATION GROWTH IMPACTS ON AN AUSTRALIAN SUBTROPICAL WATER SUPPLY RESERVOIR

EDOARDO BERTONE (1), RODNEY A. STEWART (1), HONG ZHANG (1), KELVIN O'HALLORAN (2)
(1): Griffith School of Engineering, Griffith University, Parklands Drive, Southport, Queensland, Australia
(2): Scientific Service and Data Systems, Seqwater, Brisbane, Queensland, Australia

The effects of climate changes and population growth have been assessed for Advancetown Lake, located in the Gold Coast region, Australia, by using a one-dimensional numerical model. In particular, the focus was to understand if a shift from monomixis to meromixis would take place. The results showed that, by applying the downscaled climate change projections, a gradual shift to meromictic lake characteristics would occur, with a considerable increase in partial lake turnovers after 2070. Moreover, a noticeable increase in the water temperature in the epilimnion will strengthen the stratification during summer. The model showed how the chance of partial turnovers would be proportional to the lake's volume; hence increased water demand might play a central role and keep the lake to a monomictic regime. The sensitivity analysis results showed that air temperature and short-wave radiation are the two most important inputs for the model, thus their future variations are highly relevant for determining the mixing regime of Advancetown Lake. The predicted changes in water temperature and lake circulation will affect the nutrient cycles and the frequency of algal blooms, having implications for the raw water treatment, which will have to be adapted to handle higher variability and concentrations in nutrient loading.

INTRODUCTION AND BACKGROUND

As stated by the Intergovernmental Panel of Climate Change (IPCC) in 2007, the anthropogenic increase in greenhouse gases emissions is having an effect on the most recent climate change (CC) that goes well beyond the natural causes. The main consequence is a substantial increase in temperature, with calculations predicting a rising global average surface temperature up to 5.4 °C by 2099 [1]. However, understanding and monitoring the effects of CC is challenging, because of its spatial variation and the multitude of responses within an ecosystem. Interestingly, lake ecosystems can be considered a valid sentinel for CC; in fact, besides being very sensitive to changes in climate, they appear to be able to integrate the variations occurring in the surrounding atmosphere and landscape [2]. In particular, long-term evolution of the mixing regime and in the thermal structure represent a good indicator of CC because of their directness and sensitivity to climatic forcing; additionally, they severely affect nutrients and oxygen concentrations [3], thus their long-term trends are of primary importance for the whole lake ecosystem. Since, as pointed out by previous studies [4], "stationarity is dead", the effects of CC must be taken into account to better understand the evolution of, among others, the lakes physical and biogeochemical processes, with associated implications on water quality and treatment in case the lakes or reservoirs are used as a drinking water storage.

Thermal stability and mixing patterns are expected to change as a result of future climate [5,6]; this might imply the mixing regime shifting from polymictic to dimictic, dimictic to monomictic, or monomictic to oligomictic [7,8]. Previous studies dealt with the effect of climate on vertical mixing and thermal stratification; in Lake Zurich, it was noticed a 20% increase in the thermal stabilization in the period 1947-1998, along with a 0.24°C per decade increase in epilimnetic water temperature [9], and also that the increasing air temperature lead to a suppression of deeply penetrative winter mixing events [10]. In Lake Michigan, through the use of a one-dimensional numerical model it was assessed that, under three different CC scenarios, the water temperature will increase, thus strengthening the thermal stratification; this suggested that in the future the lake might not turn over for most winters [11]. CC also brought to an increase of the mean water temperature of the Earth's deepest lake, Lake Baikal, by 1.21°C since 1946 [12].

Although the aforementioned studies show similar reactions to CC for different types of lakes, it is important to be cautious in making broad statements about the ability of lakes to capture the effect of the evolving climate, since their behavior can be quite different with different lake morphologies, catchment characteristics and geographic location [3]. Recent studies [13] analyzed the mixing processes involved in Advancetown Lake; interestingly, despite being a warm monomictic lake, a warmer than usual winter did not allow a full circulation during 2013. However, the reservoir was recently upgraded and reached for the first time the full capacity in summer 2013, thus requiring more work to break down the thermal stability. The current study, based on these findings, will investigate if the transition from monomixis to meromixis will be permanent, and which factors mostly affect this shift in the mixing regime. A qualitative assessment of the implications for the reservoir's water quality will help the bulk water supplier in implementing new strategies for a future improved water treatment management.

RESEARCH METHODS

Research domain

Advancetown Lake (Figure 1), also called Hinze Dam (153.28°E, 28.06°S), is a subtropical reservoir located in South-east Queensland, Australia. It supplies most of the water provided to the Gold Coast region. The dam was originally constructed in 1976 creating a storage capacity of 42,400 ML. However, two subsequent upgrades (the last one, 'Stage 3', completed in 2011) raised its capacity to the current 310,730 ML with an average depth of 32 m. The surface area is 9.72 km^2 while the catchment area covers 207 km^2. The reservoir presents two arms: the dam's main source of water is the Nerang River, flowing through the Numimbah Valley; the other arm consists of its tributary, the Little Nerang Creek, where the Little Nerang Dam (the first to supply water to the Gold Coast) was built in 1961. The water is drawn from the most convenient depth (typically around 3-6 m below the surface) through an intake tower located close to the dam wall, and it is distributed to the nearest potable water treatment plant located 10 km northeast. The State-government owned Seqwater is the bulk water supplier for the entire South-East Queensland region and owns and operates Hinze Dam and its associated potable water treatment plants.

Currently, water quality is primarily monitored through laboratory analysis of manually collected, weekly water samples. Nevertheless, in 2008, an in-situ Vertical Profiling System

(VPS) was installed near the intake tower (see green point A in Figure 1). The VPS consists of a YSI probe attached by a cable to a floating buoy that is automatically winched up and down the water column to collect water quality parameters such as temperature, DO, pH, conductivity, redox potential and turbidity. Collected data for the whole profile is transmitted via telemetry every three hours. The VPS location is also near the weekly water samplings site, where the depth is higher than average (typically higher then 50m).

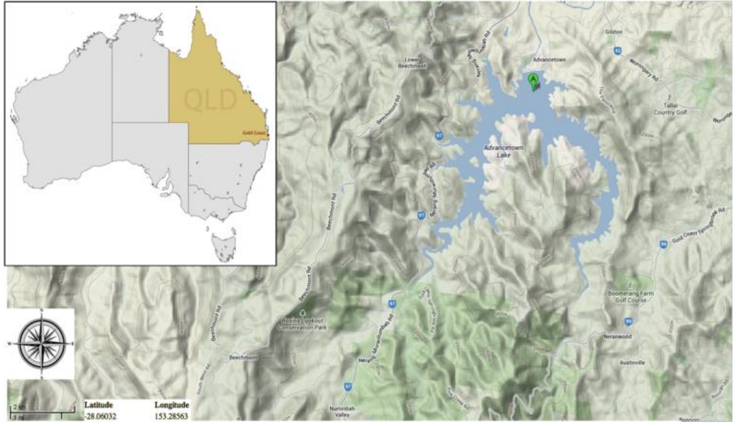

Figure 1: Advancetown Lake map; green “A” represents the VPS location.

Data collection

Through an effective collaboration with Seqwater, data from VPS and manual water samplings were made available. For the purpose of this study, only water temperature data were extracted from the VPS database. The data period starts in 2008 (when the VPS was installed), with a 3-hours frequency. To reduce the computational time, daily data was considered, thus ignoring daily variations. Meteorological data was collected from the Australian Bureau of Meteorology (BoM), and river inflow and temperature information from the Department of Energy and Resources Management of the Queensland Government (DERM).

Seasonal change factors for meteorological variables for 2030-2050 and 2070-2090 were taken from Helfer *et al*. [14]. The coefficients were derived from the average of an ensemble of 9 General Circulation Models (GCM), based on the A2 scenario from the IPCC [1]. The coefficients were recalibrated by downscaling the ensemble model to a location rather near Advancetown Lake, thus it is reasonable to assume the same coefficients for this study location. Table 1 illustrates the total seasonal variations predicted for 2090. The changes are in relation to the baseline climate, defined from 01/01/1990 to 31/12/2010 [14].

Table 1. Total variation coefficients for period 2014-2090 applied for this study, based on mean values for 1990-2010.

Variable	Unit	Summer	Autumn	Winter	Spring	Year-averaged	Year-averaged
Air Temperature	°C	+2.57	+0.77	+3.06	+4.6	+2.74	+13.47 %
Solar radiation	W/m^2	-10.67	-23.52	+16.03	+18.95	+0.21	+0.09 %
Vapor pressure	mbar	+0.30	-0.07	+0.07	+0.46	+0.19	+1.20 %
Wind speed	m/s	+0.05	-0.10	-0.27	+0.13	-0.05	-1.60 %
Rainfall	mm/day	+0.3	-0.25	-0.05	-0.09	-0.02	-1.20 %

It can be noticed how the main change regards the air temperature (+2.74°C annual-averaged final increment predicted for 2090), while the other meteorological variables will change proportionally less, although often (e.g. for solar radiation) seasonal variations are quite relevant.

Finally, six scenarios regarding different possible increases in population and associated water demand for the Gold Coast region were taken from recent studies [15].

Model calibration

General Lake Model (GLM), developed by the University of Western Australia [16] is a one-dimensional hydrodynamic model that conducts a lake water and energy balance by incorporating a flexible Lagrangian layer structure and computes vertical profiles of temperature, salinity and density. Since it is one-dimensional, horizontal invariability must be verified and assumed; nevertheless, previous studies [13] showed how the volume of Advancetown Lake is high and the discharge rate relatively low, thus leading to a high residence time (about 5 years after upgrade) and very slow horizontal velocities; hence the assumption can be made and the model applied.

In order to calibrate the parameters of the model, firstly a calibration period was chosen, going from 4/7/2009 (since on that day the water column temperature was homogenous, thus creating ideal initial conditions) to 29/2/2012. Because the main focus of this research regards thermal stratification/destratification, it was decided to optimize the variable ΔTw, intended as the water temperature differential between top and bottom of the reservoir. Thus the parameters were systematically changed in order to calibrate the model in such a way to minimize the Root Mean Squared Error (RMSE) between the target and the calculated ΔTw. Table 2 lists those parameters whose initial value was changed in order to improve the model performance. Eventually only few parameters needed a recalibration, but they brought to a substantial improvement from the initial RMSE (which was 3.77 °C).

Table 2. Parameters calibration

Symbol	Description	Initial value	Final value	Final RMSE [°C]	RMSE reduction
h_{max}	maximum layer thickness [m]	2	1.5	3.65	3%
C_m	bulk aerodynamic coeff. for transfer of momentum	0.0013	0.00195	3.13	14%
C_h	bulk aerodynamic coeff. for sensible heat transfer	0.0014	0.014	1.56	50%
C_e	bulk aerodynamic coeff. for latent heat transfer	0.0013	0.0026	1.29	17%

Model application

Once the parameters were calibrated, the model was applied to the period 2014-2090, where the input time series were repeated and changed by systematically applying the change coefficients partially illustrated in Table 1. For the periods where coefficients were not available (2014-2030; 2050-2070), a linear interpolation between the climate coefficients of the neighboring periods was performed.

Several scenarios were created and assessed; in order to see the effect of changes in each meteorological input, scenarios were created where only one single variable was changed according to CC predictions. Regarding water demand, it was considered, after an assessment of the future possible variations in population and in water demand per person, 3 different scenarios: a small conservative one, where in 2090 the water demand will be tripled; an average one, where it will be 4 times higher; and an extreme one, with a 5-times increase. An increase in water demand will basically imply and increase in the outflow from the dam, redirected to the closest water treatment plant (WTP). The volume of raw water drawn and treated is decided on a monthly frequency based on the Monthly Operating Supply Schedules (MOSS) issued for each WTP, and it depends not only on demand estimates, but also on weather, water quality, time of the year, cost of production, maintenance requirements, etc. (personal communication from WTP operators); however, a certain increase in water demand would imply the same increase in outflow, as long as the maximum treatment capacity of the treatment plant is not reached. Hence, another scenario was considered where the outflow could not exceed the current WTP maximum capacity. Finally, since Advancetown Lake is connected to the Seqwater Grid which, through a system of pipelines, connects most of the main reservoirs and a desalination plant in the South East Queensland and allows pumping water towards drier areas, it is assumed that, when the lake level will go beyond 30m (about 15% of the volume), the outflow from the dam for water treatment will be interrupted.

RESULTS

Model input variables sensitivity analysis

In order to assess which variables mostly affects the vertical thermal stratification/mixing in Advancetown Lake, sensitivity analysis was conducted by applying a 10% random error (white noise) to each model input variable time series, and then measuring the loss of performance (i.e. ΔRMSE) for the period 2009 to 2012 (see Figure 2).

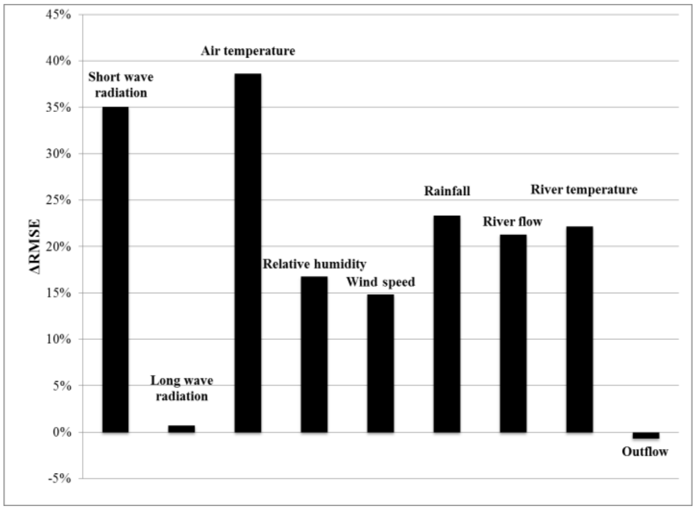

Figure 2. Thermal stratification/mixing model sensitivity analysis

Figure 2 illustrates that the two most important model input variables are air temperature and short wave radiation, because the applied error was magnified in the model performance (from 10% to more than 30%). Since in the future those two variables are supposedly the ones that will show the highest variations (see Table 1), it can be stated that they will have the strongest influence on the future mixing regime in Advancetown Lake. Most of the other input variables are also important and displayed similar levels of significance, since their random error was still substantially increased when transferred to the model outputs. However, they will all show much lower variations than air temperature or solar radiation in the future; therefore they will not affect the mixing processes with the same degree of strength. Finally, long wave radiation does not considerably affect the thermal differential and neither does the outflow. However, the amount of reservoir outflow might become more important if it is part of a long-term trend of the storage reservoir being depleted to a much lower volume (i.e. storage height substantially reduced).

Climate change and urban development impacts

In Figure 3, the future probability of a full winter lake circulation for a series of clustered periods (i.e. 2016-2035 to 2076-2090) has been assessed. Four simulations were run, considering different scenarios of water demand, as previously explained. However, for the purpose of reporting the results, the outcomes of these simulations were clustered into two storage reservoir scenarios: (a) low storage volume (< 40%) years; and (b) high storage volume (> 80%) years (Figure 3). The reason this clustering was done was to illustrate that the winter turnover was also highly dependent on the storage volume (i.e. height of vertical water column) and thus to show how the reservoir would mix in extreme volume situations (i.e. very low or high).

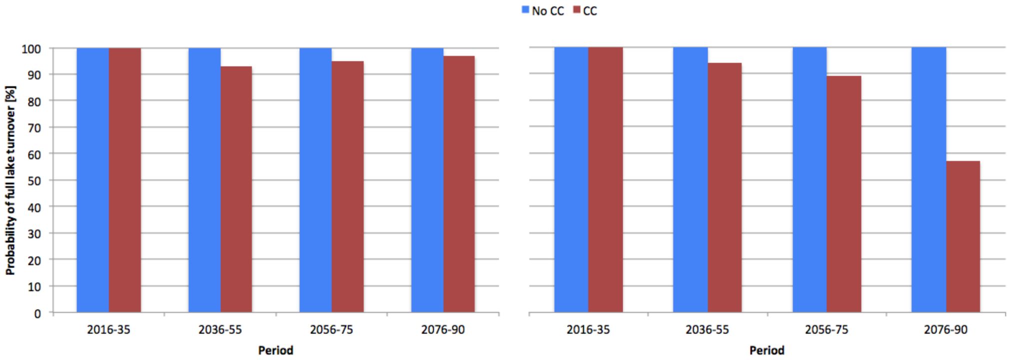

Figure 3. Probability of full reservoir destratification or turnover; (a) low storage volume years; (b) high storage volume years.

Figure 3 illustrates that if CC was not to occur, then Advancetown Lake would keep its monomictic regime regardless of its volume. However, once the predicted CC modifications to input variables are applied, the volume (i.e. water column height) plays a central role, especially at the end of the simulation period (2076-2090) when the CC changes are at their extremes. Figure 3b shows that the probability of a full circulation reduces to 60% by 2076-2090 in case of high reservoir volume. The modelling also showed that if there was a higher draw or demand on the reservoir in the future, that would decrease the water storage (i.e. Figure 3a scenario), then there would still be a extremely high probability of full lake turnover occurring, even if CC was to occur. In this case, the lower reservoir volume implies less work necessary to mix the whole water column, which would be expected. Therefore, even though CC is strengthening the typical winter thermocline, the reservoir vertical height is lower on average for this scenario, thereby requiring less work to be applied for a full lake turnover.

In conclusion, the modelling shows that CC alone has an impact on the traditional winter destratification process with a shift towards more prevalent meromixis conditions in the reservoir; however, the likelihood of partial circulation is proportional to the lake’s volume, which can be affected by e.g. an increased future water demand, or “El Nino/La Nina” events.

Another important CC effect, shown by the model in any future scenario, is the increase in water temperature both in the epilimnion and in the hypolimnion, leading to stronger and longer summer stratifications (Figure 4). Such stratifications will have an impact on the traditional biogeochemical processes of the lake, potentially presenting new water quality issues to manage.

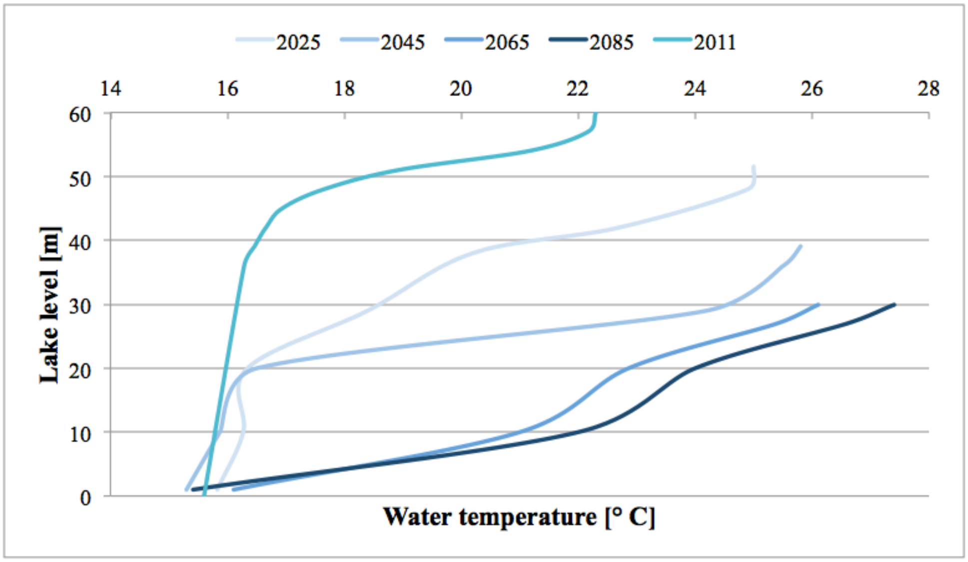

Figure 4. Summer-averaged temperature water profiles with CC and high future water demand

CONCLUSIONS

Understanding the long-term trends in the mixing regimes of a drinking water reservoir is paramount for the water supplier, since physical and biogeochemical processes interact together and a shift in mixing characteristics can deeply affect water quality.

This study assessed that, under the effect of CC, Advancetown Lake will most likely behave as a meromictic lake whenever its volume will be high, and as a monomictic whenever its volume will be low. The more frequently occurring partial circulations will be of concern for the water supplier, since there will be less oxidization of bottom layer nutrients due to them experiencing limited mixing or contact with the atmosphere. Moreover, the monimolimnion will remain anoxic, thus the release of nutrients such manganese or iron from the sediments will continue straight after the turnover. This will result in much higher nutrient concentrations that will reach the epilimnion during the next winter, if a full circulation will occur, thus creating significant issues for the raw water treatment.

Another consequence of the future changes is a substantial increase in the surface water temperature and of the strength of the stratification, in accordance with previous studies. Rising temperatures favor cyanobacteria growth [17], and thus algal blooms might occur more often; likewise, increased water temperature and stronger thermal stability imply lower oxygen solubility and faster depletion; the lower the dissolved oxygen, the sooner it will be depleted, and the earlier the nutrient release will commence. Thus, nutrients concentration might rise too.

The findings of this study will help Seqwater in long-term water management decision-making, and it can be recalibrated for other dams for updated CC projections.

ACKNOWLEDGEMENTS

The authors are grateful to Griffith University for scholarship support for Mr Bertone and to Seqwater for their technical and financial support to this collaborative project. The Griffith University Climate Change Response Program (GCCRP) is also acknowledged for supporting this conference paper.

REFERENCES

[1] IPCC, "*Climate Change 2007: the Physical Science Basis.",* Contribution of Working Group I to the 4th Assessment Report of the Intergovernmental Panel of Climate Change [Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M. and Miller, H.L. (eds.)]. Cambridge University Press, Cambridge, UK and New York, USA, 996pp. (2007).

[2] Williamson, C.E., Dodds, W., Kratz, T.K., Palmer, M., "*Lakes and streams as sentinels of environmental change in terrestrial and atmospheric processes",* Frotn. Ecol. Environ., 6, 247-254. (2008).

[3] Adrian, R., O'Reilly, C.M., Zagarese, H., Baines, S.B., Hessen, D.O., Keller, W., Livingstone, D.M., Sommaruga, R., Straile, D., Van Donk, E., Weyhenmeyer, G.A., Winder, M., "*Lakes as sentinels of climate change",* Limnol. Oceanogr., 54(6), 2283-2297 (2009).

[4] Milly, P.C.D., Betancourt, J., Falkenmark, M., Hirsch, R.M., Kundzewicz, Z.W., Lettenmaier, D.P., Stouffer, R.J., "*Stationarity is dead: a whither water management?",* Science, 219, 573-574 (2008).

[5] Hondzo, M., Stefan, H., "*Regional water temperature characteristics of lakes subjected to climate change",* Climatic change, 24, 187-211 (1993).

[6] Stefan, H.G., Fang, X., Hondzo, M., "*Simulated climate change effects on year round water temperatures in temperate zone lakes",* Climatic change, 40, 353-381 (1998).

[7] Boehrer, B., Schultze, M., "*Stratification of lakes"*, Rev. Geophys., 46(2),

[8] Livingstone, D.M., "*A change of climate provokes a change of paradigm: taking leave of two tacit assumptions about physical lake forcing",* Internat. Rev. Hydrobiol., 93, 404-414 (2008)

[9] Livingstone, D.M., "*Impact of secular climate change on the thermal structure of a large temperate central European lake",* Climatic change, 57, 205-225 (2003).

[10] Peeters, F., Livingstone, D.M., Goudsmit, G.H., kipfer, R., Forster, R., *"Modeling 50 years of historical temperature profiles in a large central European lake",* Limnol. Oceanogr., 47, 186-197 (2002).

[11] McCormick, M.J., *"Potential changes in thermal structure and cycle of Lake Michigan due to global warming",* Trans. of the American Fisheries Societies, 119(2), 183-194 (1990).

[12] Hampton, S.E., Izmenst'eva, L.R., Moore, M.V., Katz, S.L., Silow, E.A., "*Sixty years of environmental change in the world's largest freshwater lake – Lake Baikal, Siberia",* Glob. Change Biol., 14(8), 1947-1958.

[13] Bertone, E., Stewart, R.A., Zhang, H., O'Halloran, K., "*Analysis of the mixing processes in the subtropical Advancetown Lake, Australia*" Journal of Hydrology (under review; submitted January 2014).

[14] Helfer, F., Lemckert, C., Zhang, H., "*Impacts of climate change on temperature and evaporation from a large reservoir in Australia",* Journal of Hydrology, 475, 365-378 (2012).

[15] Sahin, O., Stewart, R.A., Helfer, F., "*Bridging the water supply-demand gap in Australia: a desalination case study*", European Water Resources Association (EWRA) 8th international conference, European Water Resources Association, Porto, Portugal (2013).

[16] Hipsey, M.R., Bruce, L.C., Hamilton, D.P., "*General Lake Model: Model Overview and User Information; v 1.3.2"*, available at (accessed on 12/3/2014): http://aed.see.uwa.edu.au/research/models/GLM/Download/AED_GLM_v1.3.2_20131031.pdf (2013).

[17] Paerl, H.W., Huisman, J., "*Blooms like it hot",* Science, 320, 57-58 (2008).