Effects of selective water withdrawal schemes on thermal stratification in Kouris Dam in Cyprus

Shengwei Ma,[1]* Stavros C. Kassinos,[1] Despo Fatta Kassinos[2] and Evaggelos Akylas[1]
[1]Department of Mechanical and Manufacturing Engineering, [2]Department of Civil and Environmental Engineering, Nicosia, Cyprus

Abstract

Thermal stratification and its seasonal variations in Kouris Dam in Cyprus were simulated, and the impact of five different water withdrawal schemes was studied, using the 2-D, laterally averaged CE-QUAL-W2 reservoir model. Based on the model simulations, it was found that the thermal stratification of the reservoir is significant for most of the year. Most importantly, a complete mixing of the water column, triggered by seasonal variations in meteorological conditions, occurs in late-January. Predicted thermal stratification and water temperature profiles in the reservoir are noticeably affected by water withdrawal schemes. It was found that deep-water withdrawals tend to facilitate heat transfer in the water column and deepen the water mixing layer (epilimnion), especially from September to the following January. These study results suggest that it is prudent for Kouris Dam to integrate selective water withdrawal schemes into reservoir management by using the water withdrawal effects on thermal stratification for different water quality management strategies.

Key words

CE-QUAL-W2, Kouris Dam, numerical simulation, selective withdrawal, stratification.

INTRODUCTION

Thermal stratification in deep reservoirs is known to fundamentally affect the structure and functioning of the ecosystems in these reservoirs (Ford 1990; Henery 1999; Nogueira *et al.* 1999; Boland & Padovan 2002). In practice, thermal stratification in reservoirs is affected by both natural processes (e.g. meteorological conditions) and reservoir operation schemes. Selective water withdrawal from different depths of a dam is widely used in managing reservoirs to meet the demands of different water usages. When water is withdrawn from different depths in the dam, the flow patterns and stratification and therefore water quality in a reservoir are usually altered (Kennedy 1999).

Some researchers have reported on the impacts of selective water withdrawals on thermal stratification and water quality in different regions (Stroud & Martin 1973; Martin & Arneson 1978; Fontane *et al.* 1981; Nurnberg *et al.* 1987; Filho *et al.* 1990; Han *et al.* 2000; Milstein & Zoran 2001; Casamitjana *et al.* 2003; James *et al.* 2004). Martin and Arneson (1978), for example, compared the

profiles of temperature, light penetration and other water quality parameters in a deep-discharge reservoir and a surface-discharge lake. They found that the thermal structures, and some water quality parameters, were noticeably affected by the depth of the outflow. Nurnberg *et al.* (1987) studied the impacts of hypolimnetic withdrawal on epilimnetic phosphorus concentrations and internal phosphorus loading in two lakes. They found that discharging anoxic hypolimnetic water, instead of epilimnetic water, could decrease the trophic level, especially for the smaller of the two lakes. Filho *et al.* (1990) simulated the effects of bottom outlet water discharges on stratification and water quality in Cachoeira Porteira Reservoir in Brazil, utilizing the 1-D model, CE-QUAL-R1. They found that the influence of the bottom outlet discharge was not significant in this case, because <15% of the total downstream flow was released through the bottom outflow structure in their simulations. Han *et al.* (2000) used the 1-D reservoir hydrodynamic model, DYRESM, to illustrate that using bottom water outlets in the Sau Reservoir in Spain resulted in a deeper thermocline, compared to water withdrawal from surface outlets. With a similar model, Casamitjana *et al.* (2003) simulated the different thermal stratification patterns resulting from various selective water withdrawal schemes

in Boadella Reservoir, and confirmed that an increased volume of hypolimnion water would be observed if the location of the outlet is shifted from the bottom.

These various studies suggest that the effects of selective water withdrawal on thermal stratification could be significant in some reservoirs under certain conditions. Because of different geographical locations, and therefore different climatic conditions, and different bathymetry and operation schemes of various reservoirs, however, such effects also usually varied among different reservoirs. The purpose of this study is to investigate the potential impacts of different selective water withdrawal schemes on thermal stratification in Kouris Dam in Cyprus, based on model numerical simulations. It is expected that this study will advance our understanding of the role of selective water withdrawal in the stratification and water quality dynamics in Kouris Dam, thereby allowing formulation of a sensible reservoir management scheme by integrating selective water withdrawal schemes.

STUDY SITE

Kouris Dam (34°43′N, 32°55′E) impounds the deepest reservoir in Cyprus, the third largest island in the Mediterranean Sea (Fig. 1). The maximum depth of the
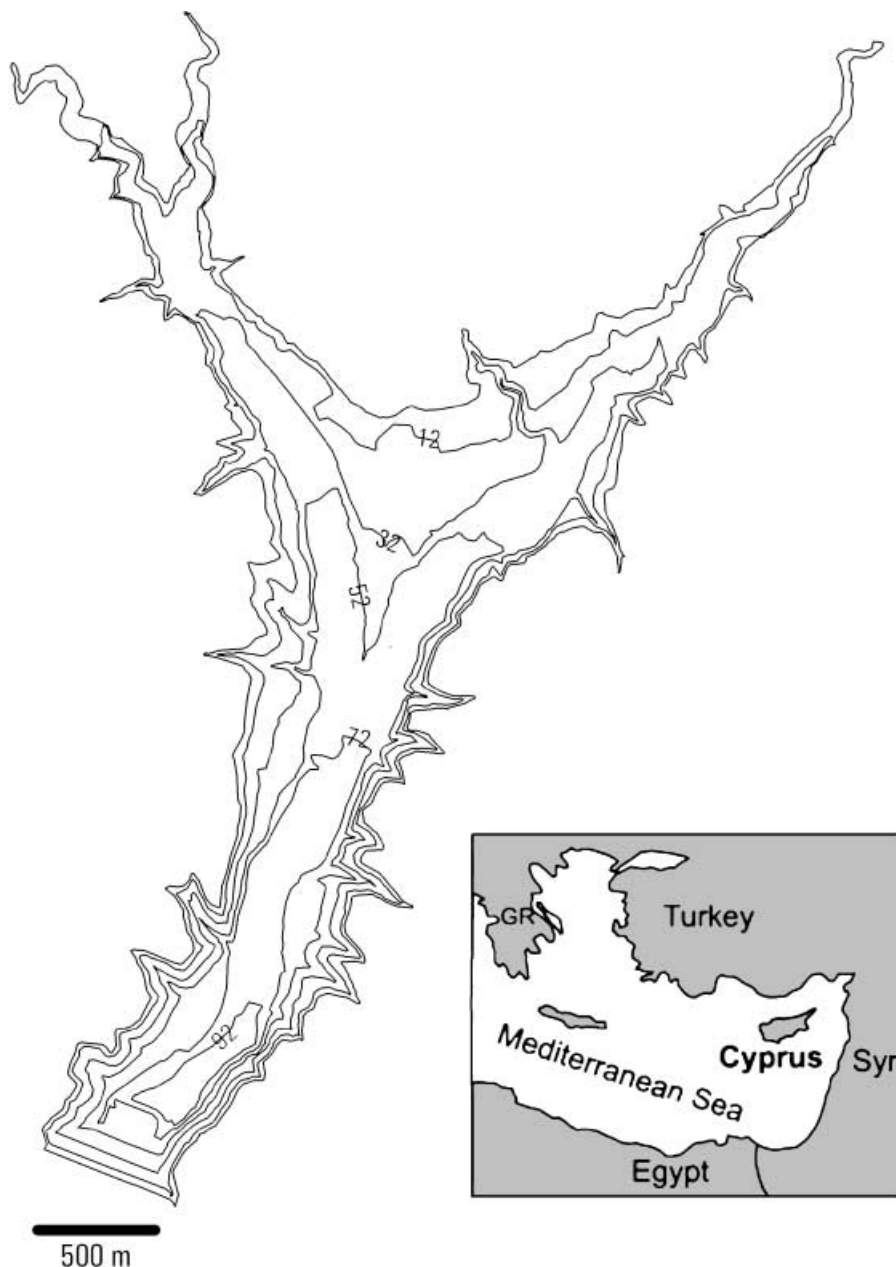

Fig. 1. Bathymetry and location of Kouris Dam (based on topographical map provided by the Water Development Department).

reservoir is 110 m, and the corresponding water volume is 115 million m³. The catchment of the reservoir, a typical mountainous area with steep valleys, encompasses an area of 308 km², with elevations ranging from 150 m at the dam to 1850 m near Mountain Olympus.

A meteorological station (312-3746, Kouris Dam) for this reservoir exists near the dam. The average temperature and dew point temperature at 2, 8, 14 and 20 h at this station for a 16-year period (1990–2005) are illustrated in Figure 2. As Cyprus has a typical Mediterranean climate with mild winters and hot, long and dry summers, ≈80% of its annual precipitation occurs between November and March. The inflows to the reservoir are mainly from three tributaries; namely, the Kouris, Kryos and Limnatis Rivers. Since 1998, an additional water volume of $\approx 12.87 \times 10^6$ m³ per year (averaged over 1998–2005) was transferred from another reservoir (Arminou Dam) outside the catchment area via a 14.5-km tunnel to Kouris Dam. The released water is used primarily for three different purposes, including irrigation, domestic water supply and downstream river recharge. The averaged monthly water inflow (including water transferred from Arminou Dam since 1998) and outflow (withdrawal and evaporation, excluding leakages and seepages) is illustrated in Figure 3.

Kouris Dam has an important role in the water supply of Cyprus because of the vagaries of the weather, which can result in a chronic water shortage on the island. It has been in operation since 1989, and some hydrological, meteorological and water quality data have since been archived. Knowledge on the thermal stratification and hydrodynamics in this reservoir, however, is still very limited. Furthermore, water releases (withdrawal) are currently done through the near-bottom outlet structure, and the impacts of such withdrawals on the stratification, and therefore water quality, in this reservoir are still unknown.

NUMERICAL RESERVOIR MODEL

The 2-D, laterally averaged CE-QUAL-W2 model, which has been widely applied to stratified surface water systems

Fig. 2. Average temperature and dew point temperature at Kouris Dam weather station (312-3746) from 1990–2005.
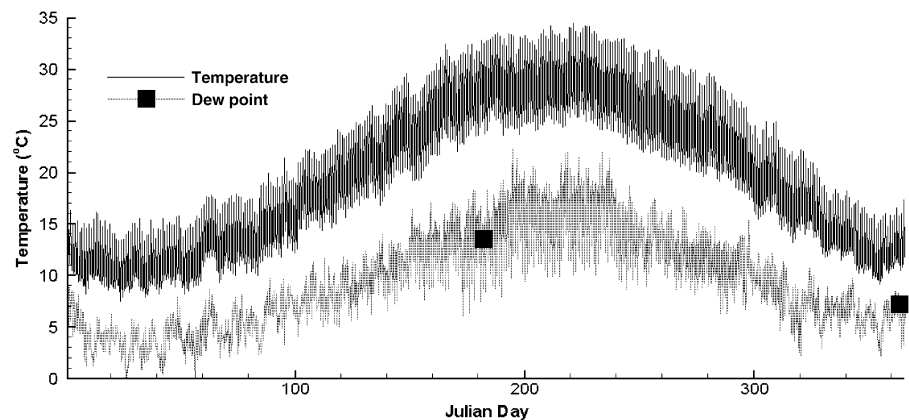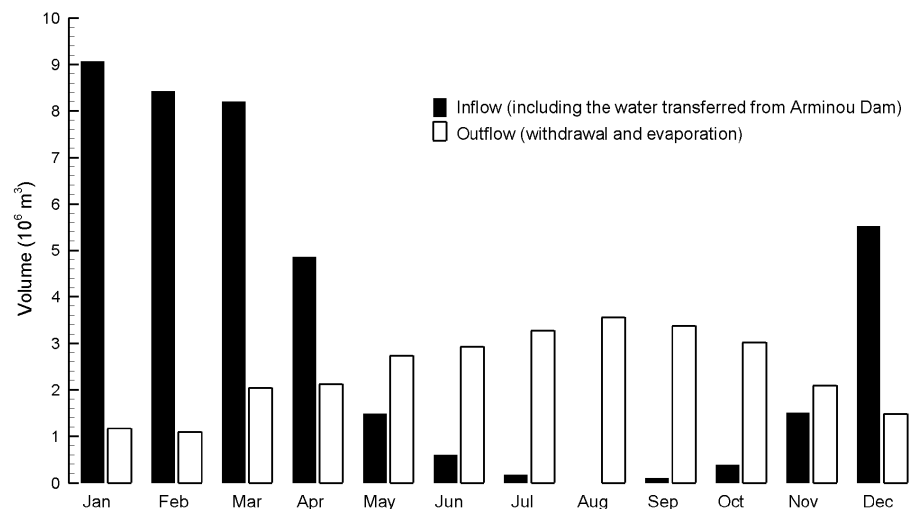
Fig. 3. Average monthly inflow and outflow of Kouris Dam from 1994–2005.

such as lakes, reservoirs and estuaries, was used in this study. It is a two-dimensional water quality and hydrodynamic FORTRAN code, supported by the US Army Corps of Engineers Waterways Experiment Station, and currently maintained at Portland State University. Water levels, horizontal and vertical velocities, temperature, and >20 other water quality parameters can be computed using this model. The model structure, governing equations, numerical algorithms and validation are thoroughly discussed in the supporting documentation (Wells 2000; Cole & Wells 2005).

The CE-QUAL-W2 model has been widely used to study thermal stratifications, hydrodynamics and water quality in deep reservoirs and lakes in various geographical conditions (Kim *et al.* 1983; Garvey *et al.* 1998; Kurup *et al.* 2000; Boegman *et al.* 2001; Deliman & Gerald 2002; Kuo *et al.* 2006). Based on application to >400 different waterbodies exhibiting a wide variety of conditions, the model has been found to be able to accurately simulate water temperature with its default parameters and settings (Cole & Wells 2005).

MODEL CALIBRATION AND SIMULATION CONDITIONS

In all simulations in this study, Kouris Dam was divided into 52 longitudinal segments and 52 vertical cells (layers). The depth of the layers varied from 2 to 3 m, and the length of the segments varied from 150 to 220 m. The model was calibrated using data from the year 2005. Daily meteorological data and monthly hydrological data were used. The simulated and observed surface water temperature in 2005 near the dam is illustrated in Figure 4. It illustrates that the model appropriately simulates the variations in water temperature, with an error usually <0.4°C using the default values. This agreement confirms that the default settings of CE-QUAL-W2 are generally sufficient for simulating temperature in different waterbodies because of the universality of most the parameters related to heat budget calculations.

To simulate the general patterns of the thermal structure of the reservoir, and the effects of different water withdrawal schemes corresponding to average conditions, 6-hourly meteorological data from station 312-3746 (Kouris Dam) and monthly hydrological data, were used in the model. The data from 1990 to 2005 were used to obtain the average meteorological conditions. The average hydrological data were derived from the period between 1994 and 2005. The initial water temperature conditions in the model simulations can be arbitrary, with no effect on the results because the converged solution is obtained by repeating the input data series until the output data series do not change. In this study, this usually can be achieved after four to eight repeat runs of the model, depending on the initial conditions of the simulation. The initial surface elevation of the reservoir was assumed to be 240 m for all model simulations.

RESULTS AND DISCUSSION
Thermal stratification in Kouris Dam

As illustrated in Figure 5, predicted seasonal variations of water temperature in Kouris Dam are obvious, and similar to like other deep reservoirs and lakes in the Mediterranean region. For the surface water layer, the minimum water temperature occurred between late-January and early March. From March to July, the water temperature increased rapidly, reaching a maximum value around 26–27°C by the end of July. From August to the following January, the reverse situation occurred. This seasonal variation in the water temperature pattern in the surface water layer is consistent with that of the air temperature (see Fig. 2). Experiencing ≈340 days of sunshine each year, and with distinct seasonal changes in this semiarid region, the surface water temperature would respond closely to the air temperature variations. For deeper layers (down to 60 m), similar seasonal variation patterns are seen. There are,
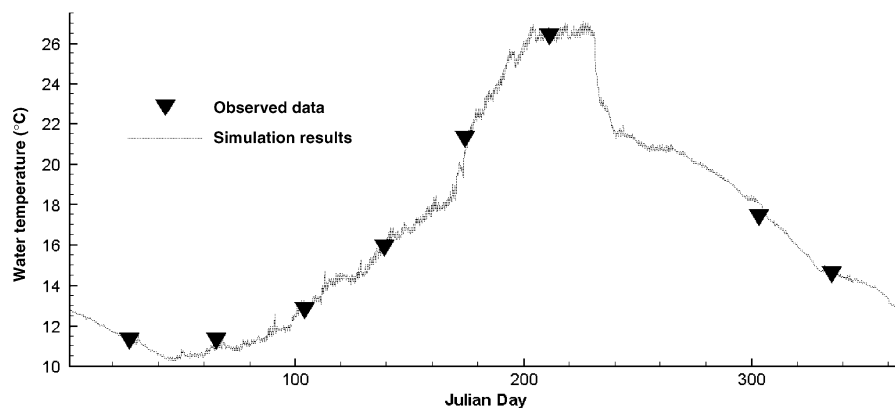

Fig. 4. Model calibration, utilizing observed water temperature data for 2005.

however, significant lags with increasing water depth. In different water layers, the predicted maximum water temperature is reached at a considerably different time, with a lag as large as ≈180 days from the water surface to the 60-m depth. For the surface layer, for example, the maximum predicted temperature occurs in July/August. In contrast, the maximum predicted temperature for 60-m depth occurs in mid-January. When the water depth is >70 m, seasonal variations in water temperature are noticeable, but not significant (i.e. <0.75°C).

Figure 5 also illustrates the process of stratification and destratification in Kouris Dam. From early March, the predicted water temperature increases in the water layers down to the 40-m depth, although the rate of increase is significantly different at different depths. From 10 April (Julian day 100) to 11 August (Julian day 220), for example, the surface water temperature increases from 14.4 to 26.7°C, with an increase rate of ≈0.1°C day^{-1}. The increase rate is ≈0.078 and 0.016°C day^{-1}, respectively, during the same period at a depth of 20 and 30 m. It is emphasized, however, that the maximum value of the increase rate of the water temperature in deep layers could be higher than that at the water surface. At the 20-m depth, for example, the predicted maximum value of the temperature increase rate was ≈0.14°C day^{-1} (from Julian day 190–237). By comparison, this value reaches 0.29°C day^{-1} (from Julian day 253–278) at a depth of 30 m. At the 40-m depth, a similar predicted increase rate (0.3°C day^{-1}) was observed from Julian day 290–310.

It is noted that the water temperature at the surface from early September begins to cool down rapidly, as a result of the decreased air temperatures during this season. Thus, the epilimnion deepens, and the mixing depth increases. By early October, the epilimnion would reach as deep as 30 m and, by early November, this depth would increase to 40 m. The stratification persists for a longer time in the deeper water depths, and there are significant lags in reaching the strongest stratification with increasing water depth. At the 20- and 30-m depths, for example, the strongest stratification occurred in August/September, ≈30–40 days later than that in the surface layer. Stratification in this layer begins to disappear in early October. For the layer between 30 and 40 m, the strongest stratification is observed in early October, ≈70–80 days later than in the surface layer. Stratification in this layer begins to disappear in mid-November. This seasonal variation in the predicted stratification pattern indicates that there is no fall turnover in Kouris Dam, because possibly of its geographical location and meteorological conditions. As shown in Figure 3, the air temperature is still above 15°C until late-November, and the cooling effects in the surface layer are not strong enough to trigger turnover in the fall. From late-January to early February, however, a turnover (complete water mixing) is observed (Fig. 5). This is ≈10 days later than the occurrence of the lowest air temperature period. The surface water begins to cool from late-August, as a result of the steady decrease in air temperature, reaching a minimum water temperature in late-January, which very likely triggers the complete water mixing.

Figure 5 also illustrates the predicted seasonal variations of thermal stratification in Kouris Dam. The thermal stratification is negligible in March, with the temperature difference throughout the entire water column being <1°C. The thermal stratification becomes obvious in May. The temperature gradient in the metalimnion during this month, however, is quite small (only ≈0.2°C m^{-1}), suggesting that the stratification is not strong. The metalimnion temperature gradient is ≈0.8°C m^{-1} by July, reaching 1°C m^{-1}
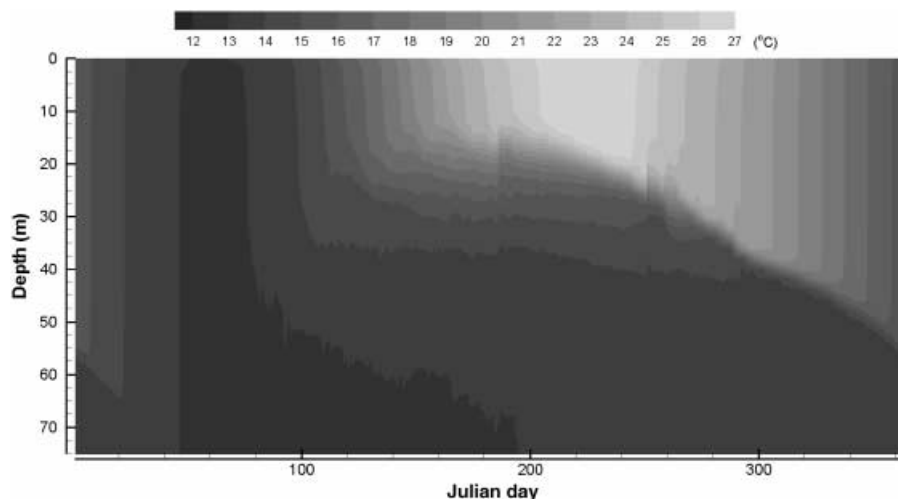

Fig. 5. Contour of predicted water temperature in Kouris Dam for near-bottom water withdrawal.

by November. This indicates that thermal stratification is stronger between May to November. The thickness of the epilimnion increases steadily after July In September, for example, it is ≈23 m, ≈40 m in November, and it can reach 60 m by January. As shown in Figure 5, after the epilimnion reaches a water layer deeper than 60 m, a complete water column mixing (turnover) can be observed in late-January, destroying the thermal stratification. It is note that the predicted water temperature is around 12°C during this complete mixing period. This finding is comparable to that seen for some deep lakes and reservoirs in the subtropical region. For Lake Kinneret, for example, the turnover was observed at a temperature of ≈14°C (Hambright *et al.* 1994).

In layers deeper than 65 m, it was found that the predicted water temperature still changes slightly during the year, although the magnitude of the variation is <0.75°C. This is caused by the water withdrawal from the bottom of the reservoir. When water is withdrawn from the bottom, the water column is partially replaced by slightly warmer water from layers above it. As shown in Figure 5, the predicted variations in water temperature in the upper layers are significant. Thus, the water temperature in the lower water layers tends to vary. The impact of this bottom-water withdrawal on the thermal structure of the reservoir is discussed in the next section.

The impacts of selective withdrawal schemes on thermal stratification

In Kouris Dam, water is usually released (withdrawn) from the bottom part of the dam. As discussed above, this withdrawal could impact stratification in the reservoir. To investigate the role of water withdrawal schemes on stratification, model simulations of four different withdrawal schemes were conducted by assuming: (i) water withdrawal from the surface; (ii) water withdrawal at a depth of ≈20 m; (iii) water withdrawal at a depth of ≈50 m; and (iv) 50% surface-water withdrawal and 50% bottom withdrawal. All other reservoir conditions were kept identical.

The impact of water withdrawal schemes on overall thermal structure

Figure 6 illustrates predicted seasonal variations in water temperature in different layers when the water is withdrawn (released) through the surface layer. It was found that the overall seasonal pattern of the stratification is similar to that of bottom-water withdrawals. Stratification, for example, begins to be obvious from May until the end of the calendar year. Furthermore, the epilimnion layer deepens steadily from the beginning of July until a complete mixing is observed in late-January, similar to that shown in Figure 5. Similar seasonal stratification patterns also were observed in the other three cases, suggesting that the seasonal thermal stratification pattern in Kouris Dam is not likely to be determined by the water withdrawal schemes. The meteorological conditions and bathymetry likely play a stronger role in the thermal stratification than the water withdrawal schemes. For Kouris Dam, the volume of water withdrawn is ≈25.33×10^6 m³ year^{-1} (average for 1994–2005), only ≈22% of the reservoir capacity. This would limit the effects of water withdrawal schemes on the overall seasonal thermal stratification patterns in the reservoir. As previously mentioned, all simulated cases exhibited a complete mixing at almost the same times (late-January to early February), implying that, although deep-water withdrawal could significantly facilitate mixing in the water column, it is not strong enough by itself to trigger a turnover. The complete mixing of the reservoir is likely the result of variations in meteorological conditions, mainly air temperature and wind.
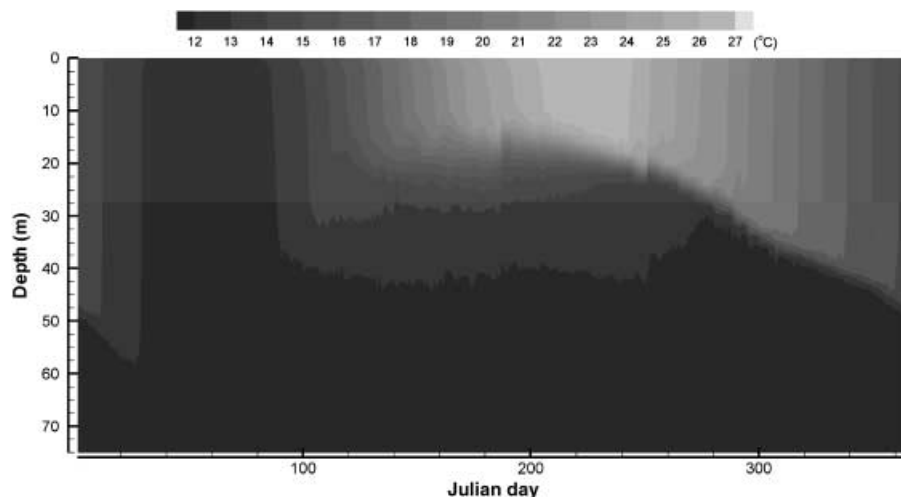

Fig. 6. Contour of predicted water temperature in Kouris Dam for surface withdrawal.

Although the water withdrawal scheme is not able to alter the overall seasonal thermal stratification pattern, its effects on the local water temperature variations are significant. When water is withdrawn from a deeper layer, the outflow of heat from the reservoir will decrease. Thus, deep-water withdrawals could facilitate the heat storage in the reservoir, and could deepen the epilimnion layer. This has been reported for some deep reservoirs (Han *et al.* 2000; Casamitjana *et al.* 2003). In Kouris Dam, it was found that deep-water withdrawal could significantly deepen the epilimnion layer during the period when the air temperature decreases (Fig. 6). For bottom-water withdrawals, for example, the predicted epilimnion layer reaches ≈20 m in early September, 30 m in early October and 40 m in November. For surface-water withdrawals, the corresponding depths are 15, 23 and 31 m, respectively.

It also was found that deep-water withdrawals noticeably increase the water temperature in Kouris Dam. Figure 7 illustrates the resultant temperature differences associated with surface- and bottom-water withdrawals. From early May to December, and in the 20- to 50-m depth range, bottom-water withdrawals result in significantly higher water temperatures, compared to surface withdrawals. The temperature differences could be as high as 7.9°C. It is noted that, after July, zones with large temperature differences coincide with the boundary of the epilimnion layer (Fig. 5). Bottom-water withdrawals deepen the epilimnion layer when the air temperature decreases (i.e. with bottom-water withdrawals, the epilimnion reaches deeper layers than those reached with surface-water withdrawal during this period). Thus, it is reasonable to expect that high temperature differences would be observed near the lower boundary of the epilimnion. During, and after, the complete water mixing period, the temperature difference is still ≈0.5–1°C, implying that the heat storage effects of bottom-water withdrawals affect the entire water column, rather than only the hypolimnion, in Kouris Dam.

Effects of water withdrawal schemes at different depths

At different water depths, both the predicted water temperature and the time to reach the maximum water temperature are affected by water withdrawal schemes. As illustrated in Figure 8, for example, for the period from May to late-August at a depth of 20 m, the water temperature with surface-water withdrawals is usually 3–4°C lower than that with bottom-water withdrawals. Moreover, the maximum water temperature at this depth with surface-water withdrawals is reached in early September, ≈15 days later than that with bottom-water withdrawals. From September to the following January, the predicted water temperature at this depth with surface-water withdrawals is also consistently lower than that with bottom-water withdrawals, although the temperature difference is not significant (≈0.5–1.0°C). For water withdrawals from a 20-m depth, the water temperature at 20 m from May to September is ≈1–2°C higher than that obtained for the same depth with surface-water withdrawal. Moreover, the maximum water temperature is reached ≈1 week earlier than that for surface withdrawals. For water withdrawals from a 50-m depth, the temperature profile at the 20-m depth is similar to that obtained with bottom withdrawals. These results suggest that water withdrawals from deeper depths would facilitate heat transfer in the water column from the surface down to the water withdrawal depth and therefore could weaken the thermal stratification in water layers above the withdrawal depth.

It is noted that, at the 20-m depth from late-September, the 20-m depth and surface-water withdrawal schemes
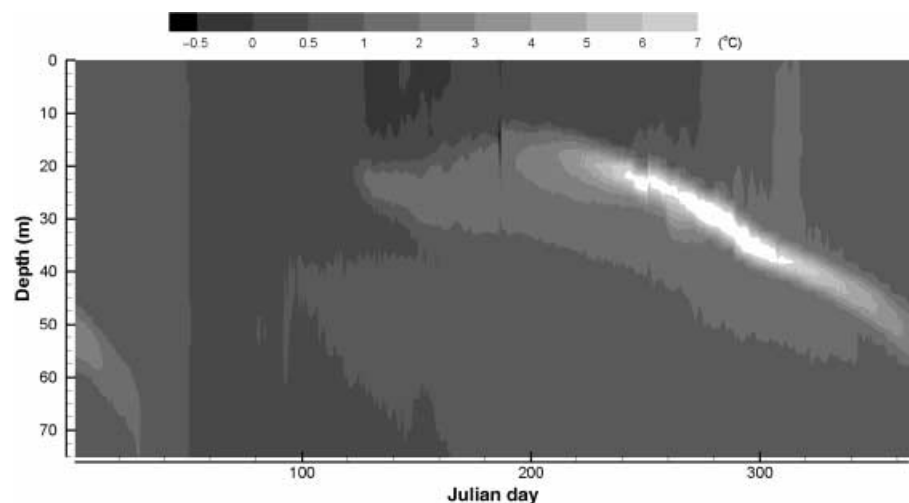

Fig. 7. Seasonal variations in predicted water temperature differences corresponding to near-bottom and surface water withdrawals.

result in negligible water temperature differences. This is likely the result of the epilimnetic thickness during these months. The epilimnion reaches a depth of 20 m or greater for both of these two cases from late-September. Thus, withdrawing water from the surface or from the 20-m depth during these months would not cause a significant difference in the heat budget in the water column. It is also interesting to note that, from May to September, the predicted temperature at this depth is insensitive to water withdrawal from the 20-m depth or from a combination of 50% water withdrawal from the surface and 50% from the bottom. During the cooling down period (from late-September to January), however, these two water withdrawal schemes result in significant temperature differences. It is interesting to note that a withdrawal scheme corresponding to a 50% surface withdrawal and a 50% bottom withdrawal during this period results in consistently higher water temperatures. This difference must be caused by the 50% withdrawal from the bottom, as the surface-water withdrawal and 20-m-depth withdrawal would not cause significant differences in water temperature at this depth during this period.

The seasonal variations of predicted water temperature with different water withdrawal schemes at the 40-m depth

are compared in Figure 9. From September until late-November, the temperature differences at the 40-m depth as a result of different water withdrawal schemes are even larger than that for the 20-m depth. At Julian day 308.5, for example, the water temperature for bottom withdrawal is ≈7.9°C higher than that for surface withdrawal. This can be contrasted to the situation for the 20-m depth, where the maximum temperature difference is ≈4.3°C. The two schemes also cause temporal differences. The predicted maximum water temperature at the 40-m depth with surface withdrawal, for example, is reached at Julian day 336, about 1 month later than that for bottom withdrawal.

It is noted that the water temperature at the 40-m depth is fairly insensitive to whether water is withdrawn from the surface or from the 20-m depth. At a 50-m depth, the temperature differences corresponding to these two withdrawal schemes are even smaller (Fig. 10), implying that, for layers deeper than the withdrawal depths, water withdrawals have limited effects on water temperature and thermal stratification. For the combination of a 50% surface and a 50% bottom withdrawal, the water temperature at the 40- and 50-m depths is significantly lower than that for the 50-m depth and bottom-water withdrawals, but significantly
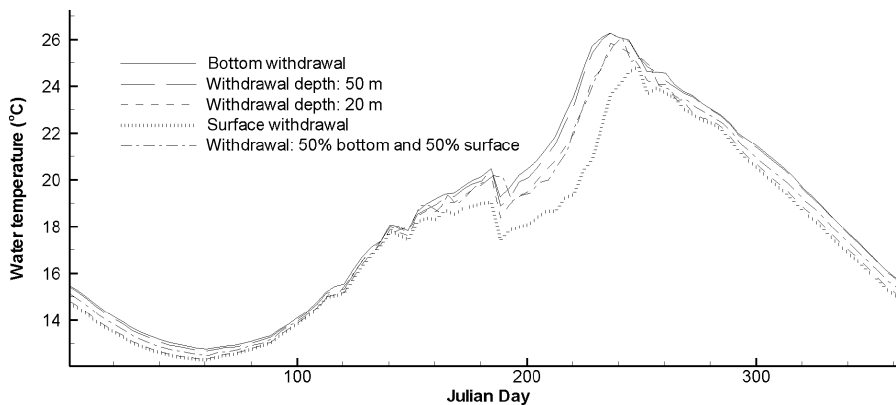

Fig. 8. Comparison of seasonal variations in predicted water temperature at the 20-m depth corresponding to different water withdrawal schemes.
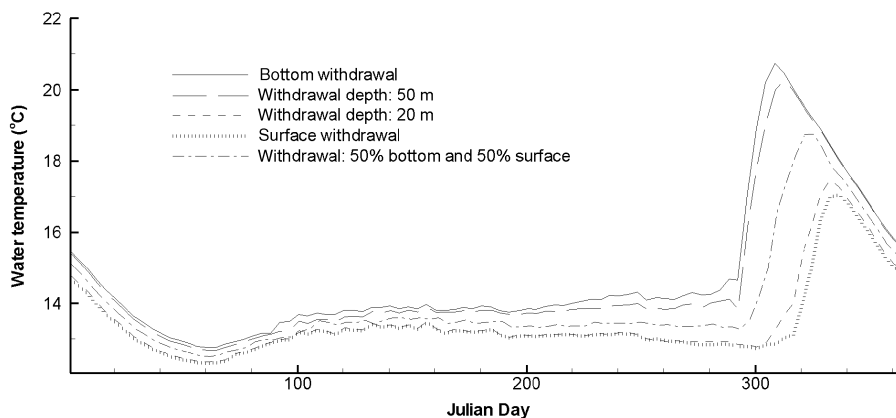

Fig. 9. Comparison of seasonal variations in predicted water temperature at the 40-m depth corresponding to different water withdrawal schemes.

higher than that with surface and 20-m depth water withdrawals. This suggests the quantity of water withdrawn also plays an important role in the thermal structure in Kouris Dam.

Figures 8, 9 and 10 also indicate that water withdrawals at different depths do not have significant impacts on the timing of the minimum water temperature being reached in all water layers. For the whole water column, the minimum water temperature is always reached during the period of complete mixing, regardless of the water withdrawal schemes. Furthermore, the differences in the predicted minimum temperatures as a result of different withdrawal schemes are not significant, compared to those of the maximum water temperature. For all simulated water withdrawal schemes, the differences in the minimum water temperature at all depths are usually <0.6°C, suggesting the heat storage effects of deep withdrawals in this reservoir would not significantly affect its thermal budgets in following years, due possibly to the relative low water withdrawal volumes, as previously mentioned.

When water is withdrawn from a deep depth, the relatively warm water from the upper layers would replace that in the deep layers, thereby facilitating heat transfer from the surface to the deeper layers. The magnitude of such thermal structure changes would depend on the water withdrawal depth, the withdrawal rate and its resulting flow field, the hydrodynamic and meteorological conditions, and the strength of the thermal stratification. This suggests that water withdrawal from certain depths could facilitate water mixing and weaken thermal stratification in the water column. It is sensible therefore to consider the water withdrawal schemes in developing reservoir management strategies.

Reservoir management implications

The main purpose of Kouris Dam is water storage for irrigation and domestic water supply. In 2004, for example, ≈56.1% of the total water release was for irrigation, and 39.4% for domestic supply. The remaining 4.5% was for downstream river recharge. This suggests that the reservoir water quality is an important index for any viable reservoir management schemes.

The water quality in Kouris Dam currently is still acceptable for its purposes. As an example, the nitrate ion concentration was between 1.4 and 7.7 mg L^{-1} in 2005. As a result of increased fertilizer and pesticide usage in the catchment area, however, the water quality of the inflow rivers has gradually deteriorated. For the upstream Kouris River (Khalassa), for example, the nitrate ion concentration in March 1984 was ≈5.5 mg L^{-1}, and 11 mg L^{-1} in March 1988. The concentration increased to 27 mg L^{-1} in March 2001. Thus, the water quality is expected to be a major concern in a couple of years in managing Kouris Dam. The selective water withdrawal schemes could affect water quality through two major mechanisms, including (i) changing the water mixing features (and therefore the pollutant transport process) in the reservoir; and (ii) changing the water quality of the released water (and therefore the quantity of pollutants exported from the reservoir system). To reduce the residence time of pollutants in the reservoir, for example, near-surface-water withdrawals could be considered in wet seasons. In dry seasons, with low external pollutant loads, hypolimnetic water withdrawal could be considered to reduce the internal pollutant loading and to remove anoxic water to alleviate the anoxic conditions in the hypolimnion. Based on the above-noted simulation results, epilimnetic water withdrawal depths should be in the range of 0–20 m. For hypolimnetic water withdrawals, the depth should be >50 m. In the case of possible water pollution accidents upstream of Kouris Dam, epilimnetic water withdrawal should be used immediately if the main objective is to reduce the accumulation of pollutants in the reservoir system. If the main objective is to minimize the effects on such pollutants on downstream water supplies, however,
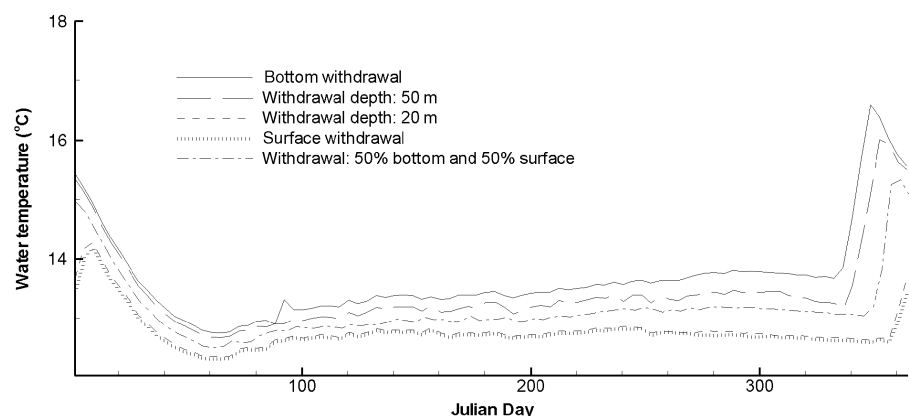

Fig. 10. Comparison of seasonal variations in predicted water temperature at the 50-m depth corresponding to different water withdrawal schemes.

near-bottom hypolimnetic withdrawal could be considered so that there is time to implement some restoration techniques in the reservoir. Detailed reservoir management strategies that incorporate selective water withdrawal schemes will be discussed in a subsequent report derived from this study.

CONCLUSIONS

Thermal stratification in deep reservoirs plays a fundamental role in regulating water quality and ecosystem evolution of a reservoir. Understanding the stratification and its main affecting factors would facilitate the study of the water quality and dynamics of the ecosystem. In this study, thermal stratification of Kouris Dam was simulated, and the impacts of selective water withdrawal schemes were analysed. The CE-QUAL-W2 reservoir model proved to be applicable to Kouris Dam for this purpose.

It was found in this study that thermal stratification in this reservoir is significant for most of the year, with a complete water mixing triggered by seasonal variations in meteorological conditions occurring in late-January. Under the simulation conditions in this study, different water withdrawal schemes for Kouris Dam are unable to alter the overall seasonal variations in the thermal stratification patterns because of relatively low water withdrawal volumes. Water withdrawal from a deep depth, however, would facilitate heat transfer from the surface to deeper water layers, therefore deepening the epilimnion. Deep-water withdrawal was found to significantly increase the water temperature for water layers above, and around, the withdrawal depth, and noticeably weaken the thermal stratification structure in the reservoir in some seasons. The magnitude of such predicted thermal structure changes depends on the water withdrawal depth, withdrawal rates and meteorological conditions. These study results suggest that it is prudent to include selective water withdrawal schemes in the management scheme for Kouris Dam.

ACKNOWLEDGEMENTS

REFERENCES

Boegman L., Loewen M. R., Hamblin P. F. & Culver D. A. (2001) Application of a two-dimensional hydrodynamic reservoir model to Lake Erie. *Can. J. Fish Aquat. Sci.* **58**, 858–69.

Boland K. T. & Padovan A. V. (2002) Seasonal stratification and mixing in a recently flooded mining void in tropical Australia. *Lake Reserv. Res. Manage.* **7**, 125–31.

Casamitjana X., Serra T., Colomer J., Baserba C. & Perez-Losada J. (2003) Effects of the water withdrawal in the stratification patterns of a reservoir. *Hydrobiologia* **504**, 21–8.

Cole T. M. & Wells S. A. (2005) CE-QUAL-W2: A two-dimensional, laterally averaged, hydrodynamics and water quality model, version 3.2. US Army Corps of Engineers Waterways Experiment Station, Technical Report EL-95-1. Vicksburg, Mississippi, USA.

Deliman P. N. & Gerald J. A. (2002) Application of the two-dimensional hydrothermal and water quality model, CE-QUAL-W2, to the Chesapeake Bay–Conowingo Reservoir. *J. Lake Reserv. Manage.* **18**, 1–9.

Filho M. C. A., De Jesus J. A. O., Branski J. M. & Hernande Z. A. M. (1990) Mathematical modelling for reservoir water-quality management through hydraulic structures: A case study. *Ecol. Model.* **52**, 73–85.

Fontane D. G., Labadie J. W. & Loftis B. O. (1981) Optimal control of reservoir discharge quality through selective withdrawal. *Water Resour. Res.* **17**, 1594–604.

Ford D. E. (1990) Reservoir transport processes. In: *Reservoir Limnology: Ecological Perspectives* (eds K. W. Thornton, B. L. Kimmel & F. E. Payne) pp. 15–41. John Wiley & Sons, New York.

Garvey E., Tobiason J. E., Hayes M., Wolfram E., Reckhow D. A. & Male J. W. (1998) Coliform transport in a pristine reservoir: Modeling and field studies. *Water Sci. Technol.* **37**, 137–44.

Hambright K. D., Gophen M. & Serruya S. (1994) Influence of long-term climatic changes on the stratification of a subtropical, warm monomictic lake. *Limnol. Oceanogr.* **39**, 1233–42.

Han B. P., Armengol J., Garcia J. C. *et al.* (2000) The thermal structure of Sau reservoir (NE Spain): A simulation approach. *Ecol. Model.* **125**, 109–22.

Henery R. (1999) Heat budgets, thermal structure and dissolved oxygen in Brazilian reservoirs. In: *Theoretical Reservoir Ecology and its Applications* (eds J. G. Tundishi & M. Straskraba) pp. 125–51. Backhuys Publishers, Leiden, the Netherlands.

James W. F., Eakin H. L. & Barko J. W. (2004) Limnological responses to changes in the withdrawal zone of Eau Galle Reservoir, Wisconsin. Water Quality Technical

Notes Collection (ERDC WQTN-MS-07). US Army Engineer Research and Development Center, Vickburg, Mississippi USA.

Kennedy R. H. (1999) Reservoir design and operation: Limnological implications and management opportunities. In: *Theoretical Reservoir Ecology and its Applications* (eds J. G. Tundishi & M. Straskraba) pp. 1–28. Backhuys Publishers, Leiden, the Netherlands.

Kim B. R., Higgins J. M. & Bruggink D. J. (1983) Reservoir circulation patterns and water quality. *J. Environ. Eng., ASCE.* **109**, 1284–94.

Kuo J. T., Lung W. S., Yang C. P., Liu W. C., Yang M. D. & Tang T. S. (2006) Eutrophication modeling of reservoir in Taiwan. *Environ. Model. Software.* **21**, 829–44.

Kurup R. G., Hamilton D. P. & Phillips R. L. (2000) Comparison of two 2-dimensional, laterally averaged hydrodynamic model applications to the Swan River Estuary. *Math. Comput. Simul.* **51**, 627–38.

Martin D. B. & Arneson R. D. (1978) Comparative limnology of a deep discharge reservoir and a surface discharge lake on the Madison river (Motana). *Freshwat. Biol.* **8**, 33–42.

Milstein A. & Zoran M. (2001) Effect of water withdrawal from epilimnion on thermal stratification in deep dual purposes reservoirs for fish culture and field irrigation. *Aquacult. Int.* **9**, 81–6.

Nogueira M. G., Henry R. & Maricatto F. E. (1999) Spatial and temporal heterogeneity in the Jurumirim Reservoir, Sao Paulo, Brazil. *Lake Reserv. Res. Manage.* **4**, 107–20.

Nurnberg G. K., Hartley R. & Davis E. (1987) Hypolimnetic withdrawal in two north American lakes with anoxic phosphorus release from the sediment. *Water Res.* **21**, 923–8.

Stroud R. H. & Martin R. G. (1973) Influence of reservoir discharge location on the water quality, biology and sport fisheries of reservoirs and tailwaters. In: *Man-Made Lakes: Their Problems and Environmental Effects* (eds W. C. Ackermann, G. F. White & E. B. Worthington) pp. 540–558. Geophysical Monograph Series, Vol. 17. American Geophysical Union, Washington, DC.

Wells S. A. (2000) Hydrodynamic and water quality river basin modeling using CE-QUAL-W2, Version 3. In: *Development and Application of Computer Techniques to Environmental Studies VIII* (eds G. Ibarra-Berastegi, C. Brebbia & P. Zannetti) pp. 195–204. WIT Press, Boston, Massachusetts.