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Comparison of reproducibility of water temperature and water temperature stratification formation by different methods in dam reservoir water quality prediction model

F. Kimura & T. Kitamura
Water Resources Environment Center, Japan, Tokyo, Japan

Y. Tsuruta & T. Kanayama
CTI Engineering Co., Ltd., Tokyo, Japan

R. Kikuchi
Dai Nippon Construction Co., Ltd., Tokyo, Japan

Y. Kitamura
Electric Power Development Co., Ltd., Tokyo, Japan

T. Morikawa & Y. Okada
Nihon Suido Consultants Co., Ltd., Tokyo, Japan

Y. Fukuda
Nippon Koei Co., Ltd., Tokyo, Japan

T. Shoji & A. Mieno
Pacific Consultants Co., Ltd., Tokyo, Japan

T. Suzuki & M. Kobayashi
Yachiyo Engineering Co., Ltd., Tokyo, Japan

ABSTRACT: In order to properly maintain the water quality of the dam reservoir, it is necessary to properly operate the dam facility and the water quality preservation facility installed. In determining these operation methods, simulation using the water quality prediction method plays an important role. However, since there are differences in the basic formula and the discretization method of each water quality prediction method, it is inferred that the reservoir characteristics simulated do not always harmonize ones by other methods from the reproducibility point of view. In this paper, we focused on the water temperature, which is the most basic item among water quality predictions of the dam reservoir. We picked up some methods of water quality prediction that have been ever applied in dam reservoirs. The simulation results are compared in term of the formation conditions of water temperature and water temperature stratification in three case studies to verify the reproducibility and the distinction of each method.

RÉSUMÉ: Afin de maintenir adéquatement la qualité de l'eau du réservoir, il est nécessaire d'exploiter correctement l'aménagement ainsi que les outils de préservation de la qualité de l'eau. Lors de la définition des méthodes d'exploitation, la simulation utilisant une méthode de prévision de la qualité de l'eau joue un rôle important. Cependant, comme il existe des différences dans la formule de base et l'approche de discrétisation de chaque méthode de prédiction de la qualité de l'eau, il est pris pour acquis que les caractéristiques simulées du réservoir ne sont pas toujours en accord avec celles provenant d'autres méthodes du point de vue de la reproductibilité. Dans cet article, l'accent a été mis sur la température de l'eau, l'élément le

plus fondamental parmi les prévisions de la qualité de l'eau du réservoir. Quelques méthodes de prévision de la qualité de l'eau déjà utilisées pour les réservoirs ont été choisies. Les résultats de la simulation sont comparés en termes des conditions de détermination de la température de l'eau et de sa stratification dans trois études de cas pour vérifier la reproductibilité et les particularités de chaque méthode.

1 INTRODUCTION

Environmental Impact Assessment (Environmental assessments) is always necessary before starting a dam project. The most important and most difficult environmental assessment is predicting water quality in the reservoir of the dam you intend to build. Numerous water quality models have been suggested worldwide. For dam engineers, however, selecting the best model for the reservoir they are considering is a challenge.

In this paper, based on the background concerning the water quality prediction of dam reservoirs, by performing the current condition recalculation using a plurality of water quality models in three verification fields having different features, by calculating the differential between the measured value and the calculated value. The degree of conformity of each model was evaluated.

2 METHOD

2.1 *Validation Fields*

Selecting both a validation field and a model is necessary for a model to do the computations to reproduce reservoir data. The following two reservoirs and one lake were chosen as validation fields. In both cases, the needed data was complete for a sufficient period of time and the Ministry of Land, Infrastructure, Transport and Tourism had given permission to use and disclose the data.

2.1.1 *Tsuruda Dam (Concrete gravity Dam)*

Tsuruda Dam, built in 1966, is located in the middle reaches of the main stem of the Sendai River (with a length of 137 km, elevation difference of 1,417 m, and basin area of 1,600 km^2) in southern Kyushu. Its purpose is flood control and power generation. The structure is classified as a medium-size dam in Japan. Specific details are given below (Figure 1).

■ Reservoir capacity: 123,000,000 m^3 ■ Maximum reservoir surface area: 361 ha
■ Dam height: 117.5 m ■ Crest length: 450.0m ■ Catchment area: 805 km^2
■ Yearly average rainfall: Around 2,800 mm ■ Average air temperature: 15.6°C

2.1.2 *Ishitegawa Dam (Concrete gravity Dam)*

Ishitegawa Dam, built in 1973, is located in the middle reaches of the Ishitegawa River (with a length of 27 km, elevation difference of 978 m, and a basin area of 140 km^2), a primary right tributary of the Shigenobu River (with a length of 36 km, elevation difference of 1,233 m, and basin area of 445 km^2) in western Shikoku in the southwest part of Japan. Its purpose is flood control, water supply, and irrigation supply. The structure is classified as a small dam in Japan. Specific details are given below (Figure 2).

■ Reservoir capacity: 12,800,000 m^3 ■ Maximum reservoir surface area: 50 ha
■ Dam height: 87.0 m ■ Crest length: 277.7 m ■ Catchment area: 72 km^2
■ Yearly average rainfall: Around 1,300 mm ■ Average air temperature: 16.1°C

2.1.3 *Kasumigaura (Natural lake and Marsh)*

Kasumigaura is a lake located in the southeast portion of Ibaraki Prefecture is a name that encompasses the four water bodies of Hitachitone River, Lake Sotonasakaura, Lake Nishiura, and Lake Kitaura. Specific details are given below (Figure 3).

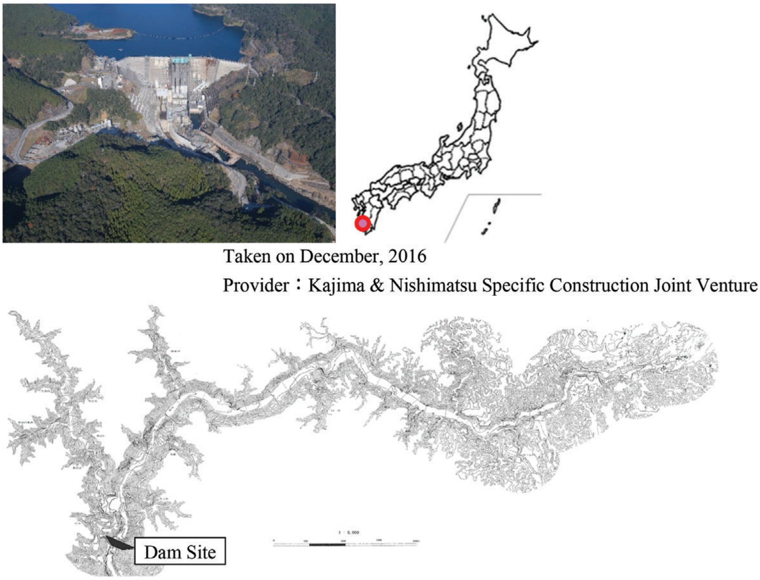

Figure 1. Tsuruda Dam location map and aerial view

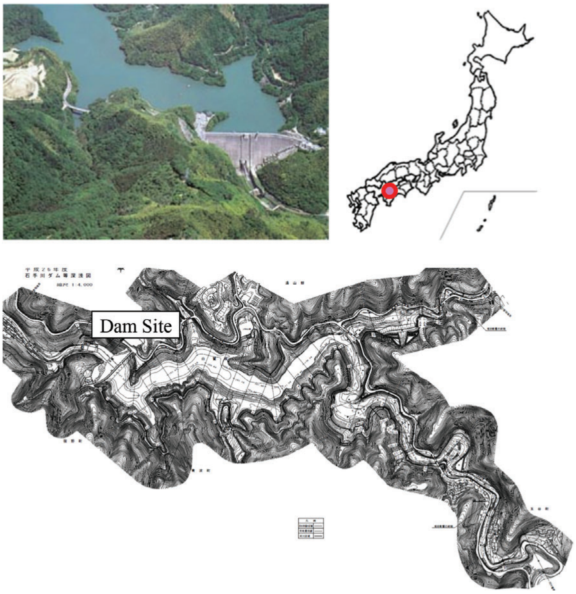

Figure 2. Ishitegawa Dam location map and aerial view

- Basin area: 2,156.7km^2
- Lake surface area: 258.5km^2
  (Lake Nishiura 172km^2, Lake Kitaura 74.5km^2, Lake Sotonasakaura 6km^2, Hitachitone River 6km^2)
- Embankment length: 249.8km
  (Lake Nishiura 120.5km, Lake Kitaura 74.5km, Hitachitone River 54.8km)

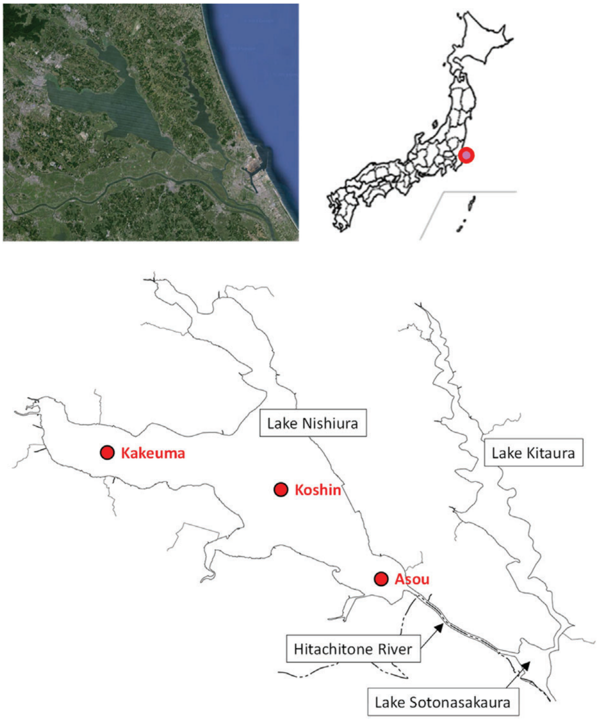

Figure 3. Kasumigaura Lake location map and aerial view

- Yearly average rainfall: 1282mm/year
- Average air temperature: 15.0°C

2.2 *Models Used*

The used model in each verification field was set based on the following concept.

- Tsuruda Dam and Ishitegawa Dam each have a relatively deep reservoir, so a model is needed that can predict thermoclines. Therefore, a 2D vertical model would seem suitable.
- Kasumigaura, on the other hand, is a wide lake and marsh, so they are 3D models that can predict water temperature distribution for wide water bodies.
- The water quality model that can be used in this project group is selected to suit the above.

Based on the above, the model applied to the three verification fields is as in Table 1.

The features of the five models used in this research are as follows.

WEC Model: A 2D vertical model built by the Water Resources Environment Center (Japan). Suited for analysis of reservoirs, it has been used in many environmental impact assessments at multipurpose dams in Japan. Free to use (although use requires permission), the source code is open.

CE-QUAL-W2 Model: A 2D vertical model (boundary/finite element) built by Portland State University. Suited for analysis of reservoirs, lakes, estuaries, and oceans. Good

Table 1. The model applied to the three verification fields

Validation Fields	Models Used
Tsuruda Dam	WEC Model/CE-QUAL-W2 Model/SMOW-T2 Model
Ishitegawa Dam	WEC Model/CE-QUAL-W2 Model
Kasumigaura Lake	Fantom3D Model/TELEMAC Model

reproducibility of water quality and water temperature distributions in reservoirs. It has been used in Japan, including Sagami Dam. Free to use, the source code is open.

SMOW-T2 Model: A 2D vertical model built by Electric Power Development (Japan), suited for analysis of reservoirs. It has been used in environmental assessments with reservoirs of dams used exclusively for power generation in Japan. Fees must be negotiated, the source code is closed.

Fantom3D Model: An orthogonal 3D model built by Tokyo Metropolitan University (Asst. Prof. Tetsuya Shintani), suited for analysis of reservoirs, lakes, rivers, estuaries, and oceans. It has been used with natural lakes, dam reservoirs, rivers, and more in Japan. The source code is closed.

TELEMAC Model: A 2D/3D finite element model built by a French natural hydraulic environment research lab. Supports analysis of rivers and lakes, excellent for hydraulic analysis. Free to use, the source code is open.

2.3 *Comparison Method*

Since the dam reservoirs that provide the validation field for this study are in the temperate zone, the study comparisons focused on the reproducibility of surface layer water temperature, and water-temperature layer formation conditions, all of which have a big impact on changes in water quality in the temperate zone.

The method of comparing the water temperature in this paper is described below.

2.3.1 *Surface layer water temperature*

For the surface layer water temperature, differentials between measured and computed values were calculated each month for the surface layer of the reservoirs (top 50 cm). Mean squares were found for differentials for three years (36 data points) and compared (Figure 4 and Figure 5).

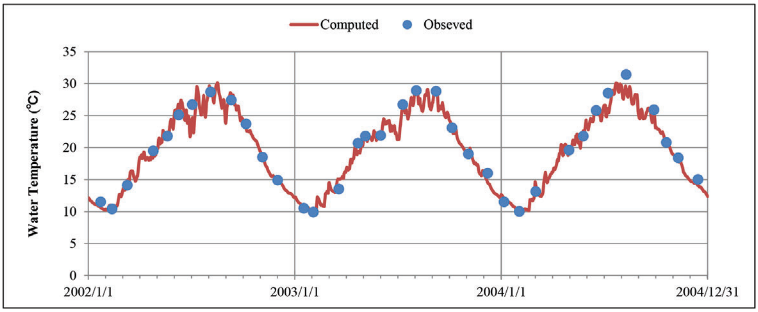

Figure 4. Method for comparing measured and computed values

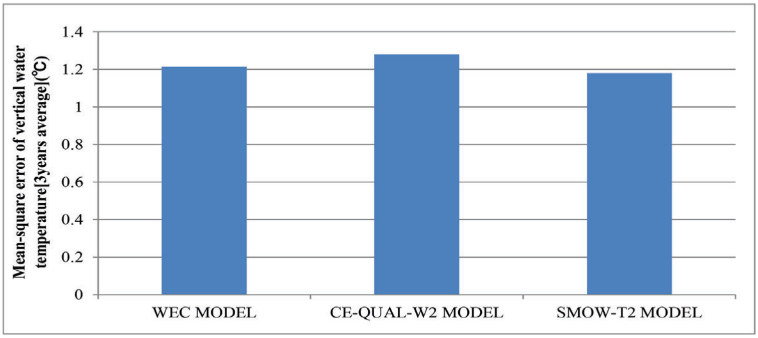

Figure 5. Method for comparing mean square differential for each model

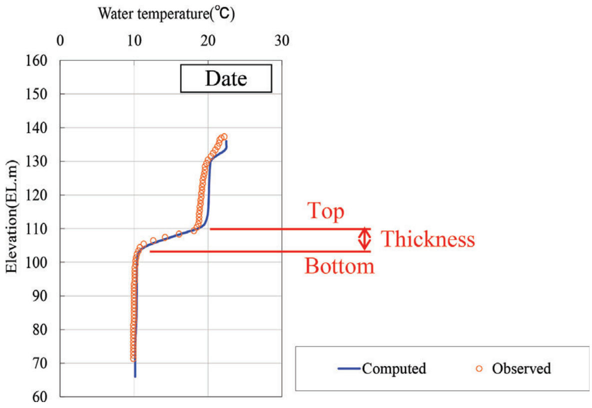

Figure 6. Method of comparing state of formation of thermoclines

Mean square differentials were calculated as follows.

$$\varepsilon = \sqrt{\frac{\sum (T_n - t_n)^2}{n}} \tag{1}$$

Tn: measured water temperature (°C)
tn: computed water temperature for the same day as the survey (°C),
n: number of data points analyzed

2.3.2 *Vertical distribution water temperature*

Many dam reservoirs form thermoclines between spring and autumn. Water does not move in the bottom part of a thermocline, so the thermocline makes the reservoir shallow in hydraulic terms, and such a reservoir is treated as vulnerable to pollution and eutrophication. That makes thermoclines one of the most important factors in reservoir water quality.

In light of the above, measured and computed values for the state of formation of a thermocline were compared when evaluating models. In this evaluation, moreover, a thermocline was defined as any place where the water temperature difference in the depth direction was at least 0.5°C/m. The depth at which such a thermocline occurred was compared to measured values. The thickness of any thermocline (layer thickness) formed near the surface layer or near the middle layer was also compared to measured values (Figure 6).

3 RESULTS

3.1 *Tsuruda Dam*

3.1.1 *Surface layer water temperature*

Generally, each of the models does a good job of reproducing seasonal changes in surface layer water temperature, and there were no great differences in results among the models (Figure 7).

3.1.2 *Vertical distribution water temperature*

Each of the models was generally able to reproduce the development of thermoclines close to where flows happen near sluice gates (altitude near 110m). However, the calculated and actual

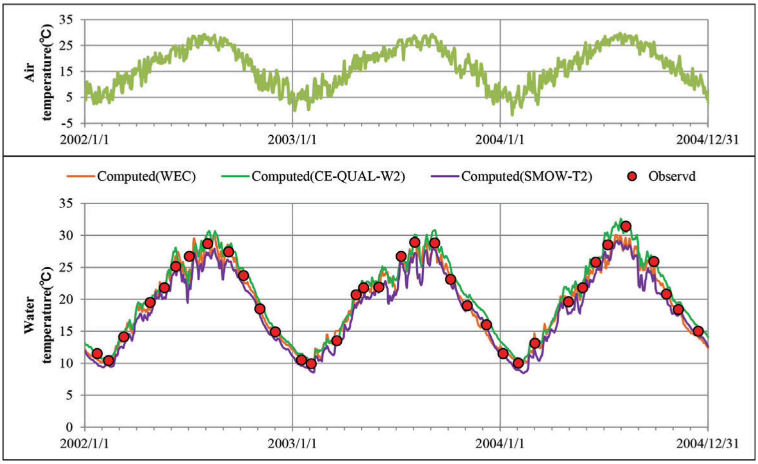

Figure 7. Change in surface layer water temperature

water temperature gradients close to thermoclines deviated according to flow conditions each year, and there were also differences between models. In particular, none of the models could adequately reproduce the lowering of thermoclines that occurs during flood (for example: 9.27, 10.19, and 11.9 in 2004. See Figure 9).

Compared to the other models, heat tended to diffuse excessively as far down as the lower layers in SMOW-T2, as shown in Figure 8 and Figure 9.

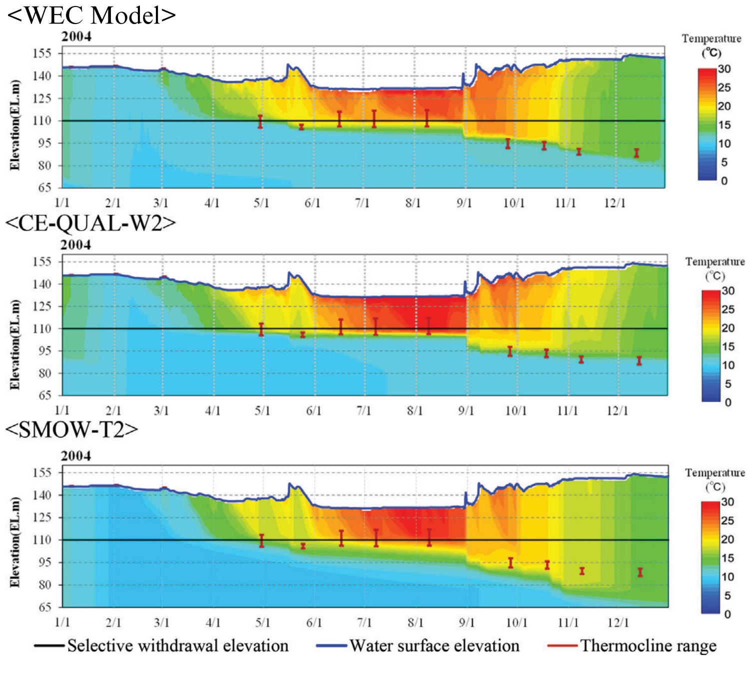

Figure 8. Change over time in water temperature vertical structure

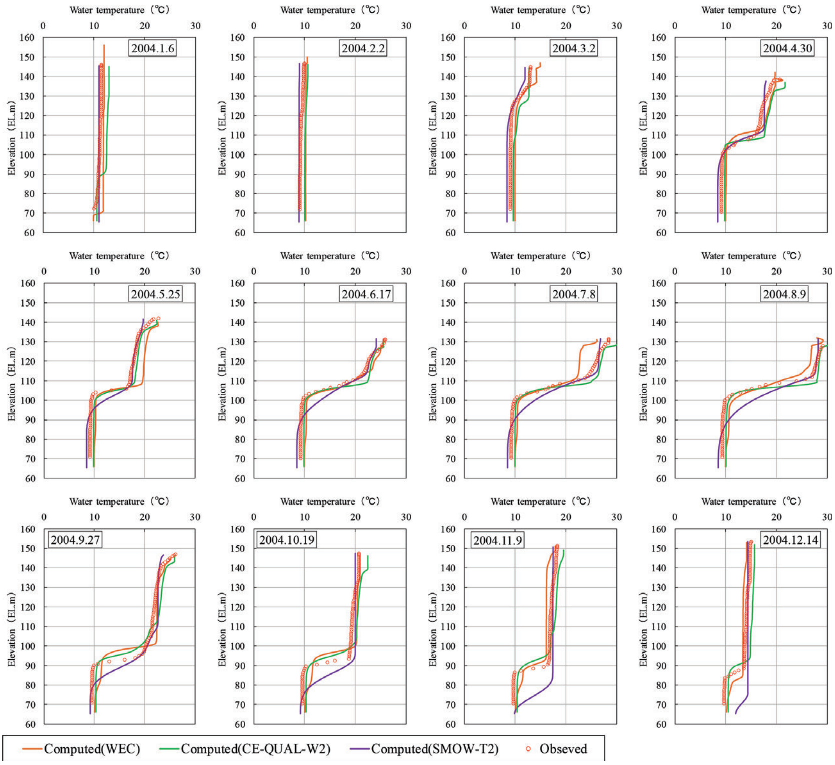

Figure 9. Temperature vertical distribution (2004)

3.1.3 *Comparison of calculating differential*

3.1.3.1 *Surface layer and Vertical distribution of water temperature*

The three-year averages of mean square differential for surface layer water temperature and vertical water temperature distribution were found for each model. Comparative results are shown in Figure 10.

The surface layer water temperature differential was 0.7°C - 1.2°C, meaning a difference of about 0.5°C among models. The mean square differential of vertical water temperature and the differential in vertical water temperature distribution was about 1.2°C, meaning the difference was small, depending on the model.

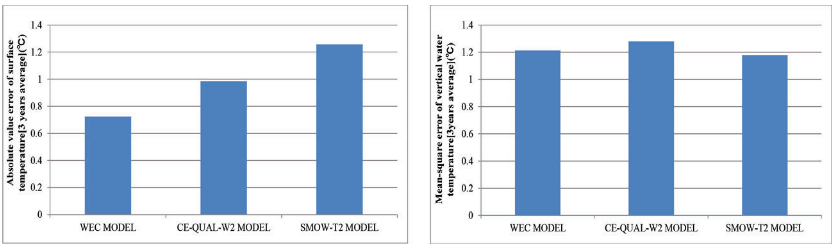

Figure 10. Comparison of mean differential between measured values and prediction results of each model (Left: surface layer water temperature/Right: vertical water temperature)

3.1.3.2 *Three-year mean of surface layer water temperature*
The three-year means of measured values and values calculated by models were found for surface layer water temperature. Comparative results are shown in Figure 11. The calculated values of WEC Model were largely the same as the measured values. And the differential in the other models was only about 1°C.

3.1.3.3 *Thermocline differential*
The reproducibility of thermocline position is shown in Figure 12, which compares mean differential in layer thickness, upper end position, and lower end position between June and September. Even in cases where there is great differential in upper end and lower end positions of

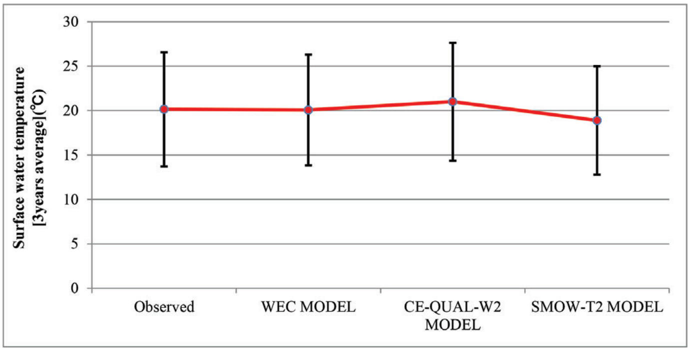

Figure 11. Comparison of surface layer mean water temperature

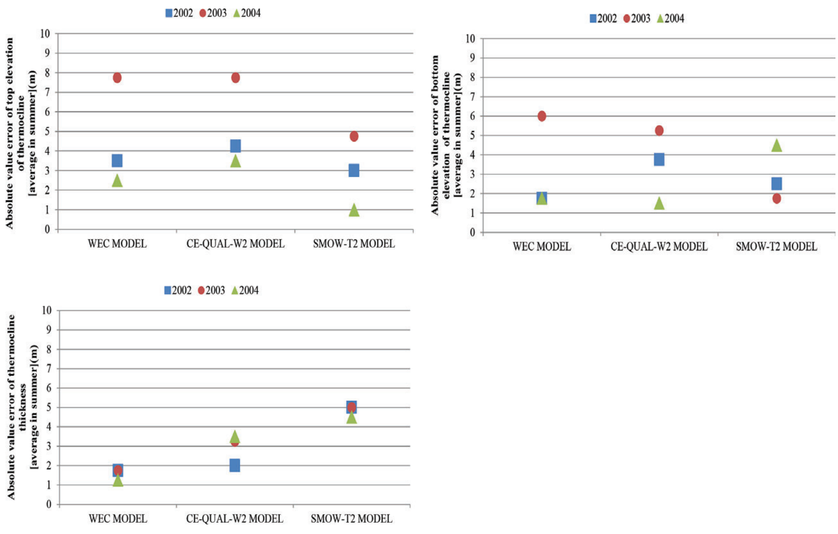

Figure 12. Mean measured values and prediction results from each model, and comparison of their distribution

the thermocline, one must be aware that the differential in layer thickness may still be small if the two ends of the thermocline are shifted to the same side.

Thermocline differential appears also to be affected by the occurrence of flood. In 2003, a year when there was flooding during the layer-forming period (spring to early summer), the differential tended to be greater than in the other years. If that year is excluded, WEC Model tends to have relatively small upper and lower end position and layer thickness differentials.

3.2 *Ishitegawa Dam*

3.2.1 *Surface layer water temperature*

Each of the models does a good job of reproducing seasonal changes in surface layer water temperature. There was a difference between the two in respect to changes in water temperature in winter. However, this seems likely to be because of the settings of the heat balance through the water surface, not because of the calculating techniques of the models themselves (Figure 13).

3.2.2 *Vertical distribution water temperature*

In both models, the summer surface layer water temperature tended to rise higher than actual measurements showed. Since this tendency happened in different models, it may be because of the weather conditions (solar radiation, air temperature, etc.) that were applied.

In CE-QUAL-W2, the water temperature when all the layers mixed because of the general circulation in the winter tended to be colder than actual measurements showed. This appeared also to affect the reproducibility of water temperature distribution for the following year. This is probably because the model overestimates the amount of heat radiation from the water surface to the atmosphere. WEC Model generally reproduces winter water temperature (Figure 14 and Figure 15).

3.2.3 *Comparison of calculating differential*

3.2.3.1 SURFACE LAYER AND VERTICAL DISTRIBUTION OF WATER TEMPERATURE

The three-year averages of mean square differential for surface layer water temperature and vertical water temperature distribution were found for each model. Comparative results are shown in Figure 16.

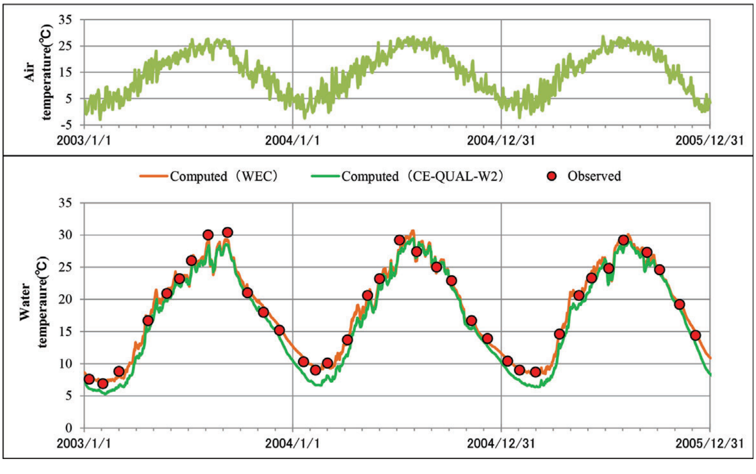

Figure 13. Comparison of surface layer water temperature

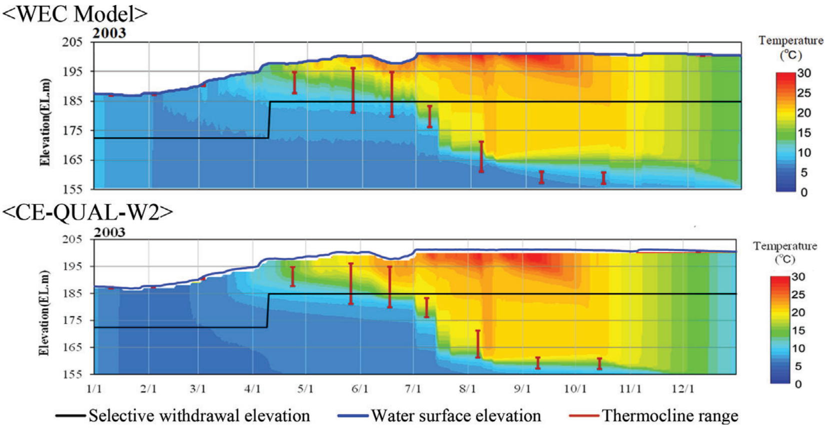

Figure 14. Change in water temperature vertical structure

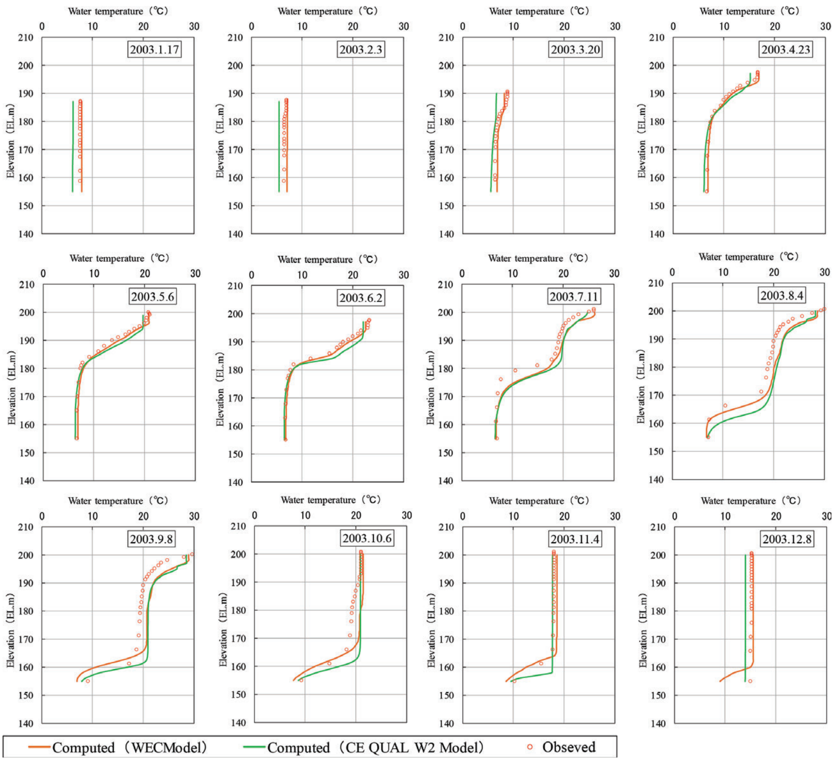

Figure 15. Temperature vertical distribution (2003)

The surface layer water temperature differential was 0.5°C - 1.4°C, meaning a difference of about 1°C between models. Also, the vertical water temperature distribution differential was 1.1°C - 1.6°C, meaning a difference of about 0.5°C between models.

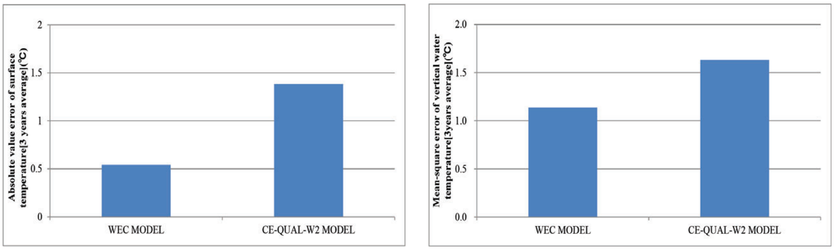

Figure 16. Comparison of mean differential between measured values and prediction results of each model (Left: surface layer water temperature/Right: vertical water temperature)

3.2.3.2 THREE-YEAR MEAN OF SURFACE LAYER WATER TEMPERATURE

The three-year means of measured values and values calculated by models were found for surface layer water temperature. Comparative results are shown in Figure 17. The calculated values of WEC Model were largely the same as the measured values.

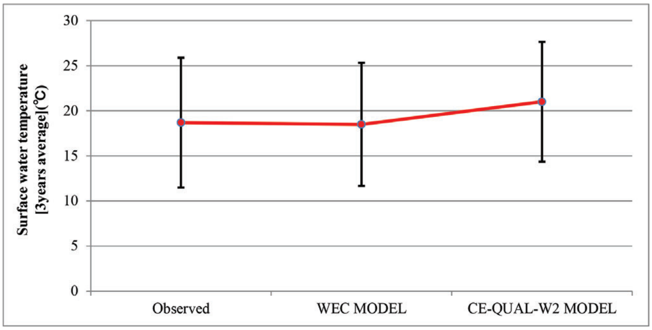

Figure 17. Comparison of surface layer mean water temperature

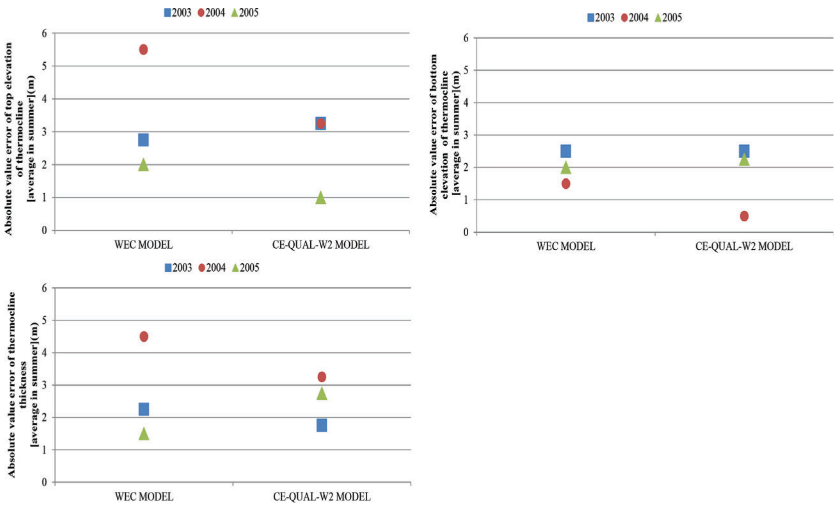

Figure 18. Mean measured values and prediction results from each model, and comparison of their distribution

3.2.3.3 THERMOCLINE DIFFERENTIAL

The reproducibility of thermocline position is shown in Figure 18, which compares mean differential in layer thickness, upper end position, and lower end position between June and September.

Thermocline differential appears also to be affected by the occurrence of flood. In 2003, a year when there was frequent flooding, the differential tended to be greater than in the other years. In both models, there were differentials of about 2 m or more, either at the upper or lower end.

3.3 *Kasumigaura*

3.3.1 *Surface layer water temperature*

The average differential between calculated value and measured value for each model (total value for 3 months from June to August of 2009, 2010 and 2011) is shown in Figure 19. At

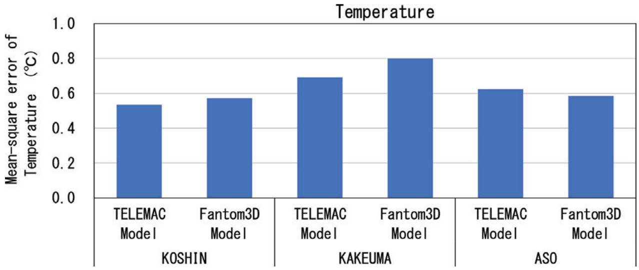

Figure 19. Comparison of mean differential between measured values and prediction results of each model

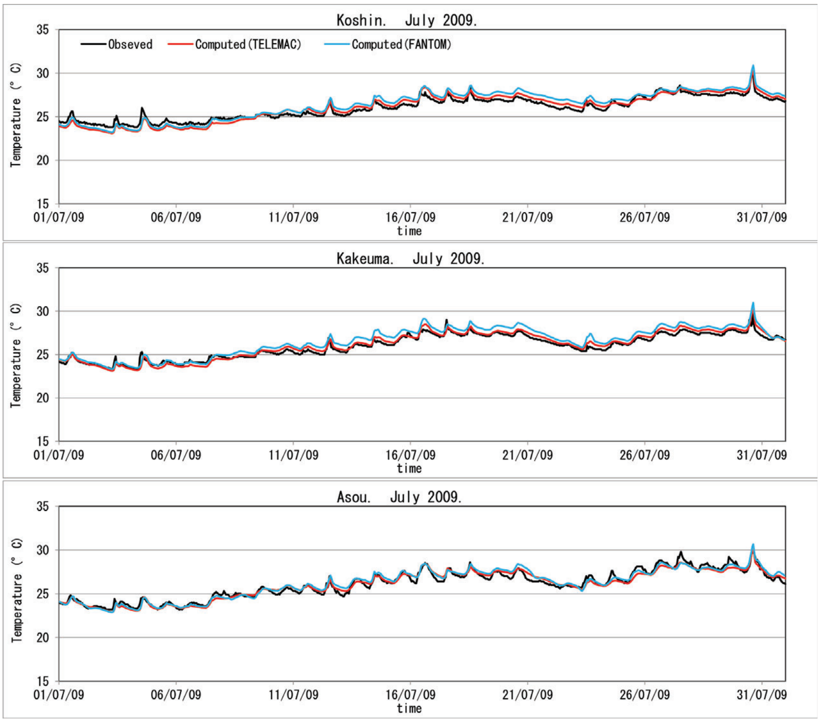

Figure 20. Comparison of actual measurements and surface layer water temperature from each model

Kasumigaura, the time series change (July 2009 as a representative example) for surface water temperature at Koshin (the lake center), Kakeuma and Aso are shown in Figure 20.

With both models, the time series change for actual water temperature at each location is reproduced with fairly good accuracy, but at Kakeuma, which equates to a bay inner section, there appears a tendency for the differential from measured value to become somewhat larger. A cause of this may be an differential in the setting for inflow water temperature (set with a correlation formula based on air temperature) in the boundary conditions for the model because it is a bay inner section.

4 CONCLUSIONS

Each of the models does a good job of reproducing seasonal changes in surface layer water temperature, and there were no great differences among the models. Weather conditions, such as solar radiation and air temperature, greatly affect the formation of surface layer water temperatures. Thus, appropriately applying the conditions relevant to the formation of surface layer water temperatures would seem to ensure reproducibility to some extent.

The models differed in their ability to reproduce water temperature gradients close to thermoclines. Compared to WEC and CE-QUAL-W2, SMOW-T2 tends to diffuse heat excessively in the lower layer. Looking at this result alone, we might conclude that hydrostatic pressure/1D multilayer models like the SMOW-T2 Model do not have good enough reproducibility. However, diffusion in the interior of the reservoir depends greatly on the parameters set in turbulence models. If these are parameters the user can adjust, it may be that reproducibility could be improved.

The calculating accuracy of a model depends to a great degree on the amount of effort put in by the user. Therefore, one cannot simply conclude that the model has limitations.

In addition, all the models tended to be unable to sufficiently reproduce the lowering of thermoclines that occurs during flooding.

It is known that close to water intake facilities, fluid layers thicker than the sluice gate occur a few tens of meters away from the sluice gate. The greater the discharge volume, the greater the fluid layer thickness. This is a factor causing the lowering of thermoclines. This phenomenon happens at a spatial scale smaller than the calculating mesh size used in this study, and so cannot easily be reproduced even in highly accurate models. Reproducing the phenomenon would probably require some approach like calculating with a finer mesh or altering the boundary conditions.