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RECONSIDERATION OF RESERVOIR OPERATIONS UNDER CLIMATE CHANGE: CASE STUDY WITH YAGISAWA DAM, JAPAN

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To investigate the adaptability of current dam reservoir operation rules under climate change condition, a dam in the upper part of Tokyo, Japan was modeled and simulated. For the dam inflow data under the present and future climate condition, hydrologic output of a general circulation model was converted into discharge data through a distributed hydrologic model. A simple type of dam model was prepared to reproduce (1) historical water levels and (2) historical dam outflows. Simulation results show that there will be very limited inflow in May and June due to decreased and shifted snowmelt inflow in the future. Under the changed climate condition, the dam outflow from January to March should be reduced and stored in the reservoir, or the current water level regulations should be revised.

Key Words: *Climate change, dam operation, water resources, snow-dominated regions*

1. INTRODUCTION

Climate change is now an unequivocal truth, and it is expected to strongly affect the hydrologic cycle in the coming decades[1,2]. Even though climate change would accelerate water cycles and therefore freshwater resources may be less limited in the next century, risk of water related problems will be still remaining in the future due to changes in seasonal patterns and increased extreme events[3,4].

Water supply condition, especially for freshwater resource in the future is difficult to assess owing to various uncertain and changing factors of nature. If any considering area is in snow-dominated regions, seasonal variation of the water resources under climate change condition becomes more apparent. In a warmer world, there will be less snowfall in winter and the melting of winter snow occurs earlier in spring, therefore much of surface runoff will be shifted in the earlier season[5].

Under this uncertain future hydrologic condition, Japan, where flood has been more considerable extreme events, may not be an exception for the water resources problem. Water supply condition in Japan is not stable even now due to its severe seasonal variation and high population density[6]. So far, this water related problems have been skillfully handled with many reservoirs and multi-purpose dams. Every reservoir has own optimized operation rules to maximize its function under given water problems. However, this current reservoir operation rules may not work properly under the changed hydrologic cycle in the future.

To evaluate current dam reservoir operation rules under the changed climate conditions, one of dam reservoirs in Japan was modeled and simulated. Future climate condition was set by the output of a very high resolution atmospheric model that was developed by the Japan Meteorological Agency (JMA) and the Meteorological Research Institute (MRI), Japan[7]. The subject area for this study is the Yagisawa Dam basin (167.6km^2), which is located at the upper part of the Tone River. The Tone River is the main water source to the metropolitan Tokyo, Japan[8], and the upstream of the basin is in snow-dominated regions.

The organization of this paper is as follow: Section 2 illustrates data and models used in this study. Section 3 and 4 provides the simulation results of hydrologic model and the virtual dam operation results and discuss with the results. Finally, Section 5 summarizes this study.

2. DATA AND MODELS

(1) Very High Resolution Atmospheric Model, AGCM20 and Hydrologic Output Data

JMA and MRI have developed a prototype of the next generation of global atmospheric model, which produces 20-km spatial and 1-hour time resolution output, for the use of both climate simulations and weather predictions[9]. The global atmospheric model (hereafter, AGCM20) performs at a triangular truncation 959 with the linear Gaussian grid (TL959) in the horizontal, which has 1920×960 of grid cells of about 20 km size, and with 60 levels in the vertical. Refer to Mizuta et al.[7] and Kitoh and Kusunoki[9] for more details on the model.

The hydrologic data used in this study are the test-running output of the AGCM20 provided by the MRI as of 2008. The model provides two separate outputs for present climate (1979~1998) and future climate (2075~ 2094). The model adopts observed monthly mean climatologic sea surface temperature (SST) as boundary condition of the controlled simulation. For the projection simulation, future SST was estimated from the previous GCM outputs simulated under the A1B scenario.

The AGCM20 output data used for this study are mainly related to hydrologic variables. Five variables as shown in **Table 1** were used as input data of a distributed hydrologic model and it was converted into discharge data. The *prcsl* indicates daily rainfall amounts reached to the soil layer, and *sn2sl* is daily snowmelt amount into the soil layer. For more accurate runoff simulations, the daily *prcsl* and *sn2sl* data were downscaled in hourly resolution using the time series of the *precipi* (rainfall + snowfall, hourly) variables, and the *evpsl* (evaporation from the soil layer, daily) and *trnsl* (transpiration from the soil root zone, daily) values were used as it is.

(2) Yagisawa Dam and Its Modeling

Yagisawa dam is located at the upper part of the Tone River basin and it has 167.6 km^2 of catchments area (see **Fig. 1**). The dam was built in 1967 for flood control, hydropower generation, and drinking water supply[10]. Observed daily water level, inflow and outflow of ten years (1994~2003) were prepared from the dam database[10] of the Ministry of Land, Infrastructure and Transport (MLIT), Japan and presented in **Fig. 2** and **3**. Day-by-day averaged values (bold blue and red lines) show the annual trends of the inflow and outflow. Average annual inflow and outflow are 16.788m^3/s and 16.921m^3/s, respectively. It has 204.3 million m^3 of total reservoir volume and 175.8 million m^3 of effective volume. The normal high water level (NHWL) is 850.0m (mean sea level), and the lowest water level (LWL) is 796.5m (see **Fig. 4**).

Table 1. Annual mean amount of AGCM20 output (20 years of average for each term)

Output of AGCM20	Annual mean of the Yagisawa dam basin		
	Present (unit: mm)	Future (unit: mm)	Changes (unit: %)
precipi	1907.27 (1,775.96)	1907.82 (1,851.03)	+ 0.03 (+ 4.23)
prcsl^1	804.76 (1,335.58)	1005.03 (1,510.99)	+ 24.89 (+ 13.13)
sn2sl^2	880.06 (269.25)	677.26 (167.55)	- 23.04 (- 37.77)
evpsl^3	110.71 (277.55)	150.81 (329.92)	+ 36.22 (+ 18.87)
trnsl^4	237.43 (240.28)	273.25 (275.84)	+ 15.09 (+ 14.80)
Net-Precipi. 1+2-3-4	1336.68 (1,087.00)	1258.21 (1,072.78)	**- 5.87 (- 1.31)**

* ( ) is the values of the Tone River basin

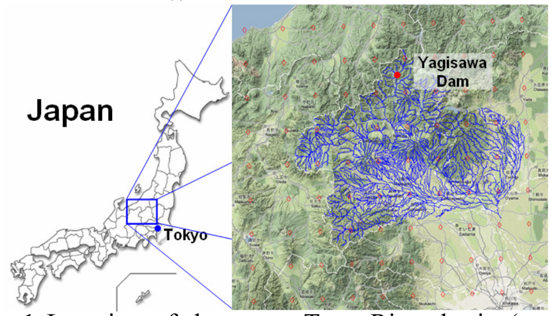

Fig. 1 Location of the upper Tone River basin (outlet: Kurihashi station, 8,772 km^2) and the Yagisawa dam basin (167.6 km^2). Red diamond marks (right) are the center of the AGCM20 output grid cells.

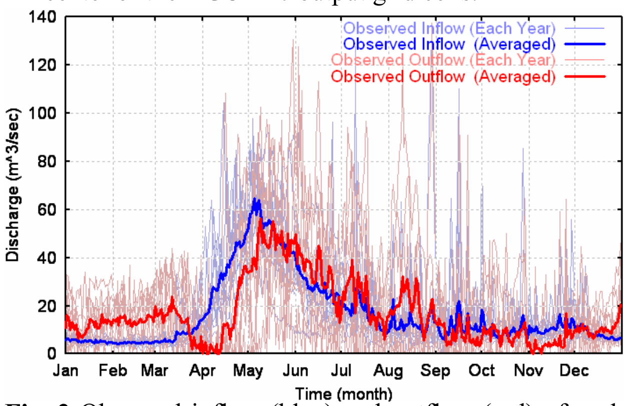

Fig. 2 Observed inflow (blue) and outflow (red) of each year (1994~2003) and day-by-day averaged values of inflow (bold blue) and outflow (bold red).

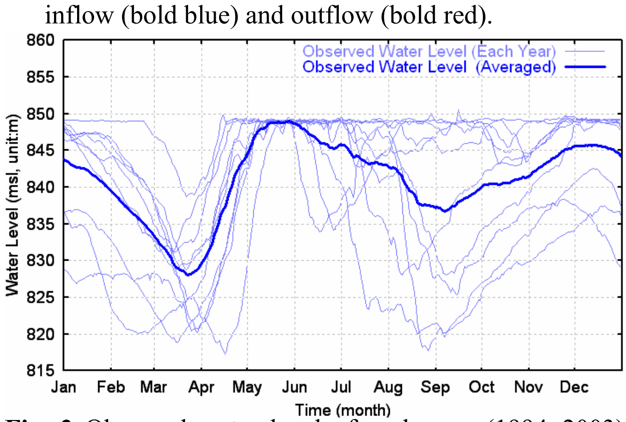

Fig. 3 Observed water level of each year (1994~2003) and day-by-day averaged values of W.L. (bold blue)

The main water source into the dam reservoir is snowmelt inflows from April to May. The reservoir prepares some storage space in the early spring for this snowmelt inflow, and provides some amount of water to the downstream. The water level reaches to the NHWL (850.0m) in the middle of May and maintains this level until July (concretely, from 21st May to 1st August). Another big release from the dam is in August and September to prepare flood inflow. During this release, water level should be higher than 830.0m until 26th August, 827.8m until 1st September, and 816.8m until 25th September. After the end of September, the dam holds inflow little by little and water level rises to the NHWL.

The observed W.L. (**Fig. 3**) generally followed the prescribed regulations, but there were also many times of irregular operations. Because the amounts and arrival times of dam inflows will be different every year and hard to expect, a certain level of irregular operation by operator's intuition might be unavoidable. However, it is not easy to consider this kind of irregularity into a dam model, and if the dam model works on the perfect inflow information, the simulation is unrealistic.

In this study, a simple type of dam model was prepared to check the aptitude of the current dam reservoir operation rules under the changed climate condition. Objectives of the dam modeling in this study are to reproduce (1) historical water levels and (2) historical outflows. The historical outflows and water levels are day-by-day averaged values of 10-years observation, which are shown in **Fig. 2** and **3**, respectively. More details of the dam model developed in this study are described in Section 4.

(3) Hydrologic Model and its Calibration

For the simulation of dam inflow using the AGCM20 output data, a distributed hydrologic model was composed for the Yagisawa dam basin, using an object-oriented hydrologic modeling system, OHyMoS[11]. The kinematic wave model for surface and subsurface flow simulation[12] was utilized in the system to simulate rainfall-runoff procedure, and river channel routing is also considered by solving the kinematic wave equation. This type of model composition was successfully applied on the Yodo River basin by Sayama et al.[13] to evaluate the impact of climate change on flood disasters in the future, including dam reservoir operation models for the flood control. However, the dam models that are introducing in this study is different to the dam model of Sayama et al.[13]

Snowmelt functions are not included in the hydrologic model of this study, and the model directly utilizes the snowmelt amount (*sn2sl*) data among the output of AGCM20. Evapo-transpiration losses are considered in the model with the AGCM20 output, *evpsl* and *trnsl*.

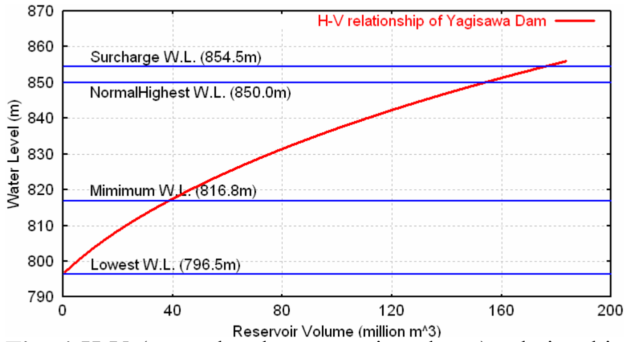

Fig. 4 H-V (water level - reservoir volume) relationship and the specific W.L. of the Yagisawa Dam.

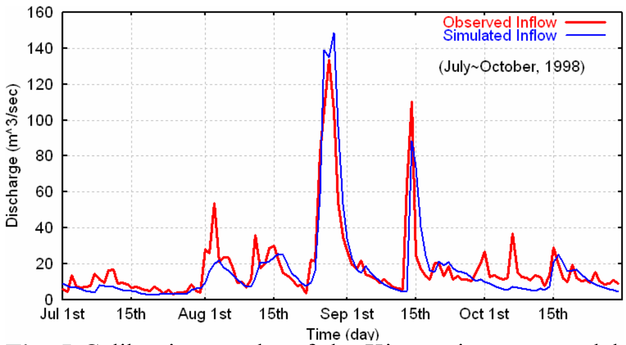

Fig. 5 Calibration results of the Kinematic wave model. The calibration was fulfilled with summer season (July~October) observation data of 1994~1998.

The hydrologic model was calibrated manually using the observed data of rainfall and daily inflow into the Yagisawa dam within the summer season (July ~ October) of five years (1994 ~ 1998). The model produces hourly discharge data, and it was up-scaled to daily and compared with the daily observed inflow data. The rainfall data was prepared using the AMeDAS data, and a monthly uniform evaporation amount was estimated from the observed data[14]. There are five parameters to be optimized in the model and they are roughness coefficient n (= 0.03 m^3/s), soil depths d_s (= 0.40 m), d_c (= 0.21 m), hydraulic conductivities k_a (= 0.108 m/s) and k_c (=0.012 m/s), which determine the velocity of saturated and unsaturated subsurface flow, respectively. As shown in **Fig. 5**, the calibrated model shows good model performances on both low flows and peak flows.

(4) Methodology

Procedures of this study to evaluate the current dam operation rules are as follows. Firstly, rainfall-runoff simulations were conducted with the calibrated hydrologic model, using the AGCM20 output for the present (1979~ 1998) and future (2075~2094) climate condition, and dam inflow data were prepared. Secondly, dam models were composed (1) to reproduce the historical water levels and (2) to reproduce the historical dam outflows. Thirdly, these two dam models simulated water level and outflow with the present and future inflow. Lastly, the simulation results were analyzed to investigate adaptability of current dam reservoir operation rules under climate change condition in the future.

3. RUNOFF SIMULATIONS WITH THE AGCM20 OUTPUT DATA

(1) Dam Inflow Simulations

Rainfall-runoff simulation to calculate Yagisawa dam inflows was fulfilled using the output of the AGCM20, and the results are presented in **Fig. 6**. As it was expected, the melting of winter snow in the future occurs earlier, and much of runoff is shifted and flattened in the earlier season. The pattern of the summer season discharge does not show noticeable changes in the future. The day-by-day averaged discharges for the present and the future provide apparent distinction of those two terms.

(2) Water Balance Checking

Average annual inflow from the rainfall-runoff simulations under present climate condition is 7.172 m^3/s (6.988 m^3/s under future climate condition), and it is equivalent to 1,349.6 mm of annual precipitation (area of the Yagisawa dam basin is 167.6 km^2). However, the annual average inflow of the observation, 16.788 m^3/s is equivalent to 3,158.9 mm of annual precipitation. Because there was a big difference of water volume between the observed and simulated inflow, it was not able to carry out proper dam model operations.

According to the AMeDAS observed data on the dam basin (Nikko-41166: 2,127.9 mm, Nas-41011: 1,865.4 mm, Fujiwara-42046: 1,777.7mm), annual precipitation amount is not sufficient to match with the annual dam inflow. However, it is also difficult to sure whether the AMeDAS has successfully observed much snowfall in a highly mountainous area. Therefore, the observed inflow was set as the base water volume, and the simulated inflow were modified to match its water amount to the observed inflow. The simulated inflows both for the present term and future term were revised by multiplying a factor 2.340, which is a ratio of the observed annual mean inflow, 16.788 m^3/s and the simulated annual mean, 7.172 m^3/s.

The revised inflows are presented in **Fig. 6** both for the present (blue line) and for the future (red line). The discrepancy of the average inflow of the present (bold blue line) to the observed inflow (bold black line) in **Fig. 6** is because of inherent error in the input precipitation. Monthly precipitation of the AGCM20 output also has some discrepancies to the observed monthly precipitation.

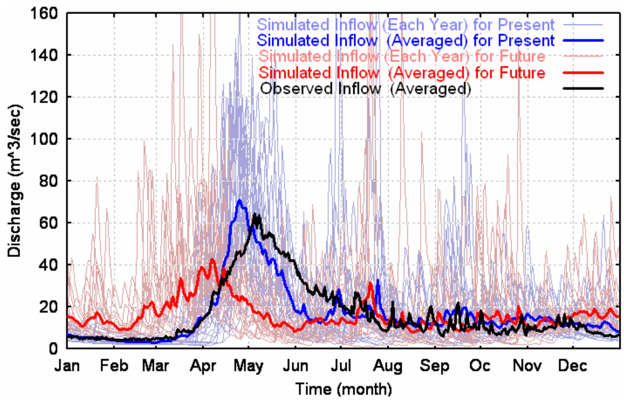

Fig. 6 Simulated inflow to the Yagisawa Dam using the AGCM20 output for the present term (1979~1998, blue) and for the future term (2075~2094, red). Much of snowmelt of present will be decreased and shifted to the earlier season because of the temperature increasing in the future. *Simulated inflow was modified to match the water balance with the observed inflow by multiplying 2.340 (=16.788m^3/s / 7.172m^3/s).

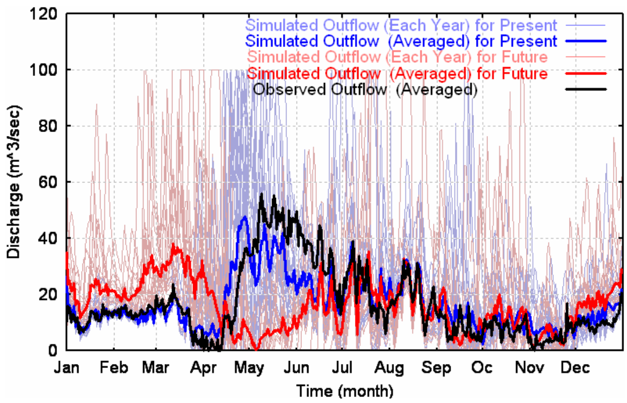

Fig. 7 Simulated (<u>for the given water level</u>) outflow from the Yagisawa Dam. Because of the shifted snowmelt season, there will be decreased water resources in May and June.

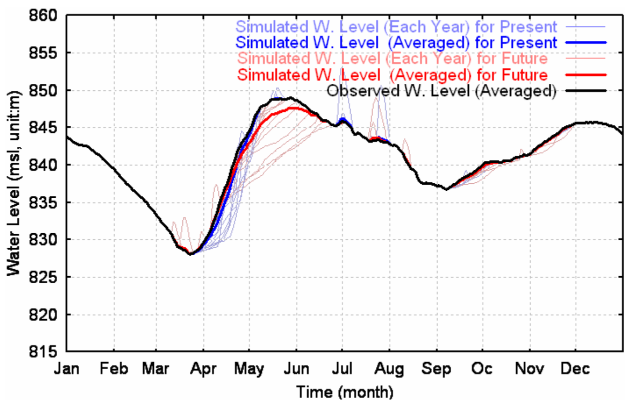

Fig. 8 Simulated (<u>for the given water level</u>) water level of Yagisawa Dam. Observed water level, which is the target of the simulation, is presented with bold black line. There are many water shortages during May and June in the future compared to the present.

4. SIMULATION OF DAM OPERATION WITH THE GIVEN CONDITIONS

(1) Simulations with the Water Level Regulations

The first dam model developed in this study is for reproducing the historical water levels (averaged values) shown in **Fig. 3**. This 10-year of average water level is the target water level in the first dam model. The simulation rules to operate the dam under this purpose are as follow: (1) if water level is higher than the target W.L., release the extra water to have the same W.L. to the target W.L., (2) if W.L. is lower than the target W.L., outflow is 0.0 m^3/s until the W.L. reaches to the target W.L., (3) dam outflow can not exceed 60.0 m^3/s, and the exceeding outflow is carried over to the next day, and (4) the relationship of the dam W.L. and the reservoir water volume is following the H-V relationship given in **Fig. 4**.

The simulated dam outflow and water level with the given water level regulations are presented in **Fig. 7** and **8**. The variant simulation results of year by year were summarized with the day-by-day averaged values. The observed outflow and water level are also presented for the reference to the simulation results analysis.

From this dam simulation results, it is able to see the apparent results of the shifted snowmelt season in the future. From January to the end of March, dam outflows of the future will be larger than the present one (see **Fig. 7**) because of abundant inflows in this season (**Fig. 6**). However, due to decreased snowmelt inflow, there will be very limited outflow in April and May (**Fig. 7**). If it is necessary to keep the water level higher than the simulation result and to release some amount of water from April to June, the target water level in March should be higher than 835.0 m in the future, and dam release from January to March should be smaller than the simulated one.

Dam simulation results with the present term data also shows some amount of discrepancy in the outflow pattern compared to the observations: over release in April and water shortage in May and June. This is mainly caused the inherent discrepancy in the inflow of the present term to the observed inflow (see **Fig. 6**), and this is originally comes from the AGCM20 output data error as explained in the previous section. After August, both dam simulation results for the present and future climate condition show successful match to the given water level and outflow as well.

(2) Simulations with the Outflow Regulations

The second dam model developed in this study is to reproduce the given dam outflow, which is the

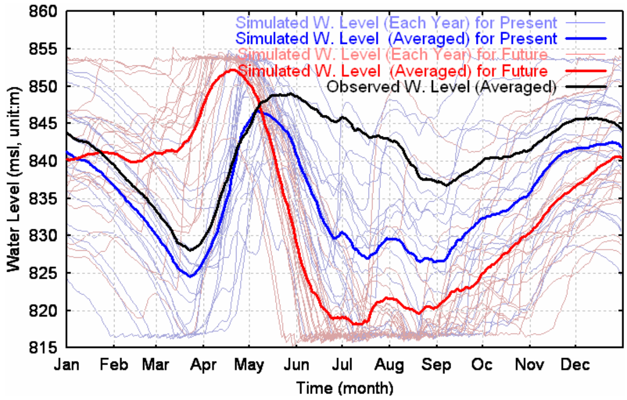

Fig. 9 Simulated (<u>for the given outflow</u>) water level of Yagisawa Dam. While the results of the present show rather similar pattern to the observed water level, the results of the future show many extreme conditions: water abundant in April and water shortage in the summer season (July~ September).

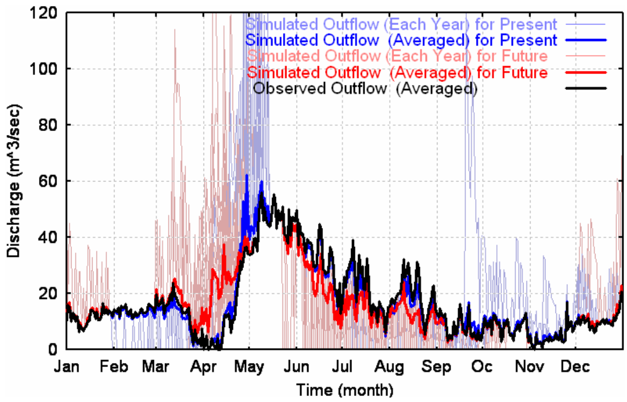

Fig. 10 Simulated (<u>for the given outflow</u>) outflow of the YagisawaDam. Both simulation results successfully keep the given condition (designed outflow) except excesses in April and shortage in summer of future.

averaged historical outflow shown in **Fig. 2** with the bold blue line. This 10-year of average outflow is the target outflow in the second dam model. The regulation rules to reproduce the given outflow are as follow: (1) if W.L. is between the minimum W.L. (816.8 m) and the surcharge W.L. (854.5 m), store the inflow and release the target outflow, (2) if W.L. reaches to the surcharge W.L., release the target outflow and inflow as well, (3) if W.L. is lower than the minimum W.L., outflow is 0.0 m^3/s until the W.L. is getting higher than the minimum W.L., and (4) the relationship of the W.L. and the reservoir volume is following the H-V relationship given in **Fig. 4**.

Dam simulation results using the given outflow regulations are presented in **Fig. 9** and **10**. Both simulation results for the present and the future are rather successfully following the designed outflow (see **Fig. 10**). Except several times of exceeding cases in April and shortage problem in summer season of the future, the day-by-day averaged outflow of the present (bold blue line) and future (bold red) are almost matched with the designed outflow (bold black).

The simulated water level with the future term data show very different pattern to the historic observation, and many extreme conditions are also found in the simulation results. There are high water levels in April, but soon after the level falls down drastically due to the increased outflow in May and June (**Fig. 10**). After all, many years of water level in the future goes down to the minimum water level (816.8 m) in the summer season (July~September). The inflow of May becomes very low in the future comparing with the current inflow (**Fig. 6**), and therefore the water volume (water level) will be significantly decreased (fell down) if there is big release as the current condition. If it is necessary to keep the current dam release pattern for some reason, such as downstream water demand and water intake in a certain season, the averaged water level presented with the bold red line in **Fig. 9** can be proposed as a new water level regulation in the future. However, reservoir water insufficiency in the summer season of the future should be carefully considered.

The simulated water level of the present also shows some difference, however, it comes from the original difference between the present term inflow and the observed inflow, especially in May and June (see **Fig. 6**).

5. CONCLUING REMARKS

The Yagisawa dam in the Tone River basin was modeled and simulated to investigate adaptability of current dam operation rules under climate change. To prepare the dam inflow of the present term (1979~2008) and the future term (2075~2094), the hydrologic output of AGCM20 were converted into discharge data using a distributed hydrologic model.

Through the dam model simulation to reproduce historical water levels, it was found that there will be very limited outflow in April and May, and it will be difficult to keep the current water level regulation in the future due to decreased and shifted snowmelt inflow. If it is necessary to release some amount of water from April to June in the future, dam outflow from January to March should be reduced and stored in the reservoir. The second dam model simulations to reproduce the current dam release pattern show that it is able to realize the present outflow pattern in the future. In this case, however, the water level regulations should be revised, and the shortage of the reservoir water in summer season should be carefully considered.

The dam models used in this study are not following the realistic operation rules, and these were developed only to evaluate current reservoir operations under climate change condition. More information on dam operations and water demand/ usage from the reservoir should be defined for more reasonable dam modeling. Further researches are on development of realistic dam operation models and proposing revised dam operation rules for the proper water resources control in the future.

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REFERENCES

1) Gedney, N., Cox, P.M., Betts, R.A., Boucher, O., Huntingford, C. and Stott, P.A.: Detection of a direct carbon dioxide effect in continental river runoff records, Nature, Vol. 439, pp. 835-838, 2006.

2) Milly, P.C.D., Dunne, K.A. and Vecchia, A.V.: Global pattern of trends in streamflow and water availability in a changing climate, Nature, Vol. 438, pp. 347-350, 2005.

3) Betts, R.A., Boucher, O., Collins, M., Cox, P.M., Falloon, P.D., Gedney, N., Hemming, D.L., Huntingford, C., Jones, C.D., Sexton, D.M.H. and Webb, M.J.: Projected increase in continental runoff due to plant responses to increasing carbon dioxide, Nature, Vol. 448, pp. 1037-1041, 2007.

4) Oki T. and Kanae, S.: Global hydrological cycles and world water resources, Science, Vol. 313, pp. 1068-1072, 2006.

5) Barnett, T.P., Adam, J.C. and Lettenmaier, D.P.: Potential impacts of a warming climate on water availability in snow-dominated regions, Nature, Vol. 438, pp. 303-309, 2005.

6) Ministry of Land, Infrastructure and Transport, Japan, Water Resources in Japan, The Governmental Report, 2007.

7) Mizuta, R., Oouchi, K., Yoshimura, H., Noda, A., Katayama, K., Yukimoto, S., Hosaka, M., Kusunoki, S., Kawai, H. and Nakagawa, M.: 20-km-mesh global climate simulations using JMA-GSM model -Mean climate states-, J. of the Meteorological Soc. of Japan., Vol. 84, pp. 165–185, 2006.

8) UNESCO-IHP Regional Steering Committee for Southeast Asia and the Pacific, Catalogue of Rivers for Southeast Asia and the Pacific - Volume IV, UNESCO-IHP Publication, pp. 95-109, 2002.

9) Kitoh A. and Kusunoki, S.: East Asian summer monsoon simulation by a 20-km mesh AGCM, Climate Dynamics, DOI 10.1007/s00382-007-0285-2, 2007.

10) Database of Dams, Ministry of Land, Infrastructure and Transport, Japan, http://www2.river.go.jp/dam/

11) Takasao, T., Shiiba, M. and Ichikawa, Y.: A runoff simulation with structural hydrological modeling system, JHHE, Vol. 14, No. 2, pp. 47-55, 1996.

12) Tachikawa, Y., Nagatani, G. and Takara, K.: Development of stage-discharge relationship equation incorporating saturated -unsaturated flow mechanism, Annual Journal of Hydraulic Engineering, JSCE, Vol. 48, pp. 7-12, 2004 (Japanese with English abstract)

13) Sayama, T., Tachikawa, Y., Takara, K., Masuda, A. and Suzuki, T.: Evaluating the impact of climate change on flood disasters and dam reservoir operation in the Yodo River basin, J. Japan Soc. Hydrol. And Water Resour. Vol. 21, No. 4, pp. 296-313, 2008.

14) Uehara S. and Sato. T.: Monthly water balance and hydrological characteristics of river basins in Japan (First report), Report of National Research Center for Disaster Prevention, Japan, Vol. 30, pp. 25~64, 1983.

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