Comparison and evaluation of Hwacheon Reservoir's hydropower generation ability before and after the Imnam Reservoir construction

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Abstract

Hwacheon Reservoir is located on the North Han River in South Korea. This reservoir was completed in 1944, and it is an important source of hydropower generation. Imnam Reservoir is located in North Korea upstream of the Hwacheon Reservoir. Construction of the Imnam Reservoir began in 1986, and was completed in 2001. According to the observed data, after the construction of the Imnam Reservoir, the amount of inflow to the Hwacheon Reservoir has been decreased. Due to the important role of the Hwacheon Reservoir in producing energy in South Korea, the optimization and comparison of its hydropower generation ability before and after the Imnam Reservoir construction has a special importance. So, for this purpose in this study, the HEC-ResPRM model was used. This model is a monthly model and it gives optimal values for release and storage by minimizing penalty functions. To evaluate the hydropower generation ability of Hwacheon Reservoir before and after the Imnan Reservoir construction, both the calculated inflow, which is without any effect of the Imnam Reservoir, and the observed inflow, which shows the effect of the Imnam Reservoir construction from 2001 to 2013, were used in the model. After running the model, the amount of release was optimized for both calculated and observed inflows. Finally, the results of the model for calculated and observed inflows were compared. The results of this study show that, after construction of the Imnam Reservoir, the amount of hydropower generation by the Hwacheon reservoir has decreased considerably.
Keywords: Han River, Hwacheon Reservoir, inflow, release, optimization, evaluation, hydropower, Hec-ResPRM, penalty functions.

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1 Introduction

Water is an important and valuable resource for living creatures, so it should be used efficiently and only as required. One way to prevent water wastage is by building water storage reservoirs. Reservoirs play an important role in reserving and preparing water for various human demands, and allocating the specific amount of water required for these different demands is possible by the effective operation of reservoirs. Reservoirs are operated for several different objectives, such as hydropower generation, water supply, irrigation, fish and wildlife preservation, flood control, navigation and recreation. One of the important objectives of reservoir operation is hydropower generation. Hydropower is cheaper than other sources (gas and fossil fuel) for providing electricity and it does not produce air pollution (Harpman [1]). So, the operation of hydropower reservoirs has a special importance. The amount of generation is varied because it depends upon reservoir water level, the amount of available water for release and the rate of electricity demand.

In South Korea, reservoirs play an important role in hydropower generation because this country is the southern part of the Korean Peninsula and it only has a land border with North Korea. These two countries do not have a good relationship, so supplying electricity over land, through North Korea, from other countries to South Korea, is not possible. However, South Korea has some large reservoirs to generate hydropower and the operation of these reservoirs holds a special importance and significant value to the country. One of the important reservoirs in this country, with regard to hydropower generation, is the Hwacheon Reservoir.

The Hwacheon Reservoir is located on the North Han River in South Korea, and it is a source of electricity in this country. This reservoir was completed in 1944, so it has been used to produce electricity for a substantial period of time. The Hwacheon Reservoir is located downstream of both the Imnam and Peace Reservoirs. The Imnam Reservoir is located in North Korea, upstream of the Hwacheon Reservoir. Construction of the Imnam Reservoir began in 1986, and was completed in 2001. After the construction of this reservoir, the amount of inflow to the Hwacheon Reservoir has considerably decreased. It has also had a negative effect on hydropower generation by the Hwacheon Reservoir. Because of the important role Hwacheon Reservoir has in producing energy in South Korea, in this study, the hydropower generation ability of this reservoir before and after the Imnam Reservoir construction was evaluated. For this purpose, the HEC-ResPRM model was used.

The HEC-ResPRM model is a monthly model and it gives optimal values for release and storage by minimizing penalty functions (Faber and Harou [2]). In HEC-ResPRM "all inflows are known with certainty during the modelled period – this gives the model the opportunity to look ahead to optimize current release knowing future inflows" (US Army Corps of Engineers [3]). In this model, negative and positive penalties represent benefits and penalties, respectively. HEC-ResPRM consists of penalty sets and composite penalties. Each penalty set represents one objective and it consists of 12 penalty functions, one for each month of the year. Composite penalties also consist of 12 penalty functions and they are the sum of the monthly penalty sets (US Army Corps of Engineers [4]). The HEC-ResPRM model has been used for many other interesting projects such as multi-reservoir operation rules for the Columbia River, operating rule optimization for the Missouri River reservoir system, multi-objective optimization with HEC-ResPRM (application to the upper Mississippi Reservoir system), etc. Applying this model to optimize reservoir operation increases accuracy and confidence of users.

2 Case study

The Hwacheon Reservoir is located on the North Han River in South Korea. The location of this reservoir is 38º07'02"N and 127º46'44"E with a 3901 km^2 drainage area. Both the Imnam and Peace Reservoirs are located upstream of the Hwacheon Reservoir. There is no information about the Imnam Reservoir because this reservoir is located in North Korea. After the construction of the Imnam Reservoir, the inflow to the Hwacheon Reservoir was altered. To control flooding due to an unexpected release from Imnam Reservoir, the Peace Reservoir was constructed downstream of the Imnam Reservoir and upstream of the Hwacheon Reservoir. The Peace Reservoir is located on the North Han River, which is a tributary of the Han River. The capacity of this reservoir is 2.61 billion m^3. Figure 1 shows a schematic of the Hwacheon, Peace and Imnam reservoirs and Table 1 shows the characteristics of Hwacheon Reservoir.

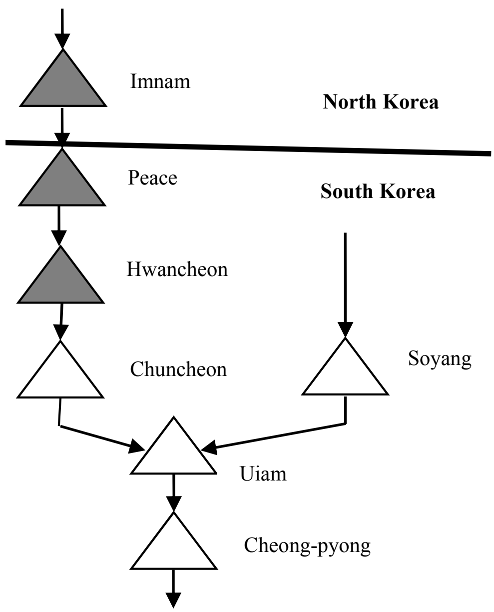

Figure 1: Schematic of the Hwacheon, Peace and Imnam reservoirs.

Table 1: Characteristics of Hwacheon Reservoir.

Hwacheon Reservoir	
Descriptions	**Values**
Year of completion	1944
Drainage area (KM^2)	3901
Total storage (MCM)	1018
Reservoir height (M)	86.5
Reservoir length (M)	435
Maximum head (M)	74.5
Reservoir surface area (KM^2)	38.9
Maximum discharge capacity (M^3/S)	9500
Number of generators	4
Generation capacity of each generator (MW)	27
Annual energy (GWH)	326
Initial reservoir storage volume (MCM)	540.92
Ending reservoir storage volume (MCM)	540.92

3 Methodology

Hwacheon Reservoir is one of the important reservoirs for hydropower generation in South Korea. The Imnam Reservoir was constructed in North Korea and its construction was completed in 2001. Imnam Reservoir construction has had an influence on the inflow and hydropower generation of Hwacheon Reservoir. To compare and evaluate Hwacheon Reservoir's hydropower generation ability, before and after the Imnam Reservoir construction, the HEC-ResPRM model was used. The first step was creating a watershed in the model, then the configuration was built and the project elements – in this case, the reservoir and the computation points – were placed in the configuration. Afterwards, the network was developed by adding the river reaches. After specifying inflow time series and adding reservoir and reach constraints, penalty functions for spillway and hydropower releases for both dry and flood seasons were created. In this project, constraint values for reach are monthly lower and upper bounds and constraint values for reservoir are lower bound, which is constant for the whole year and for Hwacheon Reservoir is 360 MCM and upper bounds, which in Hwacheon Reservoir are 1018 and 805 MCM for dry and flood seasons respectively. Furthermore, an alternative was created and the initial and ending reservoir storage volumes were defined for the model. Inflow data was also defined for the model in the alternative section. Finally, after running the model, the values were optimized for before and after the Imnam Reservoir construction.

In this study, both the calculated inflow, which is without the effect of the Imnam Reservoir construction, and the observed inflow, which has been affected by the Imnam Reservoir construction from 2001 to 2013, were used in the model. The calculated inflow was obtained using the observed precipitation in the Hwacheon Basin after the Imnam Reservoir construction from 2001 to 2013, and the relationship and correlation coefficient between the precipitation in the Hwacheon Basin and the inflow of the Hwacheon Reservoir before the Imnam

Reservoir construction from 1968 to 1985. The relationship and correlation coefficient between the precipitation and inflow levels for the month of August from 1968 to 1985, is shown in Figure 2. Finally, the results of the model for the calculated and observed inflow were compared.

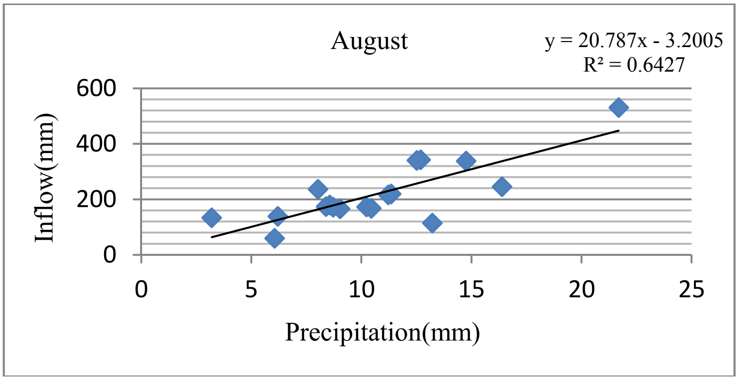

Figure 2: The relationship and correlation coefficient between precipitation and inflow for the month of August from 1968 to 1985.

4 Results

As previously mentioned, the construction of the Imnam Reservoir has had a major effect on the Hwacheon Reservoir inflow. In this study, both the calculated inflow, which is without the effects of the Imnan Reservoir construction, and the observed inflow, which is with the effects of the Imnan Reservoir construction were used. The calculated and observed inflows are presented in Table 2 and Figure 3. Release during flood season is larger than the release over the dry season. Because of this, two different penalty functions were created for hydropower release. Figures 4 and 5 show the penalty function curves of hydropower release for the dry and flood seasons for calculated inflow. As indicated in Figures 4 and 5, the dry season releases between 134.185 and 223.6416 MCM and the flood season releases between 135.66 and 226.0992 MCM do not have any penalties.

The HEC-ResPRM model optimizes hydropower release using pre-release before high inflows. Pre-release occurs before a high inflow to avoid the high penalties resulting from high releases. Figures 6 and 7 show the optimized storage and hydropower release for the calculated and observed inflows, respectively. If the power release, spillway release, and storage values are smaller or larger than the defined values without any penalties in the penalty functions, then the model considers a penalty for the smaller and larger values, as shown in Figures 8 and 9. After running the model, the optimized values were obtained as the result of the model. The result of the model for hydropower release and power generation is presented in Tables 3 and 4 and Figures 10 and 11. The monthly and annual power generation decreases in the Hwacheon Reservoir, due to the Imnam Reservoir construction, are presented in Table 5.

Table 2: Observed and calculated inflow of Hwacheon Reservoir from 2001 to 2013.

Months	Observed inflow	Calculated inflow
January	37.05385	32.8
February	22.66154	32.3
March	37.33846	83.2
April	64.38462	255.3308
May	77.11538	165.6462
June	95.43846	165.2231
July	647.1308	839.4846
August	634.3769	805.9615
September	225.7077	456.0077
October	46.09231	99.06923
November	33.72308	85.3
December	23.16154	56.9

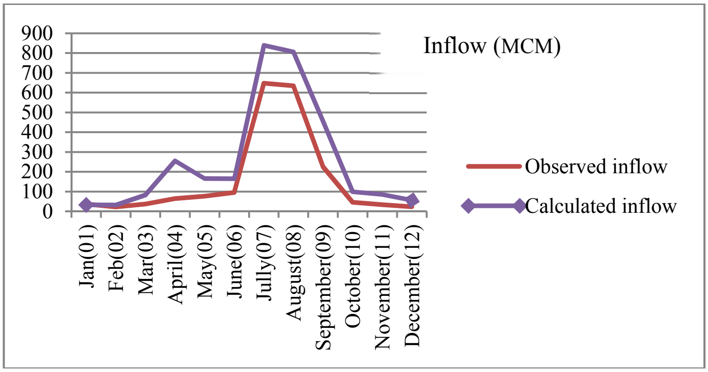

Figure 3: Observed and calculated inflow of Hwacheon Reservoir from 2001 to 2013.

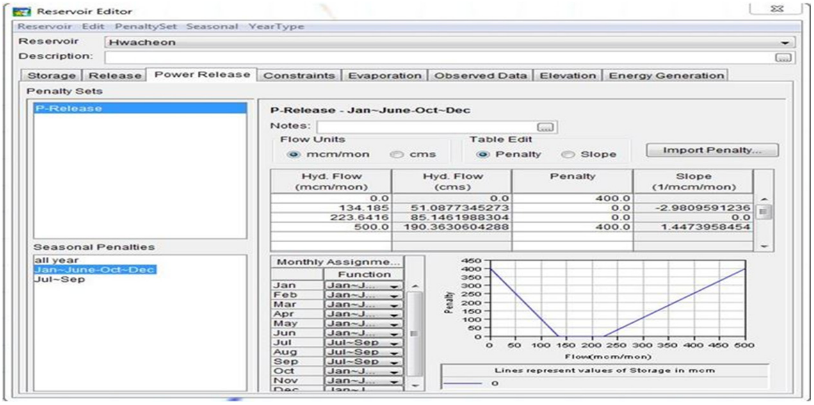

Figure 4: Penalty function curve of hydropower release in the dry season for calculated inflow.

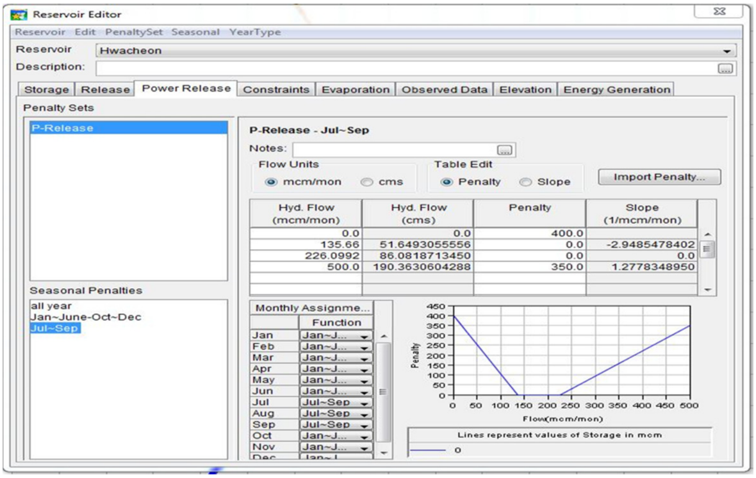

Figure 5: Penalty function curve of hydropower release in the flood season for calculated inflow.

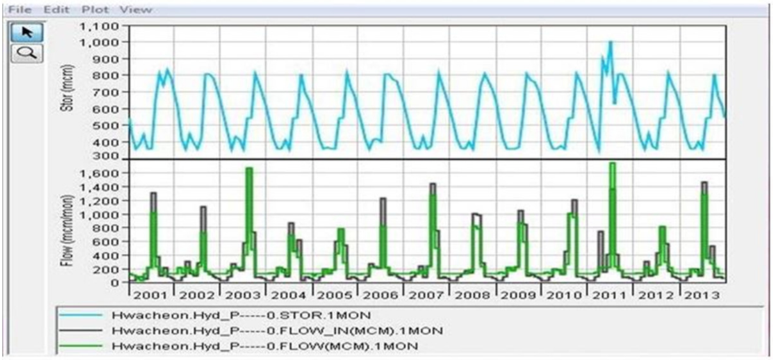

Figure 6: Optimized storage and hydropower release of calculated inflow.

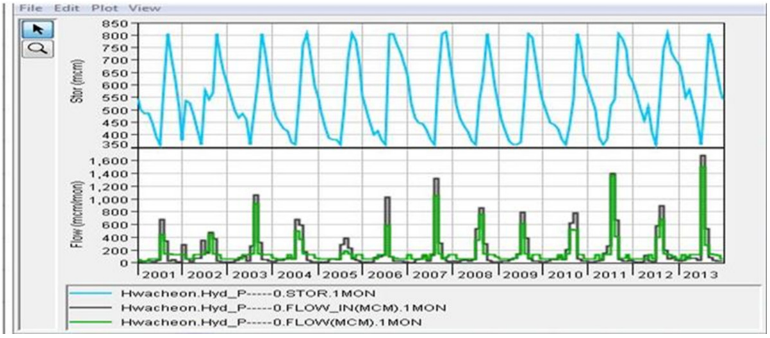

Figure 7: Optimized storage and hydropower release of observed inflow.

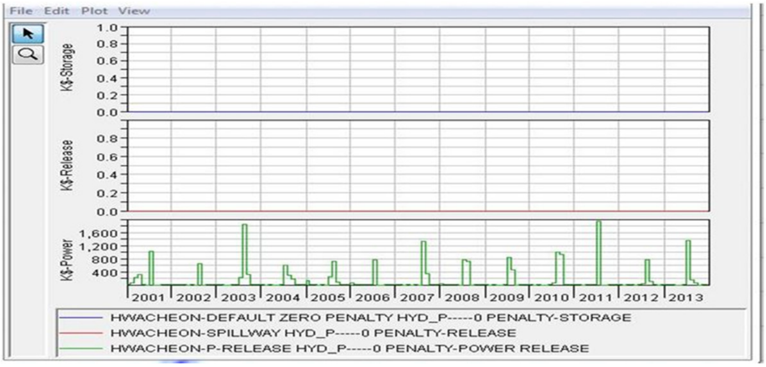

Figure 8: Penalties of hydropower release, spillway release and storage for calculated inflow.

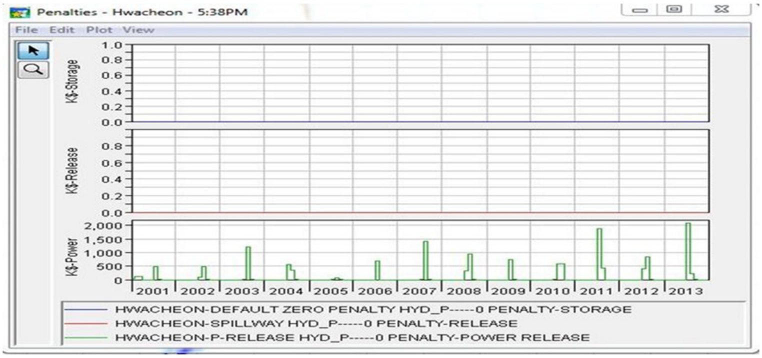

Figure 9: Penalties of hydropower release, spillway release and storage for observed inflow.

Table 3: Optimized hydropower release and power generation values of observed inflow (with effects of Imnam Reservoir construction).

Date	**Optimized values of observed inflow**	
Months	**Hydropower release (MCM)**	**Power (MW)**
January	81.76923077	13867.61
February	69.18461538	11733.33
March	69.40769231	11771.16
April	77.42307692	13130.52
May	113.9153846	19319.42
June	98.06923077	16632
July	500.2692308	84842.88
August	461.9	78335.67
September	149.2230769	25307.4
October	114.9923077	19502.06
November	117.5615385	19937.78
December	90.61538462	15367.87

Table 4: Optimized hydropower release and power generation values of calculated inflow (without effects of Imnam Reservoir construction).

Date	Optimized values of calculated inflow	
Months	**Hydropower release (MCM)**	**Power (MW)**
January	128.8384615	21850.29
February	142.8846154	24232.44
March	134.8461538	22869.16
April	186.8461538	31688.07
May	172.9230769	29326.79
June	175.4538462	29756
July	698.3230769	118431.7
August	702.3923077	119121.8
September	318.9769231	54096.71
October	147.1846154	24961.69
November	134.3384615	22783.06
December	134.2	22759.57

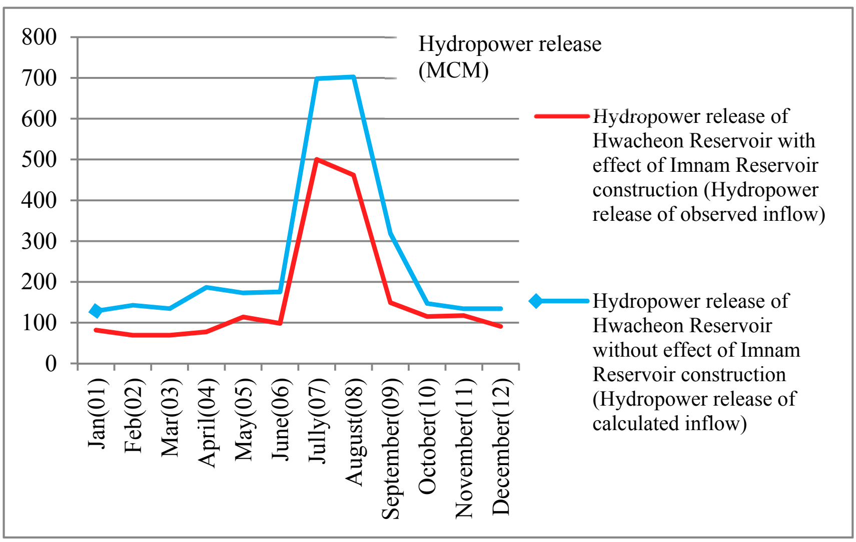

Figure 10: Optimized hydropower release of Hwacheon Reservoir with and without effects of Imnam Reservoir construction.

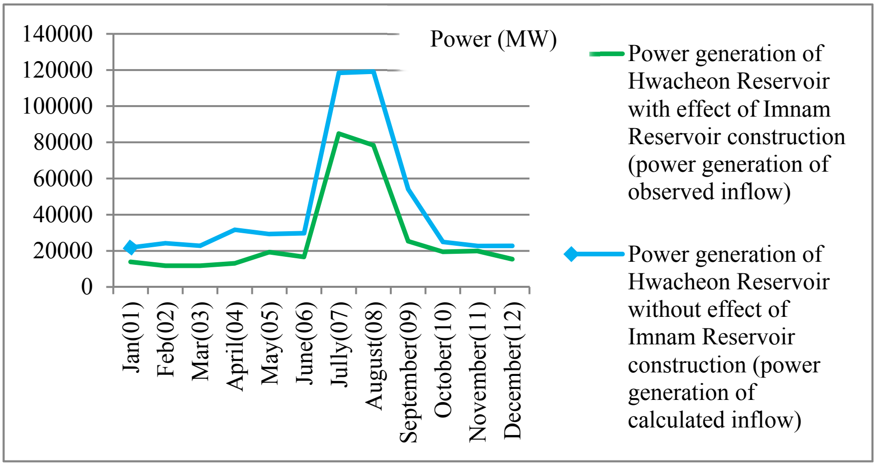

Figure 11: Power generation of Hwacheon Reservoir with and without effects of Imnam Reservoir construction.

Table 5: Monthly and annual power generation decreases in the Hwacheon Reservoir due to Imnam Reservoir construction.

Months	Monthly power decrease (MW)
January	7982.68
February	12499.11
March	11098
April	18557.55
May	10007.38
June	13124
July	33588.83
August	40786.16
September	28789.31
October	5459.637
November	2845.273
December	7391.709
Average monthly power decrease (MW)	16010.8
Annual power decrease (MW)	192129.6

5 Discussion and conclusion

As a result of the construction of the Imnam Reservoir, the inflow to the Hwacheon Reservoir has been affected (Heo and Kim [5]). As presented in Table 2 and Figure 3, after the Imnam Reservoir construction, which took place from 2001 to 2013, the monthly inflow to the Hwacheon Reservoir has decreased on a monthly basis throughout the year, excluding January. The monthly inflows in the month of

January, from 2001 to 2013, are lower than 28 MCM; except for January 2002, which had an inflow of 291.8 MCM. This large amount of inflow during January 2002 caused the monthly observed inflow from 2001 to 2013 to be greater than the calculated inflow for this period. However, the HEC-ResPRM model has full awareness of this period of operation and it optimizes values over the whole period of operation. Therefore, the occurrence of a high value during the operation period does not have a great effect on the final model result. The model distributes the effect of an unexpected inflow value over the whole operation period. As presented in Tables 3 and 4 and Figures 10 and 11, an unexpected value does not have a major effect on the results of the model.

In this project, throughout the entire operation period, storage stays between 360 and 1018 MCM; this is because these two mentioned values had been defined in the model as the lower and upper bounds of storage. Spillway release values remain between the defined values without any penalties in the penalty functions. In flood season, the inflow values are huge, and to prevent the high penalties due to huge power release, the model considers the entire period of operation and it reduces the penalties through the pre-release before a high inflow. However, monthly hydropower releases in the flood season are larger than the defined values, which do not have any penalties. So, as illustrated in Figures 6 and 7, the model does not consider any penalties for storage and spillway release; however, in flood season, because of multiple power releases, the model considers penalties for hydropower releases during the flood season.

After running the model, the optimized values for power generation have been obtained. As presented in Figures 10 and 11 and Tables 3 and 4, there are significant differences between the values of hydropower releases and the power generation of Hwacheon Reservoir, before and after the construction of the Imnam Reservoir; this is a direct result of the reduced inflow to the Hwacheon Reservoir after the Imnam Reservoir construction. In addition, the stability and regularity of the Hwacheon inflow after construction of the Imnam Reservoir has been changed. For instance, inflows in some months in both the dry and flood seasons are higher or lower than the usual and expected amounts. Although, it should be noted, that after construction of the Peace Reservoir, this inflow irregularity has been somewhat equilibrated. The main result of this study is conclusive in showing that the construction of the Imnam Reservoir has had a considerably negative effect on both the inflow and the hydropower generation ability of the Hwacheon Reservoir. After the construction of the Imnam Reservoir, the inflow, hydropower release and power generation of the Hwacheon Reservoir have decreased. The annual and average monthly power generation decreases in the Hwacheon Reservoir, as a direct result of the Imnam Reservoir construction, are 192129.6 and 16010.8 MW, respectively.

Acknowledgement

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References

[1] Harpman, D. A., Assessing the short-run economic cost of environmental constraints on hydropower operations at Glen Canyon Dam. Land Economics, 75(3): 390-401, 1999.

[2] Faber, B. & Harou, J., Multiobjective optimization with HEC-ResPRM – application to the upper Mississippi Reservoir system. Operating reservoirs in changing conditions, pp. 215-224, 2006.

[3] US Army Corps of Engineers. Developing operation plans from HEC prescriptive reservoir model results for the Missouri River system (Chapter 4), Hydrologic Engineering Center, pp. 39-87, 1992.

[4] US Army Corps of Engineers., HEC-ResPRM prescriptive reservoir model (Chapter 4), Quick start guide, Hydrologic Engineering Center, pp. 1-37, 2011.

[5] Heo, J. & Kim, T., Operation of Hwacheon Reservoir using emergency spillway in South Korea. Proceedings of international symposium on reservoir management in tropical and sub-tropical regions, ICOLD 70th annual meeting, 2002.