Numerical Modeling of Operation and Hydrologic Effects of Xinfengjiang Reservoir in Southern China

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Keywords: *Reservoir operation, SWAT, Xinfengjiang reservoir, East River (Dongjiang), southern China*

EXTENDED ABSTRACT

A reservoir system is generally functioned for multiple purposes, which normally include water supply for irrigation, industrial and domestic use, hydropower generation, flood control, navigation, and recreation. Therefore, its operation can involve complicated hydrologic, environmental, and economic constraints with conflicting management objectives. In this study, a reservoir system, Xinfengjiang Reservoir, of the East River basin in southern China is investigated.

The East River and its tributaries in southern China are regulated by three major reservoirs: Xinfengjiang, Fengshuba and Baipenzhu (see Figure 1). Among them, Xinfengjiang reservoir with a storage capacity of 14 billion m^3 is the biggest and controls nearly one-fourth of the drainage area above Boluo (Figure 1), which is the main flow gauging station near the river mouth of the East River basin. This study aims at understanding the operational mechanism of Xinfengjiang reservoir and the hydrologic changes caused. The inflow to the reservoir is simulated using the SWAT (Soil and Water Assessment Tool), and the outflow from the reservoir is simulated by two methods. One is a built-in algorithm in the SWAT, controlling outflow with a target release, and the other is a scheme developed in this study. The new scheme is based on mainly the linear regression relation of the daily change in reservoir storage against reservoir storage on previous day and net reservoir inflow. The results reveal that the new scheme can indeed enhance the outflow simulation. However, it is also found that the operation of Xinfengjiang reservoir is dominated by the hydropower demand according to its outflow observations.

Based on the analysis of the linear regression, we suggest that the available inputs (inflow and reservoir storage) may be sufficient to model the reservoir operation. Moreover, we can infer that the reservoir inflow has a larger influence on the reservoir operation in wet season than that in dry season, while reservoir storage has a larger influence on the reservoir operation in dry season than that in wet season.

The magnitude of the effects of a given reservoir on outflow will depend on its storage capacity and operating rule. In order to investigate the hydrologic effects of Xinfengjiang reservoir, monthly flows at the outlet of Xinfengjiang catchment between no-reservoir simulation and observed reservoir outflow for the period of January 1965 to December 1974 are investigated. The reservoir operation reduces the river peak flow and seasonal fluctuations greatly. The average standard deviation and coefficient of variation of outflow reduce by about 55% and 48% respectively comparing with that of inflow. According to the relative deviation, the reservoir operation alters monthly flow at the outlet of Xinfengjiang catchment and at the Boluo gauging station by about 55.6% and 21.0% respectively.

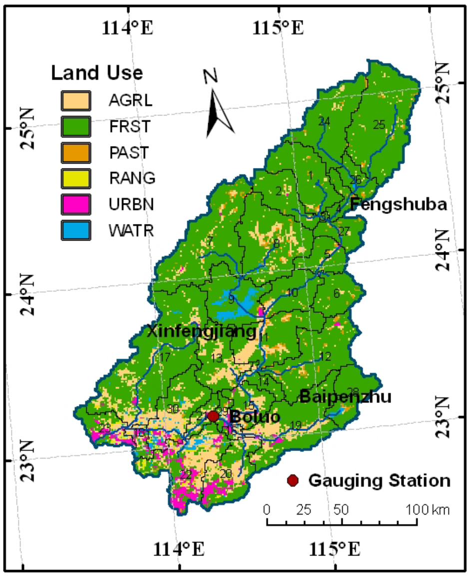

Figure 1. The location of Xinfengjiang reservoir and the land use of the East River basin in southern China.

1. INTRODUCTION

Reservoir operation is one of the challenging problems for water resources planners and managers. A summary of different methods (such as Dynamic Programming, Linear Programming and Non-linear Programming, etc.) used for surface water reservoir management had been reviewed by Yeh (1985).

In the case of a reservoir built for flood control, a consistent relationship between impoundment and change in flow variables can be expected (Batalla *et al* 2004). However, for a reservoir built for irrigation and hydroelectric generation, we should expect the relation to be noisy because flood reduction normally would not be a main purpose (Walker 1985).

Regardless of its purposes a reservoir alters the downstream flow regime of rivers (Williams *et al.* 1984), and the environmental effects may be caused by the resultant hydrologic alterations. In order to measure the hydrologic impacts of dams on the monthly level, Ritcher *et al.* (1996) accounted for two characteristics, i.e. magnitude and duration of flows, while Lajoie *et al.* (2007) considered the influence of watershed size and seasons. Additionally, some researchers took into account the root mean square error (Hanasaki *et al.* 2006), coefficient of variation or coefficients of skewness (Maheshwari *et al.* 1995) to evaluate the hydrological alteration by reservoirs.

Using hydrologic numerical models, and simulating, evaluating and understanding the behaviors of reservoir operation, we can determine whether the whole basin system and the hydrologic processes involved in it can be represented reasonably. This paper simulates the operation of a multi-year and multi-purpose reservoir, Xinfengjiang reservoir (noted as XFJR hereafter) of the East River in southern China, and examines its induced hydrologic effects.

2. STUDY AREA AND DATA

The study area and data used herein are the same as those introduced in the studies of Chen and Wu (2007) and Wu *et al.* (2007). For completeness, a brief introduction is given here.

XFJR is located in the East River basin. The East River (named Dongjiang in Chinese) lies between latitude 22°34′ and 25°12′N and longitude 113°24′ and 115°53′E. In this study, the streamflow observations from Longchuan and Boluo flow gauging stations are used to calibrate the simulation results. The controlled drainage area of the Boluo station is 25,325 km^2, and the average annual discharge is about 739 m^3/s (23.3 billion m^3/yr). The basin is near the coast of the South China Sea and belongs to the monsoon dominant climate region, with considerable variations in the spatial and temporal distributions of precipitation over the region. Therefore, in return, rationally allocating water through reservoirs is valuable for managing, exploiting and conserving water resources effectively over the area.

In the East River basin, there are three reservoirs: Xinfengjiang, Fengshuba, Baipenzhu with the capacities of about 14, 2, and 1.2 billion m^3 respectively (See Figure 1). XFJR, which is the largest one in the basin, started to operate in October 1959. The drainage area of Xinfengjiang catchment is about 5,740 km^2 and XFJR is near the outlet of the catchment. The area of the water surface expansion of XFJR is about 305 km^2, and the average annual outflow is about 195.7 m^3/s.

The basin features, soil and land cover data are specified for the study area in the SWAT hydrologic model (Arnold *et al.* 1998). For driving the SWAT, the land cover data with 1 km resolution are used, and the land uses are divided into six groups: Agriculture, Forest, Pasture, Range, Urban Area and Water Surface. In addition (see Figure 1), the FAO (Food and Agriculture Organization of the United Nations) soil map with 0.5 km resolution is used.

The available daily meteorologic forcing, including precipitation, maximum and minimum surface air temperatures, wind speed and relative humidity (Feng *et al.* 2004) are also used in this study.

3. METHOD

3.1. Daily Inflow and Outflow of XFJR

Due to the absence of measured daily inflow data to the reservoir, the simulated streamflow from the SWAT model is used in this study. Considering the fact that only daily reservoir outflow and monthly reservoir storage are available, the daily reservoir storage should be obtained based on the following equation:

$$v = v_{pre} + i - o \qquad (1)$$

where v and v_{pre} are the reservoir storages on the given day and on the previous day, o is the observed reservoir outflow, and i is the net reservoir inflow which is calculated using the following equation.

$$i = inflow + pcp - evp - seep \quad (2)$$

where *inflow* is the stream flow entering the reservoir on a given day, *pcp* the precipitation over the reservoir water surface, *evp* the amount of evaporation from the water surface of the reservoir, and *seep* the amount of seepage out of the reservoir storage (All units here are in volume).

The amounts of *inflow, pcp, evp,* and *seep* are obtained from SWAT model, while *o* is observed. The initial reservoir storage is set at 6.2828 billion m^3 for January 1965, which was the reservoir storage measured in December 1964. Then the daily reservoir storage is obtained using the above equations. In order to check whether this method is feasible or not, monthly average reservoir storage are then compared with the observed monthly average reservoir storages.

3.2. Simulation of Reservoir Operation

For reservoir simulation, SWAT provides four different methods for calculating the volume of outflow: measured daily flow, measured monthly flow, average annual release rate for uncontrolled reservoir, and controlled outflow with target release (Neitsch *et al.* 2001). The last one, which is suitable for the simulation of large reservoirs, is used herein. In this study, an algorithm based on the linear relation of daily change in reservoir storage against net reservoir inflow and storage is also developed.

Simulation by controlled outflow

For the target release approach (Neitsch *et al.* 2001), the principal spillway volume, v_{pr}, corresponds to maximum flood control reservation, while the emergency spillway volume, v_{em}, corresponds to no flood control reservation. Reservoir outflow is calculated as follows:

$$o = \frac{v - v_{targ}}{ND_{targ}} \quad (3)$$

where o and v are the same as in equation (1), ND_{targ} is the number of days required for the reservoir to reach target storage, and v_{targ} is the target reservoir volume for a given day (m^3).

Simulation by linear regression equations

We observe that there is an explicit linear relation of the daily change in reservoir storage (Δv) against net reservoir inflow (i) and reservoir storage (v). This linear relation is noticeable in wet season (from April to September) in the East River. Therefore, the following linear equation is suggested in this study.

$$\Delta v = a + b \times v + c \times i \quad (4)$$

where Δv is the change in reservoir storage on a given day (10^8 m^3), which is calculated by subtracting storage on previous day from storage on the given day (for calculation of daily storage, see equation (1)), v is the reservoir storage on the previous day (10^8 m^3), i is the net reservoir inflow on the given day (10^8 m^3). So the unit of constant coefficient, *a,* is 10^8 m^3, while the coefficients, *b* and *c*, are dimensionless. Based on 10 years (1965 – 1974) of daily storage and inflow, we can determine coefficients *a*, *b*, and *c* for each month using linear least-square method, where the total sum of squared deviations of simulated Δv from measured Δv is minimized. The results are listed in Table 1.

Table 1. Linear regression equations for each month using 10-year data (1965 – 1974).

Mon	Linear Relation (Δv =)	Corr Coeff
Jan	$-0.097 - 0.0007 \times v + 1.03\ i$	0.61
Feb	$-0.083 - 0.0008 \times v + 0.94\ i$	0.58
Mar	$-0.070 - 0.0017 \times v + 1.20\ i$	0.76
Apr	$+0.015 - 0.0026 \times v + 1.03 \times i$	0.98
May	$+0.010 - 0.0023 \times v + 1.00 \times i$	0.98
Jun	$-0.144 - 0.0002 \times v + 1.02\ i$	0.99
Jul	$-0.258 + 0.0013 \times v + 1.03 \times i$	0.97
Aug	$-0.246 + 0.0006 \times v + 1.04 \times i$	0.90
Sep	$-0.161 - 0.0007 \times v + 1.20\ i$	0.87
Oct	$-0.102 - 0.0011 \times v + 1.01\ i$	0.89
Nov	$-0.075 - 0.0015 \times v + 1.12\ i$	0.69
Dec	$-0.038 - 0.0021 \times v + 1.10\ i$	0.86

Once the initial storage (e.g. storage as in Dec 1964) of a certain simulation period (e.g. 1965 – 1974) is given and net reservoir inflow is simulated by SWAT, the daily change in reservoir storage can be obtained using the equations listed in Table 1. The daily storage and outflow can then be obtained.

4. RESULTS AND DISCUSSION

4.1. Different Simulation Schemes

This newly-developed algorithm for XFJR (Table 1) is then incorporated into the SWAT model to simulate daily storage and outflow. Table 2 presents the evaluation results of simulated monthly average reservoir storage and outflow during that period by the two methods – controlled outflow with target release and linear regression relation. It can be seen that the simulated outflow by the new method is closer to the observation than by the SWAT built-in algorithm, based on relative bias, relative deviation and correlation coefficient. The three items improve by about 68%, 19% and 88% respectively. The simulation of storage by the new method is also found to improve greatly.

Table 2. Comparison of the reservoir simulation by the two methods - controlled outflow and newly-developed linear regression relation.

Evaluation Terms		Relative Bias	Relative Deviation	Corr Coeff
SWAT	Storage	0.141	0.18	0.88
	Outflow	0.007	0.26	0.35
New* scheme	Storage	0.003	0.10	0.93
	Outflow	0.003	0.22	0.66

* Inflow in new scheme is estimated by SWAT.

4.2. Operation of XFJR

XFJR is a multi-year operation reservoir (characterized by inter-annual allocation of water) and is for multi-purpose (mainly for hydropower generation, irrigation, and flood control). It is possible for XFJR to hold the flood water during the wet season in a year as long as its water level is not very high at the beginning of such a season. Normally, XFJR is regulated based on other objectives rather than flood control since its water level is lower than the flood controlled water level - 114m (Table 3).

Table 3. Flood control water level of XFJR.

Time period	Water level (m)
Apr 1 – Jun 30 (First half of flood season)	114 (Flood control level)
Jul 1 – Sep 30 (Last half of flood season)	115
Other time (Non-flood season)	116 (Normal level)

Figure 2 shows the historical daily storage, inflow and outflow from 1965 to 1974. It can be seen that the highest reservoir water level during this period is about 112 m, and is much lower than the prescribed flood control level during most other periods (see Table 3). This suggests that the operation of the reservoir may not concern the flood control problem much. The figure also indicates, in case of a high water year (e.g. 1968), the reservoir holds as much flood water as possible and the storage increases in the wet season, so as to maintain a relatively constant outflow (vary gently around the annual average outflow). In case of a low water year (e.g. 1969 to 1970), the reservoir releases more water and storage decreases so as to maintain a relatively constant outflow. Consequently, we may infer that the reservoir operation during the 10 year period (1965-1974) is mainly controlled by hydropower demand, irrigation, and navigation.

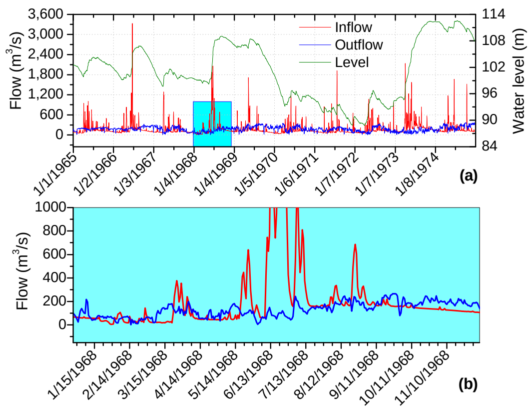

Figure 2. Daily reservoir inflow, outflow, and storage during 1965 through 1974.

Some fundamental statistical analysis of the historical daily inflow and outflow is also carried out, results of which are shown in Table 4. As can be seen, the standard deviation of inflow in dry season (Jan to Mar and Nov) is less than that of outflow. This may support the point that the variation of inflow is not a dominant factor influencing the reservoir operation. In the wet season, the standard deviation of inflow is much larger than that of outflow. The values listed in Table 4 are also presented in Figure 3.

Both Table 4 and Figure 3 show that annual average outflow is obviously greater than inflow in the dry season (October to March the following year) and storage is decreasing. This is caused by the increased release to maintain a certain outflow (e.g. to meet hydropower demand) from the reservoir in dry season. However, in the wet season (April to July), outflow is obviously less than inflow and storage is increasing. This is caused by storing flood water in the reservoir in the wet season to still maintain a certain amount of outflow (i.e. certain demand).

Table 4. Statistical analysis of the daily historical inflow and outflow.

Mon	Average (m^3/s)		Standard Deviation (m^3/s)		Coefficient of Variation	
	Inflow	Outflow	Inflow	Outflow	Inflow	Outflow
Jan	94.1	153.5	52.3	68.6	0.56	0.45
Feb	91.2	153.7	54.5	70.1	0.60	0.46
Mar	96.1	168.9	65.8	72.1	0.68	0.43
Apr	226.0	142.3	261.5	74.7	1.16	0.53
May	287.1	142.2	261.2	66.9	0.91	0.47
Jun	369.1	175.4	453.7	67.7	1.23	0.39
Jul	229.1	195.2	213.2	63.6	0.93	0.33
Aug	209.4	228.9	115.0	60.0	0.55	0.26
Sep	170.0	205.8	88.9	63.1	0.52	0.30
Oct	159.1	196.5	137.2	72.0	0.86	0.36
Nov	125.0	179.6	51.1	67.4	0.41	0.38
Dec	121.7	178.5	95.5	81.1	0.78	0.45
Ave	**181.5**	**176.7**	**154.2**	**69.0**	**0.77**	**0.40**

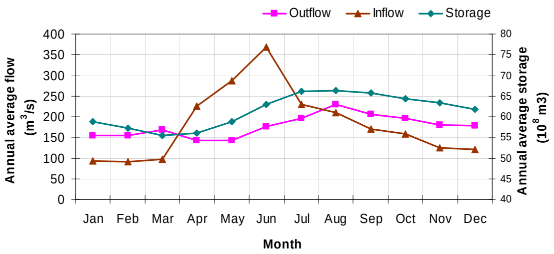

Figure 3. Annual average inflow, outflow and storage in each month over 10 years (1965 – 1974).

4.3. Analysis of Linear Regression Equation

Linear regression equation obtained based on 10 years of data could reflect the general reservoir operation to a certain degree. This shows that inflow and storage are factors in determining the reservoir operation. The contributions of each term in the linear regression equation to the change in reservoir storage are examined. We use annual average reservoir inflow and reservoir storage over 10 years (from 1965 to 1974) for each month as the inputs to the equations listed in Table 1. The results are shown in Figure 4.

The daily change in reservoir storage (Δv) should reflect how the reservoir is operated. From Figure 4, it can be found that reservoir inflow has a tendency to increase the reservoir storage, because its contribution to Δv is positive. The amount of its contribution becomes larger and larger as time approaches the wet season and then becomes less and less as time approaches the dry season with the maximum value normally observed in June and minimum in February.

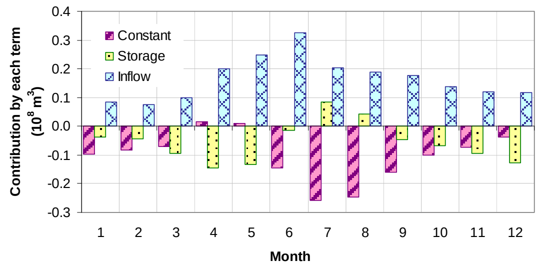

Figure 4. Contribution to the daily change of reservoir storage by each term in the linear regression equations for each month.

We can also see that the reservoir inflow has a tendency to increase the reservoir storage in July and August, and has a tendency to decrease the storage in the other months. This reflects the fact that reservoir operator is inclined to release water as the water level in the reservoir goes up in the pre-flooding season (April to June) so as to hold more possible flood water later, and store water in the post-flooding season (July and August) to maintain a relatively higher water level for the consideration of power generation. In dry season (September to March), the amount of inflow is small, so the reservoir operator has to release water to meet the demand for power generation and other purposes such as navigation, water supply, arresting seawater intrusion, etc. That is why, as we have seen, the amount of the contribution by the storage is negative (i.e. releasing water) in this period. The reservoir inflow in dry season, mainly caused by base flow from the upstream sub-basins, usually becomes less and less, with the minimum value observed at the end of the dry season (February to March). Then the absolute amount of the contribution by the reservoir storage becomes relatively larger and larger with the maximum value observed in April to compensate the less inflow for the sake of power generation and other demands from downstream. And in June, the influence of the reservoir storage on the reservoir operation reaches the minimum level when the influence of the inflow on the reservoir operation reaches the highest level.

Inflow should be the only factor which will increase the reservoir storage, while both storage term and constant term basically aim at decreasing the reservoir storage. So the contribution by the latter two terms can be taken as a whole. The contributions by the two parts is shown in Figure 5. As we have seen, the contribution by one part is positive and the other is negative.

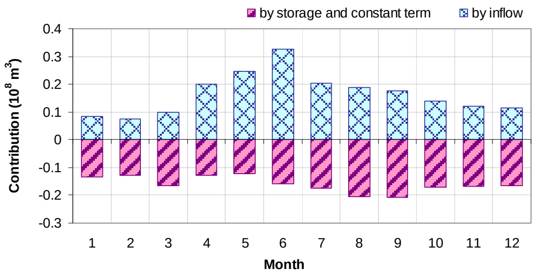

Figure 5. Comparison of contribution by storage and constant terms and that by inflow term.

The ratio of the absolute contributions between these two parts is shown in Figure 6. From the figure, it can be observed that the contribution by both storage term and constant term is low in the wet season when the contribution by inflow reaches a relatively high level. The ratio becomes larger and larger from the end of the wet season to the end of the dry season (July to March next year). During this period the contribution by inflow becomes small due to the reducing baseflow in dry season.

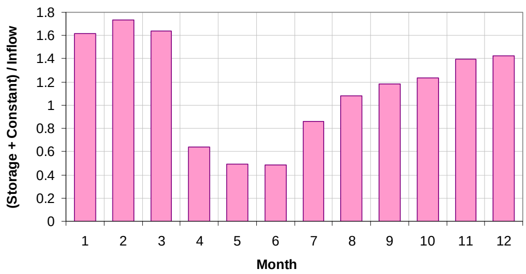

Figure 6. Ratio of contribution by storage and constant terms to that by inflow term.

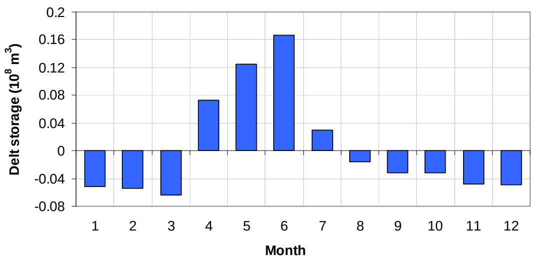

Figure 7. Annual average change of reservoir storage in each month of 10 years (1965 – 1974).

The sums of the three items presented in Figure 4 are shown in Figure 7. The figure reveals that the contribution by inflow (positive) dominates in main wet season (April to July), while the contribution by the other (negative) dominates in the other months.

Therefore, it can be concluded that reservoir inflow has a larger influence on the reservoir operation in the wet season than that in the dry season, while reservoir storage has a larger influence on the reservoir operation in dry season. Moreover, the influence of inflow on the reservoir operation becomes less around dry season and becomes larger around the pre-flooding season (April to June). From the correlation coefficients presented in Table 1, it can be seen that the linear regression relation can indeed reflect the actual reservoir operation well, especially in the wet season with correlation coefficients ranging between 0.97 and 0.99.

4.4. XFJR's Influence on Downstream Flow

It is intuitive that the larger the reservoir capacity in relation to the natural flow in the river, the greater the hydrologic effect of the reservoir is likely to be (Batalla 2004). In order to investigate the hydrologic effects of reservoir operation, monthly flow at the outlet of Xinfengjiang catchment between no-reservoir simulation (natural flow) and observed reservoir outflow covering the period January 1965 to December 1974 are evaluated. Through a comparison, it can be seen that the no-reservoir simulation (natural flow) produces large fluctuations, and peaks generally occur in the period from May to July (see Figure 2). Reservoir operation reduces peak flow and seasonal fluctuations in discharge greatly. The relative deviation (see equation (5)) is then used to evaluate the difference between the two scenarios.

$$RD = \frac{1}{n}\sum \frac{|y - x|}{\bar{x}} \times 100\% \qquad (5)$$

where x refers to the monthly natural flow (with no reservoir simulation), and y refers to the observed outflow at the outlet of Xinfengjiang catchment. Relative deviation data is 55.6% and, therefore, we can say that the operation of XFJR alters the monthly flow at the outlet of Xinfengjiang catchment by about 55.6%.

Likewise, in order to explore the effects of XFJR operation on flow at Boluo, we design two scenarios. One is simulating monthly flow at Boluo without XFJR (scenario I), and the other is simulating monthly flow at Boluo with XFJR but just reading in the observed outflow at the outlet of Xinfengjiang catchment (scenario II). In this case, x refers to the simulated natural flow at Boluo (scenario I: with no-reservoir simulation), and y refers to the observed outflow (scenario II) at Boluo. According to the relative deviation calculated using equation (5), the operation of XFJR alters the monthly flow at Boluo by about 21.0%, which is close to the ratio of drainage area of Xinfengjiang to the drainage area controlled by Boluo (24.5%).

In addition, we observe, Figure 2, that XFJR regulates water not only between the wet season and the dry season, but also between high water year and low water year. According to the comparison between daily inflow and outflow and the comparison between annual average monthly inflow and outflow (Figure 3), larger inflow is reduced greatly in the wet season and less inflow is raised. Moreover, from Table 4, it can be seen that the standard deviation and average coefficient of variation of outflow reduce by about 55% and 48% respectively, compared with that of inflow.

5. CONCLUSION

For reservoir simulation, the original reservoir simulation scheme (the controlled outflow with target release) in the SWAT might not be suitable for a large reservoir with multi-year regulation such as the XFJR. Although the simulation of XFJR has been improved using the new scheme proposed herein, further research is still needed for identifying the basic features of these simple equations. However, we can infer, from this study, that the reservoir inflow has a larger influence on the reservoir operation in the wet season than that in the dry season, while the reservoir storage has a larger influence in the dry season than that in the wet season.

In addition, our results suggest that the XFJR produces substantial alterations to the flow regime. According to the calculations of relative deviation, the reservoir operation alters the monthly flow at the outlet of Xinfengjiang catchment and at the Boluo gauging station by about 55.6% and 21.0%, respectively.

6. ACKNOWLEDGEMENTS

This study is supported by the NSFC/RGC JRS Project (N HKU 747/03).

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