Has the Three-Gorges Dam made the Poyang Lake wetlands wetter and drier?

Q. Zhang[1], L. Li[2,3,#], Y-G. Wang[4], A. D. Werner[5], P. Xin[3], T. Jiang[6] and D. A. Barry[7]

[1]State Key Laboratory of Lake Science and Environment, Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences, Nanjing, 210008, China

[2]State Key Laboratory of Hydrology-Water Resource and Hydraulic Engineering, Hohai University, Nanjing, 210098, China

[3]National Centre for Groundwater Research and Training, School of Civil Engineering, The University of Queensland, St Lucia, Queensland, 4072, Australia

[4]Centre for Applications in Natural Resource Mathematics (CARM), School of Mathematics and Physics, The University of Queensland, St Lucia, Queensland, 4072, Australia

[5]National Centre for Groundwater Research and Training, School of Environment, Flinders University, GPO Box 2100, Adelaide, Australia

[6]National Climate Centre, China Meteorological Administration, Beijing 100081, China

[7]Laboratoire de technologie écologique, Institut d'ingénierie de l'environnement, Faculté de l'environnement naturel, architectural et construit (ENAC), Station 2, Ecole polytechnique fédérale de Lausanne (EPFL), 1015 Lausanne, Suisse

Resubmitted to *Geophysical Research Letters* on 5 September, 2012

To whom all correspondence should be addressed. Tel: +61 7 336 53911. Email: l.li@uq.edu.au

Abstract

The Three-Georges Dam holds many records in the history of engineering. While the dam has produced benefits in terms of flood control, hydropower generation and increased navigation capacity of the Yangtze River, serious questions have been raised concerning its impact on both upstream and downstream ecosystems. It has been suggested that the dam operation intensifies the extremes of wet and dry conditions in the downstream Poyang Lake, and affects adversely important local wetlands. A floodgate has been proposed to maintain the lake water level by controlling the flow between the Poyang Lake and Yangtze River. Using extensive hydrological data and generalized linear statistical models, we demonstrated that the dam operation induces major changes in the downstream river discharge near the dam, including an average “water loss”. The analysis also revealed considerable effects on the Poyang Lake water level, particularly a reduced level over the dry period from late summer to autumn. However, the dam impact needs to be further assessed based on long-term monitoring of the lake ecosystem, covering a wide range of parameters related to hydrological and hydraulic characteristics of the lake, water quality, geomorphological characteristics, aquatic biota and their habitat, wetland vegetation and associated fauna.

Introduction

Dams have been built for thousands of years to regulate river flows for flood control and to secure adequate water supply. In modern times, hydropower generation and navigation motivate further the construction of dams. Despite their benefits, dams have become increasingly controversial. Advocates cite the need for even more dams to address challenges of global climate change, energy production and water shortages, while opponents argue on the basis of adverse social and environmental impacts [3,5,7]. Large dams, in particular, produce major ecological changes in rivers, and surrounding terrestrial and wetland ecosystems [3,7].

Dams influence both upstream and downstream ecosystems. Inundation upstream may result in irreversible damage to local terrestrial ecosystems. Reservoirs behind dams trap waterborne materials including sediments and hinder migration pathways for aquatic species. Dam operation affects the flow regime, sediment transport, and water temperature and quality downstream. Some of these changes are immediate and obvious, but others are gradual and more difficult to predict [3,7].

Perhaps no dam has caused more debate about the benefits and impacts than China’s Three-Georges Dam (3GD), the world’s largest, built on the Yangtze River [8]. Construction of the 3GD commenced in 1997; operations began in 2003 and it became fully functional in 2008. The dam has produced benefits in terms of flood control, hydropower generation and expanded river navigation capacity [2]. It also has resulted in or will potentially cause major changes to the river system, including the Poyang Lake [6], a key tributary of the Yangtze River downstream of the dam and the largest freshwater lake in China (Fig. 1). With extensive wetlands, the lake hosts an important ecosystem and provides habitat for migratory birds [6]. The lake is generally shallow with an average depth around 8 m, and thus the functioning and extent of its ecosystem are sensitive to water level changes.

Compared to its prior state, the 3GD makes two major changes in the river discharge pattern over an annual cycle: an increase in May and a decrease in September. The former is intended to increase the reservoir's storage capacity for flood mitigation generated by heavy upstream summer rainfall. This operation coincides with the Poyang basin rainy season, which is typically 1-2 months ahead of the upstream rainy period [10]. It is hypothesized that the increased discharge may raise the river water level at the lake mouth (Hukou) and thus constrain the drainage of the lake to the Yangtze River (*blocking effect*; Fig. 1), worsening flooding in the lake area. Around September, the discharge is reduced to increase the water level in the reservoir for power generation. The change may lead to lower water levels in the river downstream and thus increase the drainage of the lake (*emptying effect*), intensifying "drought" in the lake area over the dry season [10].

The hypothesis of the blocking and emptying effects has not been tested rigorously with existing data. Yet a proposal has been put forward to build a floodgate at the lake mouth to regulate the lake water level by controlling the flow between the lake and river [6]. To assess the hydrological changes in the lake in response to the dam operation, we analyzed hydrological data collected from the dam and lake areas (Fig. 1a,b) prior to and after the dam operation. Generalized linear statistical models [11] were developed to discern possible impacts of the 3GD on the downstream flow and water level. Ideally, a combined approach integrating both statistical and physical/hydrological modeling should be used to analyze the system. However, this is not feasible at present due to the lack of a wide range of essential data needed for building a physical process-based model (e.g., long-term, distributed data of meteorological conditions, catchment topography and land use, catchment hydrogeology, river morphology, lake bathymetry and water uses).

Details of the data, statistical analysis and modeling are given in the supplementary materials.

River flow regulation imposed by the dam

The dam regulation is based mainly on the needs of flood control and hydropower generation. The reservoir water level data reflect both this regulation principle and the weather conditions (Fig. 2). In addition to three stages of mean level rise evident in Fig. 2, the annual trends of the water level were characterized by two seasonal adjustments: a water level decline between February and May and a rise between September and November, except for 2003 (which was treated specially in the data analysis). These water level variations resulted from increased and decreased discharge from the dam to downstream, respectively.

Analysis of the discharge data is essential for investigating the effects of the dam on the downstream ecosystems. Since the dam operation period has not been long, the post-dam discharge data collected up to the end of 2008 do not necessarily contain the natural variability that exists in this complex hydrological system. Hence, direct comparison of the annual cycles of averaged discharge rates prior to and after the dam is not adequate for identifying the dam impact. We examined the ratio of the total discharge near the dam site to total rainfall depth upstream over periods of interest. This ratio, equivalent to an effective catchment area (ECA), reflects the rainfall-runoff response of the upstream catchments under natural conditions (prior to the dam) and subjected to the dam impact (after the dam), as measured by the river discharge downstream near the dam site.

The analysis focused on two periods within the annual cycle: before and after September (≤ and > day 250 respectively, according to the annual water level rise at the reservoir). The year 2003 was excluded because of the initial, dramatic reservoir water level rise in that year. The ECA was calculated on the basis of 5-y cycles before and after the dam was built. The results (Table 1) overall show a lower ECA for the period after September over the 2004-2008 cycle, compared with the same period for all the previous 5-y averages over the past 25 y. For the period before September, the ECA appears to be less different between the 5-y cycles before and after the dam. Averaged over all years, the ECA decreased from 355.44×10^9 to 345.46×10^9 m^3 per m rainfall for the period before September, and from 568.42×10^9 to 528.33×10^9 m^3 per m rainfall for the period after September, after the dam was built. In the total of 365 d, the reduction was from 404.42×10^9 to 386.70×10^9 m^3 per m rainfall. These results imply that for the same amount of rainfall, less water flowed downstream.

Based on the averaged ECA values and average rainfalls (mm/d) over 1968-2008 – 3.2 and 2.0 mm/d for the periods before and after September, an apparent daily water loss was estimated to be 32.6 and 83.6 million m^3/d for the two periods, respectively. A constant average loss (over 365 d) was calculated as 48.7×10^6 m^3/d (c_1), or 17.8×10^9 m^3 annually. The effect of the dam due to increased discharge is indicated by a reduced water loss of $c_2 = 48.7 – 32.6 = 16.1 \times 10^6$ m^3/d (gain) for the first period (≤ day 250). Conversely, the reduced discharge led to an increased water loss of $c_3 = 48.7 – 83.6 = -34.9 \times 10^6$ m^3/d (loss) for the second period (> day 250). While the difference in the water loss between the two periods is related to the dam operation, the cause of the constant loss is not readily clear. The water storage within the reservoir associated with the mean water level rise would have contributed to this loss of discharging water, but only for 2003 when the water level rose from 70 to 135 m (dead reservoir storage ~13 × 10^9 m^3 [9]) and 2006 with the water level further rising to 156 m (dead reservoir storage ~10 × 10^9 m^3 [9]). Moreover, the dead reservoir storage could not explain the portion of water loss over the first period. We suggest that increased evaporation from the water surface of the reservoir (formed after the 3GD was built) and underground leakage due to the water level rise (by up to 175 m at the dam site) were also responsible. Based on measured annual evaporation rates from three stations near the 3GD (942 mm on average) and an estimated reservoir water surface area of 0.662 × 10^9 m^2 [9], we estimated the amount of water loss due to increased evaporation to be 0.62 × 10^9 m^3, ~3.5% of the total loss. This indicates that underground leakage and perhaps other unknown processes contribute largely to the water loss.

Statistical modeling of the data was conducted to examine further the dam impact. To incorporate possible nonlinear relationships between the responses of the discharge to upstream rainfall, we adopted a semi-parametric approach based on generalized additive models (GAMs). This approach allows each individual covariate effect to be assessed non-parametrically [4,11]. A GAM is a generalized linear model with a linear predictor given by a sum of smooth functions of the covariates and a conventional parametric component. The method is general with smooth terms represented by penalized regression splines. By allowing nonparametric fits, well-designed GAMs enable good fits of the training data with relaxed assumptions on the actual relationship. The link function (s_g) relates the expected value of the distribution to the predictors (covariates). An identity link was used to maintain a linear relationship between flow and rainfall, and thus the mean flow was given by $E(\text{Flow}) = X\beta + s_g(\text{d})$, where X is the design matrix of the input rainfall data and $s_g(\text{d})$ is the smooth cyclic function. Although the statistical model is not based on descriptions of the hydrological processes, the effects of these processes are included implicitly in the model. For example, the cyclic function in the model accounts for the evaporation effect (further details in the supplementary materials).

Two predictive models of discharge at the dam based on observed upstream rainfall data were established, representing conditions before (1980-2002) and after (2004-2008) the dam, respectively. The simulation results agreed reasonably well with the data in both cases (Fig. 3). To avoid possible over-fitting of the data, cross-validation [11] was conducted to ensure that the final models were the most reliable. Both models were then applied to simulate the discharge based on averaged daily rainfalls over three different data-collection periods: before and after the dam, and the entire period. Consistent trends and differences between the predictions by the two models are evident in the simulation results (Fig. 4). The differences indicate the effects of the dam operation. Overall, the post-dam model predicts reduced discharges from the dam – an average loss of about 5% of discharging water occurred in all three cases. While both periods before and after September showed reduced discharges as suggested by the above data analysis, the models provided further insight into the changes. A slight increase of the discharge was predicted as a response to the dam operation around May to lower the reservoir water level for flood control. After September, the predicted discharge reduction was expected as a result of the dam operation to raise the reservoir water level for power generation. It is likely that the reduced discharge in the summer months was partly associated with increased evaporation from the large surface area of the reservoir.

This analysis demonstrates that the dam regulation leads to considerable changes of discharge in the river (immediately) downstream, in particular, relatively high and low discharge rates corresponding to the dam operation before and after the upstream rainy season, respectively. How much these changes will affect Poyang Lake remains an open question.

Effects of the dam on the Poyang Lake

The lake behaves in a more complicated way than the 3GD reservoir. The discharge from the lake at the juncture with the river (lake mouth or Hukou) is determined by the water levels in the lake (relative to the water level in the river), which in turn are affected by both the lake discharge at Hukou and inflows from local rivers to the lake (Fig. 1d). The hydraulic conditions in the lake system are temporally dynamic and spatially variable.

Analysis of the Hukou water level relative to the local rainfall in the lake area showed a slightly wetter condition than usual for the time period around May when the 3GD discharged more water. The dry condition with a relatively low water level at Hukou was also evident for the period of increasing dam storage, but comparable with the result from the last previous 5-y period. In both cases, the lake water level changes at Hukou could not be considered as being extreme.

Following the approach applied to the dam discharge data, statistical models (GAMs) were developed to simulate the lake water level variations in response to local rainfall and rainfall upstream of the dam. Again, the data were simulated separately for the periods before and after the dam construction. The models used an initial baseline water level (e.g., water level 60 d before) to predict the water level for the next period (i.e., the next 60 d). This periodic initialization was found to be essential for the prediction because of the cumulative behavior of the lake water – for example, a high level may last for a number of days despite dry weather conditions. Analyses were conducted with different initialization periods (30, 60 and 90 d). Overall the model predictions captured the trend of the lake water level variation but with significant scatter (Fig. 5), reflecting the complexity of the lake hydrological system. Despite the scatter, the interaction term accounting for the dam impact was found to be significant with a weighting coefficient of -14 mm/mm rainfall and indicating a lake water level drop up to 1.78 m over the second period (> day 250) of the year due to the 3GD water storage.

Both the pre- and post-dam models were applied to predict the lake water level changes under the same averaged rainfall conditions at the lake and upstream of the dam (over the whole data-collection period). The results from models with the three different initialization periods consistently show differences between the predictions of the two models, indicating a considerable dam impact. The lower water level predicted by the post-dam model from July to October is consistent with the hypothesized impact of the 3GD on the lake water level due to reduced discharge over the period of increased water storage in the reservoir and intense evaporation (Fig. 6). However, the predicted water level rise in November and December cannot be explained by the dam operation. A similar water level rise predicted for the early months of the year appeared to occur ahead of the increasing discharge from the dam, which is inconsistent with the blocking effect of the dam operation prior to the rainy season upstream. These results suggest that the dam's impact on the Poyang Lake may be dominated by the drought created in the autumn when the dam discharges less water in order to raise the reservoir water level for hydropower generation.

Discussion and concluding remarks

Since the completion of the 3GD, a number of large scientific research programs have been set up to examine potential impacts of the dam on upstream and downstream ecosystems [1]. The responses of the ecosystems to the dam are likely to be multiple, varied and complex. Consequently, assessment of impacts of the dam should be based ideally on large amounts of long-term data relating to: hydrological and hydraulic characteristics of the river and tributaries (including lakes), water quality, geomorphological characteristics, aquatic biota and their habitat, riparian and wetland vegetation and associated fauna, and direct use of the resources of the river and its floodplain by local people. However, given the importance of various issues related to major proposals of scientific research and monitoring on key ecosystems downstream, analyses of the changes in these systems are urgently needed. For the Poyang Lake, such urgency is further escalated by a currently proposed project of building a floodgate to control the flow between the lake and the Yangtze River.

Using generalized linear statistical models, we analyzed the hydrological and hydraulic data collected from the dam and lake areas. Both direct data analysis and data simulations demonstrated the alteration of the river discharge downstream near the dam as a result of the dam operation. In particular, a large amount (~5%) of water was found missing possibly due to underground leakage and other unknown processes. The analysis also revealed a considerable impact imposed by the dam on the rise and fall of the water level in the Poyang Lake during the wet and dry seasons, respectively. The "*emptying effect*" on the lake water level due to the dam operation in the dry season was evident despite the complication by a large degree of scatter due to the complexity of the hydrological system around the lake. Further analyses based on more extensive post-dam data are needed to ascertain the dam impact on the lake system. The findings presented here suggest that the lake behavior is likely to be controlled by local factors that are modulated by the dam. Therefore, the construction of a floodgate to control the flow between the lake and the Yangtze River requires further consideration of these effects. Current and future monitoring programs must include a wide range of parameters, including those of secondary importance, since the modulating effect of the dam may be subtle and gradual, compared to the strong seasonal variations that occur due to climatic variability within the Poyang catchment itself.

Acknowledgements:

This work was supported by the National Basic Research Program of China (973 Program, 2012CB417003 and 2012CB417005). The authors acknowledge constructive comments from two anonymous reviewers, which led to improvement of the paper.

References

[1] http://www.973.gov.cn/English/Index.aspx, last accessed 26 August 2011.

[2] Chinese National Committee on Large Dams. 2011. Three Gorges Project. http://www.chincold.org.cn/english.asp, last accessed 17 July 2012.

[3] Graf, W. L., 1999. Dam nation: A geographic census of American dams and their large-scale hydrologic impacts. *Water Resources Research*, 35: 1305-1311.

[4] Hastie, T., Tibshirani, R., 1986. Generalized additive models. *Statistical Science*, 1: 297-310.

[5] Kittinger, J. N., Coontz, K. M., et al., 2009. Toward holistic evaluation and assessment: Linking ecosystems and human well-being for the Three Gorges Dam. *Ecohealth*, 6: 601-613.

[6] Li, J., 2009. Science News: Scientists line up against dam that would alter protected wetlands. *Science*, 326: 508-509 (Oct. 23).

[7] McCartney, M, 2009. Living with dams: Managing the environmental impacts. *Water Policy*, 11: 121-139.

[8] Qiu, J., 2011. Nature News: China admits problems with Three Gorges Dam. *Nature* (May 25).

[9] Wang, X., Linage, C., et al., 2011. Gravity Recovery and Climate Experiment (GRACE) detection of water storage changes in the Three Gorges Reservoir of China and comparison with in situ measurements. *Water Resources Research*, 47, W12502.

[10] Wang, Y. C., Lai, X. J., et al., 2011. Effect of the Three Gorges Reservoir on the water regime of the Lake Poyang wetlands during typical water regulation period. *Journal of Lake Sciences*, 23: 191-195 (in Chinese).

[11] Wood, S.N., 2006. *Generalized Additive Models: An Introduction with R*. Chapman and Hall/CRC Press.

Table 1. Estimated effective catchment area ($\times 10^9$ m^2) for periods before and after September over 5-y periods.

	1978-1982	1983-1987	1988-1992	1993-1997	1998-2002	2004-2008
≤ day 250	327.46	351.08	358.92	364.01	379.76	345.46
> day 250	630.04	612.93	678.23	538.60	609.88	528.33
All days	391.03	405.80	422.10	403.45	425.22	386.70

Figure captions

Fig. 1 Map of the study areas showing data collection locations (a,b), rainfall patterns upstream of the dam and in the Poyang Lake area (c), and the hypothesized response of the lake to dam operation, including factors involved in the system, and trends and events for the wet season scenario (opposite effects for the dry season) (d).

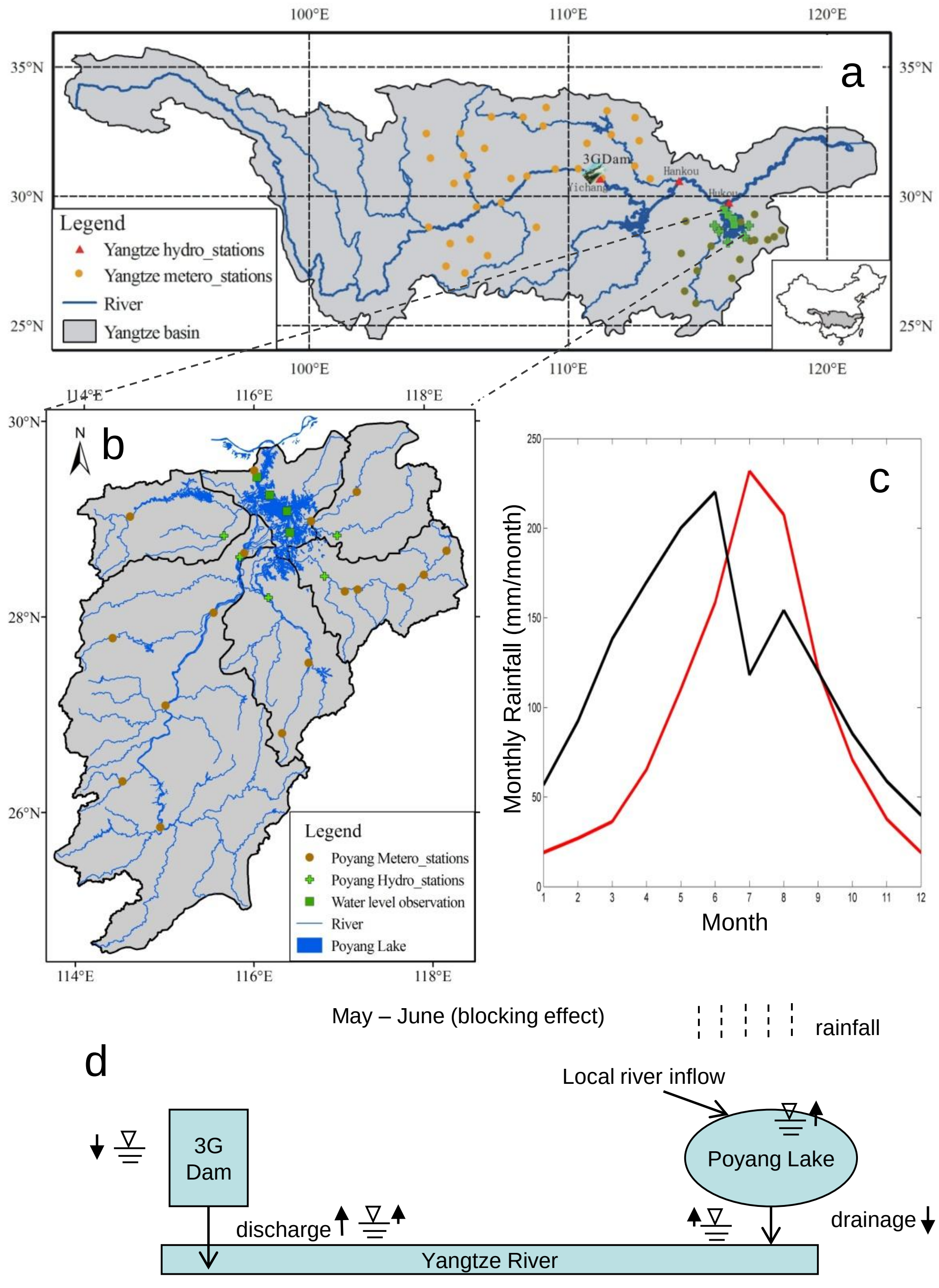
Fig. 2 Variations of water level in the reservoir.

Fig. 3 Comparison between model predictions (red) and data (blue) of the discharge at the dam.

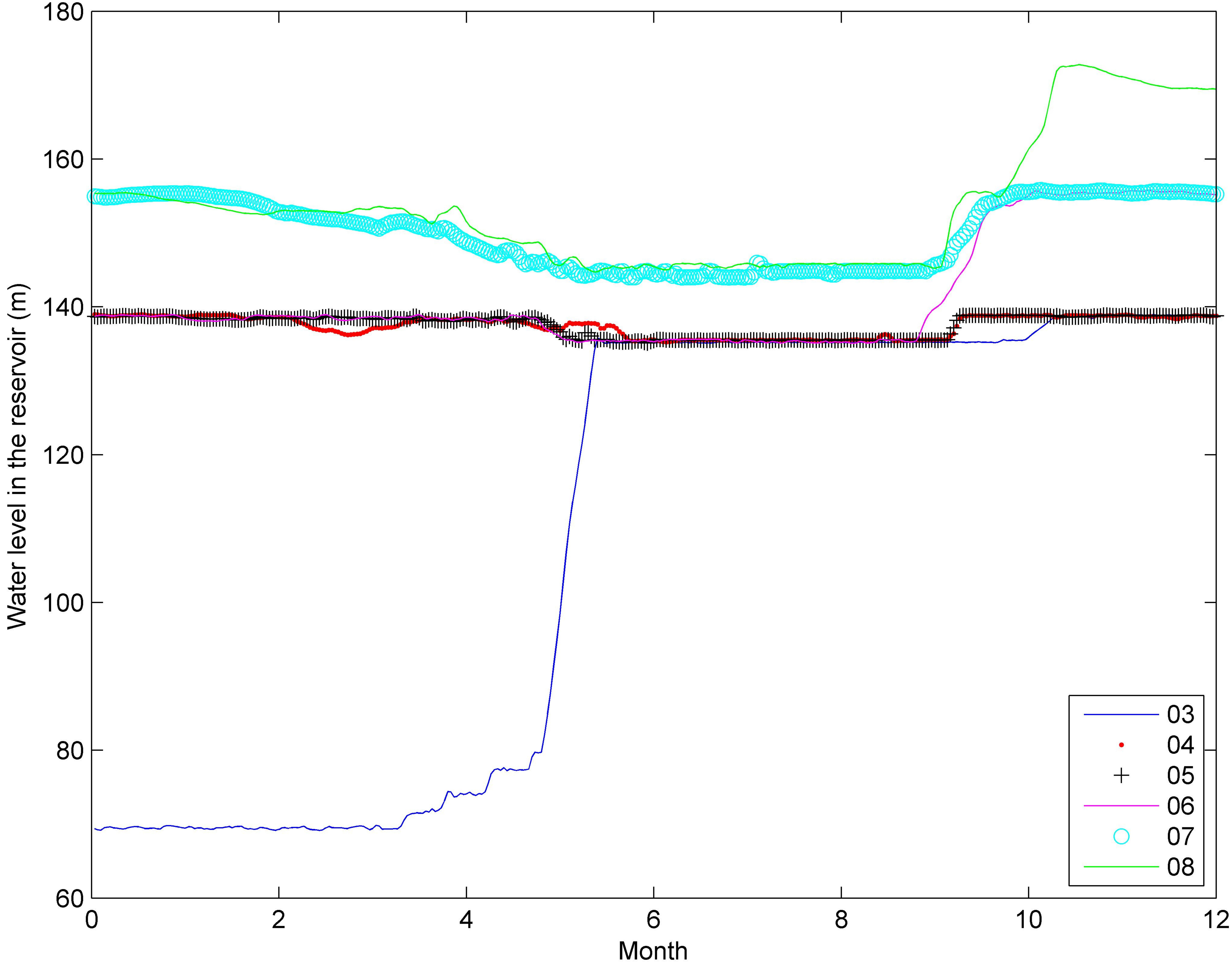
Fig. 4 Predicted discharge using the models with and without the dam impact, and based on averaged daily rainfall over different periods.

Fig. 5 Comparison of simulated and observed water levels in the lake.

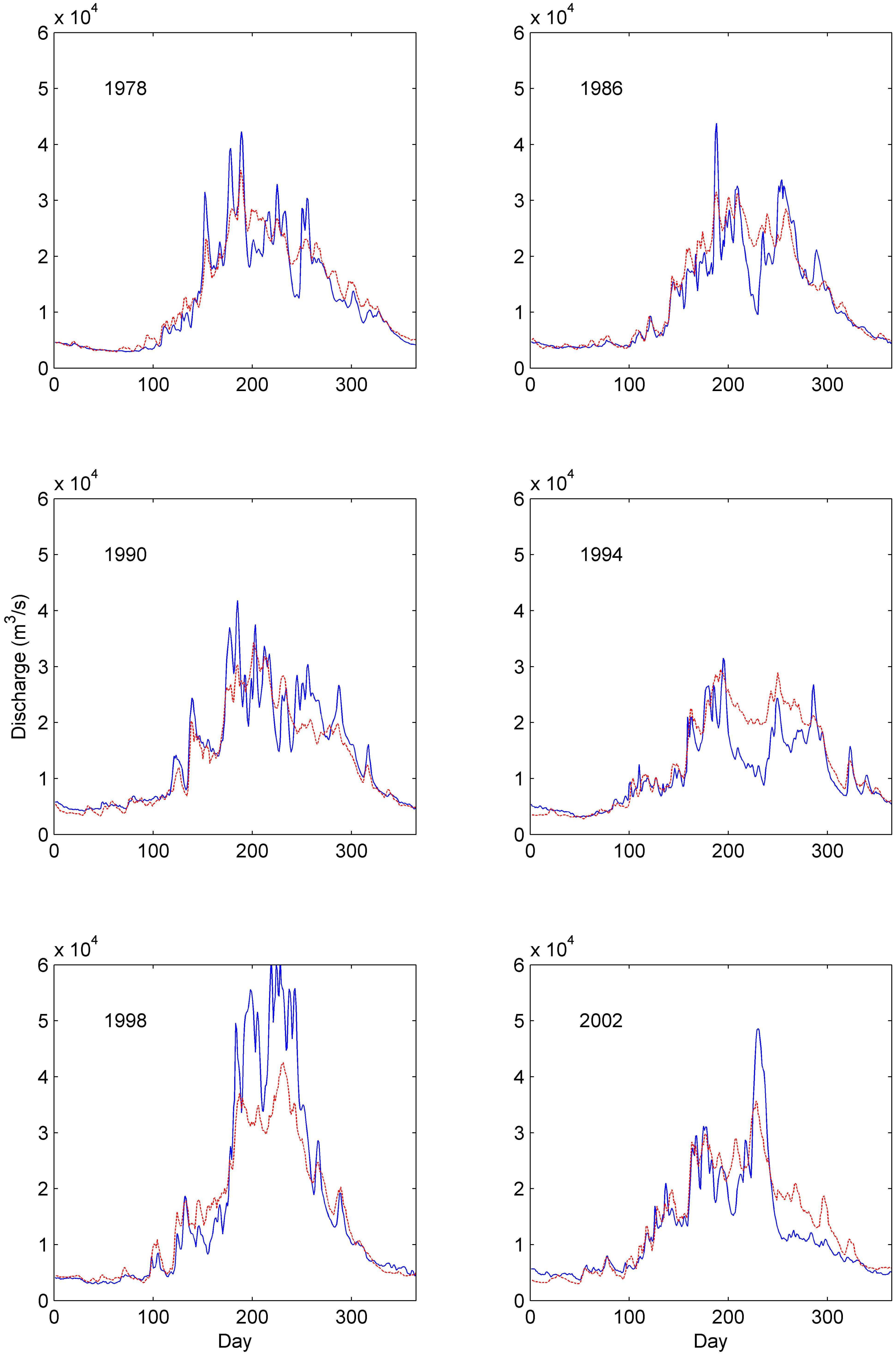
Fig. 6 Predicted lake water levels using the models with and without the dam impact, and based on three different initialization periods.

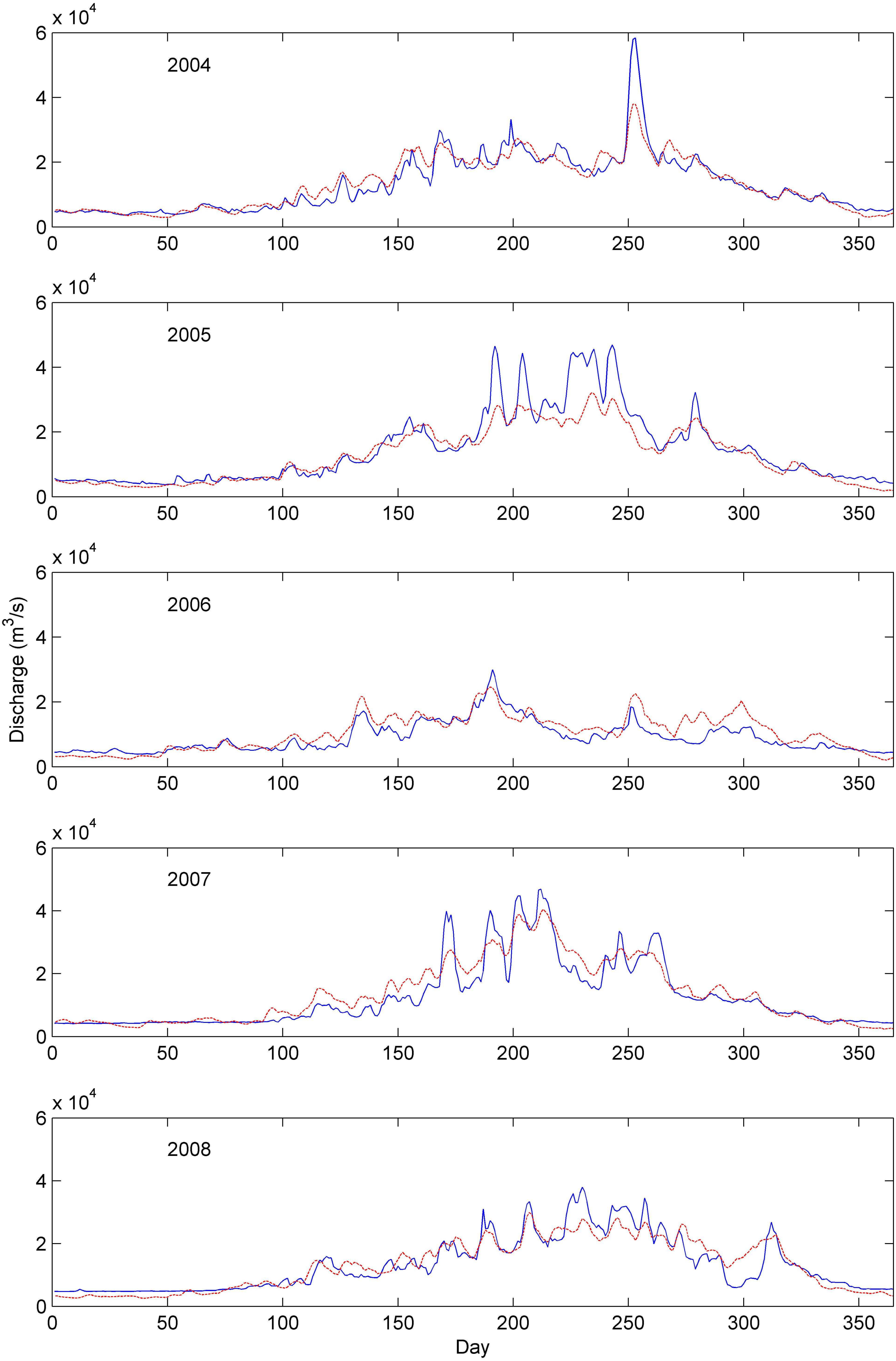


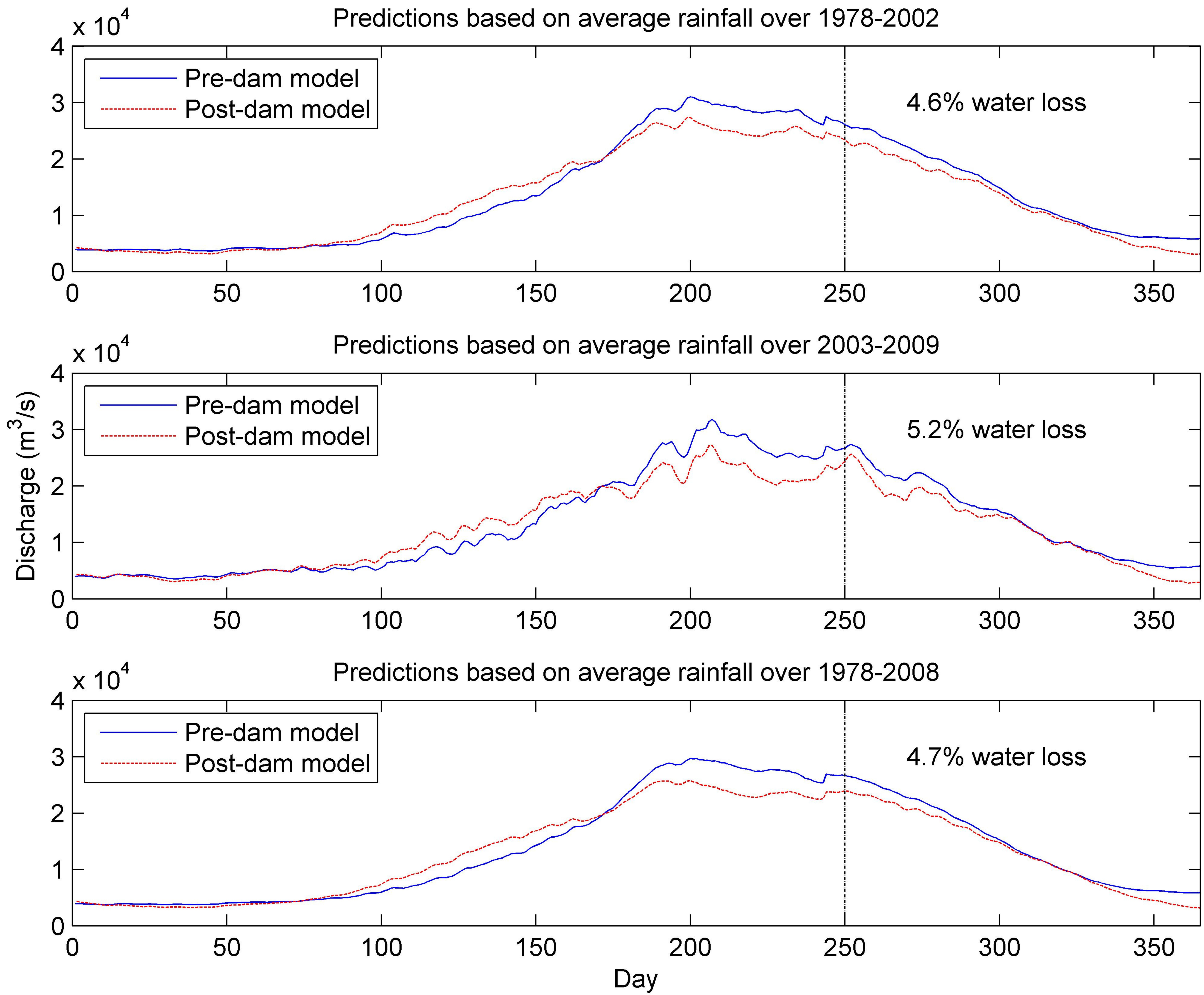
a
100°E
110°E
120°E
35°N
30°N
25°N
3GDam
Yichang
Hankou
Hukou
Legend
Yangtze hydro_stations
Yangtze metero_stations
River
Yangtze basin
b
N
114°E
116°E
118°E
30°N
28°N
26°N
Legend
Poyang Metero_stations
Poyang Hydro_stations
Water level observation
River
Poyang Lake
c
Monthly Rainfall (mm/month)
Month
0
50
100
150
200
250
1
2
3
4
5
6
7
8
9
10
11
12
May – June (blocking effect)
rainfall
d
Local river inflow
3G Dam
Poyang Lake
discharge
drainage
Yangtze River



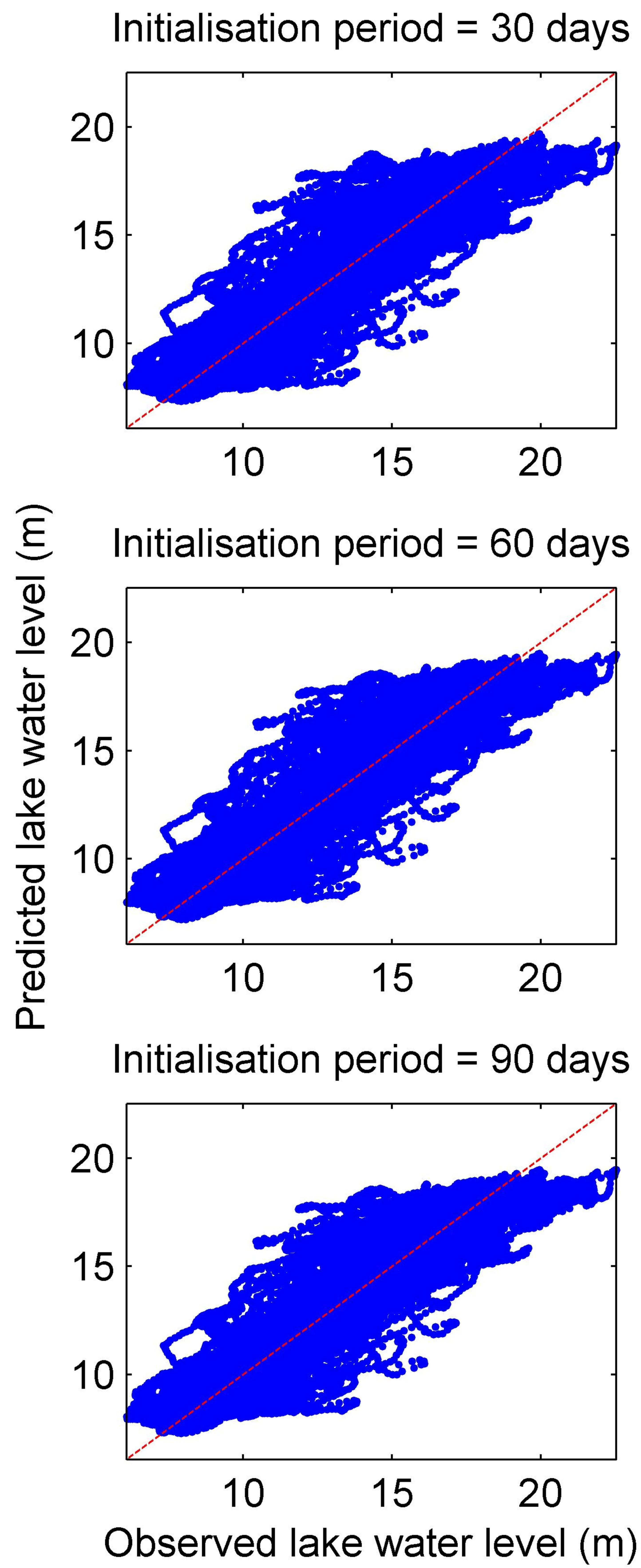
Water level in the reservoir (m)
Month
180
160
140
120
100
80
60
0
2
4
6
8
10
12
03
04
05
06
07
08


x 10^4
1978
1986
1990
1994
1998
2002
Discharge (m^3/s)
Day
0
100
200
300
0
1
2
3
4
5
6

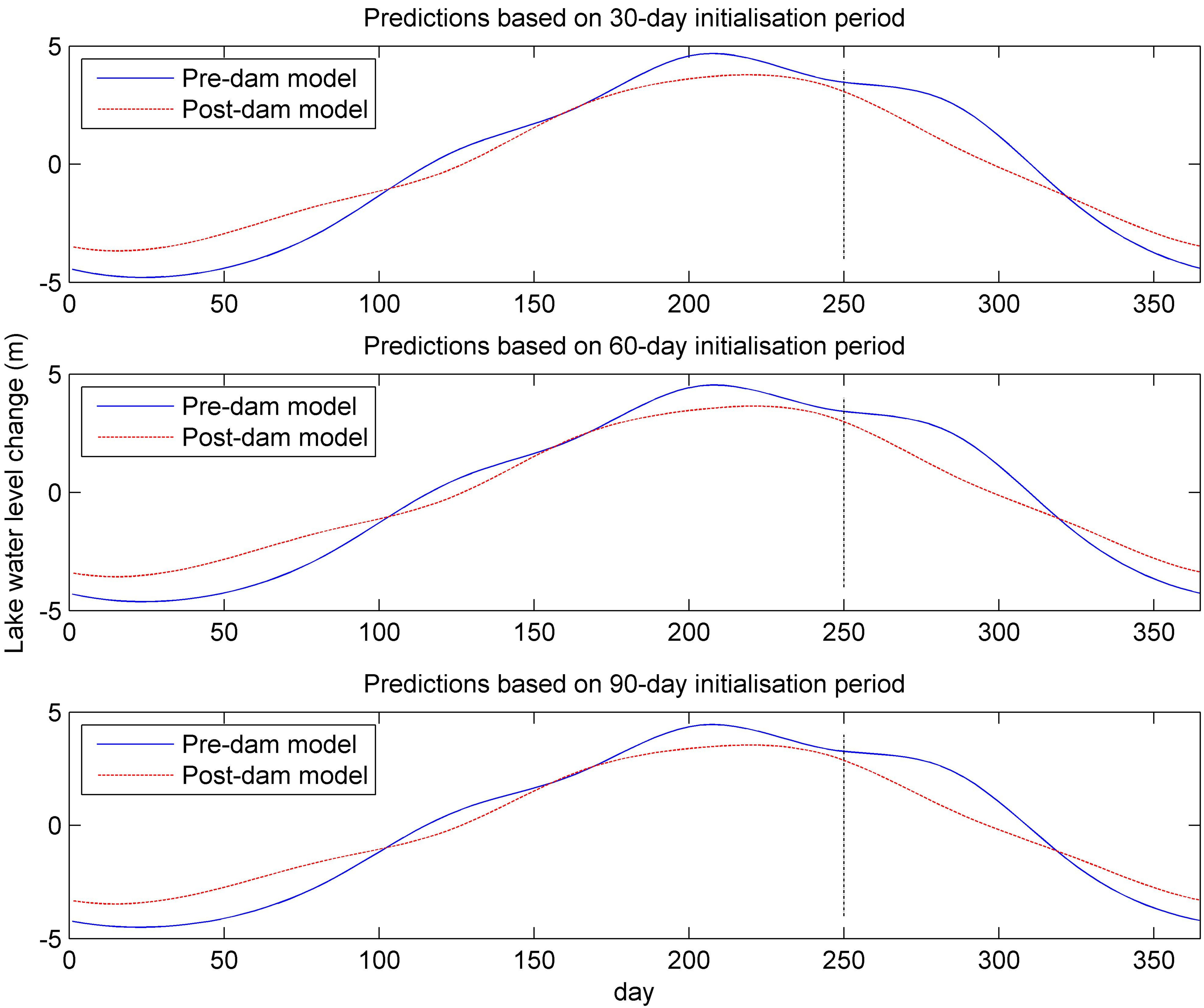

x 10^4
2004
2005
2006
2007
2008
Discharge (m^3/s)
Day
0
50
100
150
200
250
300
350
0
2
4
6



Predictions based on average rainfall over 1978-2002
x 10^4
Pre-dam model
Post-dam model
4.6% water loss
Predictions based on average rainfall over 2003-2009
Discharge (m^3/s)
5.2% water loss
Predictions based on average rainfall over 1978-2008
4.7% water loss
Day



Initialisation period = 30 days
Initialisation period = 60 days
Initialisation period = 90 days
20
15
10
10
15
20
Predicted lake water level (m)
Observed lake water level (m)


Predictions based on 30-day initialisation period
Pre-dam model
Post-dam model
Predictions based on 60-day initialisation period
Pre-dam model
Post-dam model
Predictions based on 90-day initialisation period
Pre-dam model
Post-dam model
Lake water level change (m)
day
5
0
-5
0
50
100
150
200
250
300
350