Available online at www.sciencedirect.com

ScienceDirect

Journal of Hydro-environment Research 9 (2015) 569–581

Journal of Hydro-environment Research

www.elsevier.com/locate/jher

Research paper

Risk analysis for seasonal flood-limited water level under uncertainties

Yanlai Zhou [a,b,c,*], Shenglian Guo [a], Jijun Xu [b,c], Xiaofeng Zhao [d], Lini Zhai [e]

[a] *State Key Laboratory of Water Resources and Hydropower Engineering Science, Wuhan University, Wuhan, 430072, China*
[b] *Changjiang River Scientific Research Institute, Changjiang Water Resources Commission, Wuhan, 430010, China*
[c] *Hubei Province Key Laboratory of River Basin Water Resources and Ecological Environment Science, Changjiang River Scientific Research Institute, Wuhan, 430010, China*
[d] *Hubei Provincial Water Resources and Hydropower Planning Survey and Design Institute, Wuhan, 430064, China*
[e] *Hubei Water Resources Research Institute, Wuhan, 430070, China*

Received 16 January 2014; revised 9 May 2015; accepted 18 May 2015

Available online 28 May 2015

Abstract

For floodwater utilization, seasonal flood-limited water level (FLWL) plays a more and more role in compromising between flood control and beneficial use in reservoir operation during flood season. The prerequisite of determining a seasonal FLWL is that flood control risks should not be increased in reservoir operation as compared with the original operating rule using a fixed FLWL. In this paper, a risk analysis model for deriving seasonal FLWL that considers uncertainties of hydrology, hydraulic condition and reservoir volume is proposed and developed. The risk analysis model consists of three modules: the first is a hydrological uncertainty analysis module, the second is a hydraulic uncertainty analysis module, as well as the third is a reservoir volume uncertainty analysis module. The acceptable risk constraints are given, and the upper limitation of seasonal FLWL is estimated by using Monte Carlo simulation. The China' Wanjiazhai reservoir (WR) is selected as a case study. The application results show that (1) the hydrological uncertainty and the reservoir volume uncertainty are major contribution factors to seasonal FLWL while the discharge capacity uncertainty is inapparent influence of seasonal FLWL, (2) the most reasonable upper limitations of seasonal FLWL in WR during main-flood and post-flood seasons are 972.3 and 974.1 m, respectively, which considers hydrological uncertainty, minimum hydraulic capability and minimum reservoir volume. The relative magnitudes of seasonal FLWL and the flood water utilization rates during main-flood and post-flood seasons are 0.65% and 61.05%, as well as 0.84% and 81.60%, respectively. Seasonal FLWL can effectively enhance flood water utilization rate without lowering the annual flood control standard compared with annual FLWL.

Keywords: Risk analysis; Seasonal flood-limited water level; Uncertainty

1. Introduction

With the rapid economic development, the role of reservoirs has become more and more important to meet society's energy and water requirements. Reservoirs are among the most efficient tools for integrated water resource development and management. By altering the spatial and temporal distribution of runoff, reservoirs serve many purposes, such as flood control, hydropower generation, navigation, recreation and ecology. The flood-limited water level (FLWL), which is the most significant parameter to govern the tradeoff between flood control and conservation, is determined mainly according to design flood estimation from annual maximum (AM) flood series, while it neglects seasonal flood information (Yun and Singh, 2008; Li et al., 2010; Chen et al., 2010). FLWL is mainly determined by reservoir regulation using the annual design storm or annual design flood. According to the Chinese Flood Control Act, reservoir water levels generally are not allowed to exceed FLWL during flood season, to provide adequate storage for flood prevention. When the flood season can be divided into multiple sub-seasons, the storage allocation for flood control is varied seasonally as advocated by the US Army Corp of Engineers (1998), and the seasonal FLWL can obtain more economic profits without lowering flood protection standard.

The problem between flood control and conservation for reservoir operation during flood season has drawn the attention of many investigators. Multiple duration limited water level (or

* Corresponding author. State Key Laboratory of Water Resources and Hydropower Engineering Science, Wuhan University, Wuhan, 430072, China. Tel./fax: +86 27 68773568.

E-mail address: zyl23bulls@whu.edu.cn (Y. Zhou).

http://dx.doi.org/10.1016/j.jher.2015.05.001

1570-6443/

seasonal FLWL) and dynamic limited water level for flood control are two effective approaches to increase water storage of a reservoir while maintaining its security for flood control in practical operation (Yun and Singh, 2008). Two types of flood control operation, which are "FLWL is too low due to enhancing flood prevention capacity" and "FLWL is too high due to increasing conservation profits", should be avoided in practice. From a conservation profit standpoint, it is desirable to maximize the supply water volume or hydropower generation, while from a flood safety standpoint; it is desirable to maximize the flood control volume. Therefore, a reasonable upper limitation of seasonal FLWL or dynamic control of FLWL must be estimated in advance at the planning and designing stages. Diao and Wang (2010) analyzed four uncertainties, i.e. hydrological, hydraulic, stage-storage uncertainty and time-delay uncertainty, as well as their probability distributions, in order to obtain an integrated risk rate of flood control operation mode, however, this study applied univariate probability analysis for flood frequency that may lead to an over- or underestimation of the hydrological risk. Bastian et al. (2010) presented probability analysis of hydrological loads for the design of flood control systems using copulas. Bivariate probability analyses for different flood variables using copulas are used to overcome the problem of univariate probability analysis. Li et al. (2010) proposed a dynamic control operation model that considers inflow uncertainty, i.e. the inflow forecasting error and uncertainty of the flood hydrograph shape. The upper limitation of FLWL is estimated by using Monte Carlo simulation. Chen et al. (2013) proposed a simulation-based optimization model for dynamic control of FLWL that made an effective tradeoff between the flood control and hydropower generation for Qingjiang River cascade reservoirs. Zhou et al. (2014) proposed a simulation-based optimization model for dynamic control of FLWL of mixed cascade reservoir systems. Zhou and Guo (2014) proposed a simulation-based optimization model for seasonal control of FLWL incorporating flood forecasting error. However, above researches about seasonal FLWL or dynamic control of FLWL have analyzed uncertainties of hydrology (including observed floods and forecast information), hydraulic condition or reservoir volume quantities in isolation, their results do not address issues between flood control and conservation for water management that may lead to an over- or underestimation of flood control risk. This research is an attempt to provide a quantitative approach combining models from hydrology, hydraulic condition, reservoir volume and operational research. Particularly, bivariate probability analyses based on Copula function and typical flood hydrograph methods have been applied to effectively estimate the hydrological risk.

The paper is organized as follows: Section 2 introduces study area briefly, after which the current operation rules of the investigated reservoir are discussed. Section 3 addresses the method adopted in this study, which comprises six parts: introduction of the modelling framework for risk analysis of seasonal FLWL (Section 3.1), setup of the hydrological uncertainty analysis module (Section 3.2), setup of the hydraulic uncertainty analysis module (Section 3.3), setup of the reservoir volume uncertainty analysis module (Section 3.4), setup of the risk constraints (Section 3.5), and determination of seasonal FLWL by Monte Carlo simulation (Section 3.6). In section 4 the simulation results for three risk sources in isolation, combined risk sources for determination of seasonal FLWL, as well as sensitivity analysis for three different sources of uncertainty are presented and discussed. The conclusions are drawn in Section 5.

2. Study area

2.1. Wanjiazhai reservoir

Wanjiazhai reservoir (hereafter called WR), located in the northwest China, has a drainage area of 3.95×10^5 km^2 which accounts for 52.5% of the Yellow River basin. The upstream of Yellow River is intercepted by the WR, with a length of main course about 3.5×10^3 km. The WR has a normal pool level at an elevation of 977 m (Yellow Sea datum, hereinafter using elevation), a total reservoir storage capacity of 8.96×10^8 m^3, of which (1) 4.48×10^8 m^3 is design flood control storage based on annual FLWL as well as (2) 14.0×10^8 m^3 is an annual supply water volume. The project of WR consists of two major parts, the large dam across the Yellow River, the hydroelectric power station houses. There are 6 sets of hydraulic turbines installed in the powerhouses, with 18.0×10^4 kW for each set, total 108.0×10^4 kW in installed capacity, which will produce an annual electricity output of 27.5×10^8 kW h.

2.2. Current operation rules of WR

The comprehensive benefits of the WR include flood control, power generation, water supply, etc. The current operation water levels during the annual cycle in WR are shown in Fig. 1 (black bold line). For the month July, the reservoir water level will be lowered to the FLWL of 966 m. During flood season (from July 1st to October 31st), the reservoir will generally be operated at this low level. The inflow exceeding the release capacity of the power station will be discharged through the spillways. The reservoir water level will be drawn down to 966 m after the flood. In November, the reservoir water level will be raised gradually to the normal water level of 977 m. From the December to the end of May in the following year, the reservoir should be kept as high level as possible to allow operating the power station for supplying water and regulating the peak load of the electrical grid. Then the water will be lowered further before the end of June.

Although the current operation rules are very easy to implement in practice, there are several limitations during flood season as revealed by historical operation records from 1955 to 2007: (1) the reservoir inflow during flood season accounts for approximately 64% of total annual runoff, but the power generation during this period is only about 45% of the annual total. The floodwater utilization rate is relative lower, (2) the release capacity of the 6 sets of turbines of WR is unable to regulate the peak load of electrical grid during the high load demand in summer, (3) the WR situated in the semi-arid area cannot be refilled to the normal water level at the end of refill period (end of October) in most of years.