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面向航运的金沙江下游水库群中长期多目标协同调度

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摘　要:三峡水运新通道建成后,长江川境段航道将成为金沙江下游航道与长江上游重庆段之间的瓶颈航段,制约长江黄金水道运能的发挥,长江川境段航道等级提升迫在眉睫,但受环境保护制约传统航道整治措施难以实施。在此背景下,开展金沙江下游水库群中长期航运–发电多目标协同调度研究,探索利用金沙江下游梯级水库群的调蓄作用,增加枯水期长江川境段河道流量、提高长江川境段航道等级的可行性。本文以向家坝水电站枯水期最小下泄流量最大和梯级总发电量最大为目标,构建了金沙江下游梯级水库群航运–发电多目标协同调度模型,并采用逐步优化算法进行航运–发电多目标协同调度模型的求解计算。丰水年、平水年、枯水年的实例研究结果表明:本文所提的航运–发电多目标协同调度模型在丰水年、平水年、枯水年能够将向家坝水库的最小下泄流量分别提升43.97%、23.53%和19.48%,而金沙江下游梯级水电站群的总发电量分别减少0.76%、1.72%和1.02%,枯水期梯级最小出力的减幅分别为36.32%、36.68%和38.03%,其对电网的发电影响相对有限,可由其他电源予以补充。研究成果可为金沙江下游梯级水库群航运–发电多目标协同调度提升长江川境段航道等级提供技术支撑和决策参考,有助于长江黄金水道建设和交通强国战略的实施。

关键词:金沙江下游水库群;最小下泄流量;中长期调度;航运–发电多目标协同;梯级总发电量

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长江黄金水道作为长江经济带建设的重要依托,是区域经济高质量发展的重要基础[1–2]。长江干线川境段(水富—川渝交界彩溪口)航道全长258 km,是长江黄金水道的重要组成部分,是四川和云南省优化沿江产业布局、调整国民经济结构、以新质生产力引领社会经济高质量发展的关键。随着三峡水运新通道建成后,川境段航道将受到三峡新通道运输的辐射影响,运量将大幅增加,对川境段航道条件和通过能力提出了更高的要求,川境段航道将成为金沙江下游航道与长江上游重庆段之间的瓶颈航段,制约黄金水道运能的发挥。

根据《四川省内河水运发展规划(2023—2035)》,将长江川境段航道规划等级[3]划分为:水富至宜宾合江门段(长度为30 km)现状等级为5级,2035年规划等级为2级;宜宾合江门至泸州彩溪口(长度为228 km)现状等级为3级,2035年规划等级为1级。但受制于生态环保要求,单纯通过梯级渠化和深挖河槽、修筑整治建筑物的方式来提升长江川境段航道等级实施难度大。因此,结合《长江流域控制性水工程联合调度管理办法(试行)》,通过开展面向航运的金沙江下游梯级水库群中长期多目标协同调度研究,适当增加最末一级向家坝水库枯水期的最小下泄流量,是提高长江川境段航道等级的关键[4]。

制约中长期航道等级提升的主要问题是枯水期河道流量小、水位低,造成大型船舶的通航尺寸和通航水深无法被满足。为满足枯水期的河道航运补水需求,势必需要调整梯级水库群的枯水期消落运行方式,进而对梯级水电站群的发电量和发电企业的收益造成影响。针对航运与发电的多目标协同调度问题,国内外学者开展了相关的研究。褚明华等[5]总结了三峡水库在防洪、抗旱供水、发电、航运、生态环境、应急等方面的调度实践情况;程晓东等[6]提出了以防洪安全为前提、考虑发电等综合利用需求、以航运

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为主要调度目标的三峡水库调度方式；李杰[7]、田锐[8]建立生态–航运–发电多目标优化模型，Chen[9]、Huang[10]等研究了防洪、经济和生态的多目标协调策略，周建中[11]、张睿[12]等构建了水库群汛期多目标协同调度模型；谢雨祚[13]、Cheng[14]等研究了梯级水库短期发电联合调度模型，Cohen[15]、Giuliani[16]等研究了不确定条件下水库群适应性调度方法，Wang[17]、Jin[18]、李洁玉[19]等建立了黄河流域水沙调控多目标协同模型，艾学山[20]、杨悦[21]等研究了梯级水库群的多目标优化问题，Dash[22]、Dang[23]等探讨了考虑大尺度供需平衡的水库群调度运行策略。目前，考虑航运的优化调度研究大多以单一水库为调度对象，鲜有针对流域大规模梯级水库群的航运–发电多目标协同调度研究。

为充分发挥金沙江下游大型梯级水库群的调蓄作用，提升长江川境段航道等级，本文开展金沙江下游水库群中长期航运–发电多目标协同调度研究，并结合不同水平年的实例计算，进一步分析本文所构建的水库群航运–发电多目标协同调度模型及其求解算法的可行性，以期为金沙江下游梯级水库群航运–发电多目标协同调度提升长江川境段航道等级提供技术支撑和决策参考。

1　协同调度模型构建

结合下游河道枯水期航运补水的需求，本文以提高向家坝水电站最小下泄流量为航运目标、以梯级总发电量最大化为发电目标，构建金沙江下游梯级水库群航运–发电多目标协同调度模型。

1.1　目标函数

1）航运目标

该目标旨在为下游河道航运提供更大且均匀的旬平均通航流量，具体目标函数如下：

$$F=\max\min\left(M_{末,1},M_{末,2},M_{末,t},\cdots,M_{末,T}\right) \tag{1}$$

式中：F为梯级最末一级水电站年内最小出库流量尽可能大的计算指标，m^3/s；$M_{末,t}$为梯级最末一级电站在第t时段的出库流量，m^3/s，由梯级最末一级电站在第t时段的发电流量$Q_{末,t}$和弃水流量$S_{末,t}$两部分组成，即$M_{末,t}=Q_{末,t}+S_{末,t}$；T为年内计算总时段数。

2）发电目标

梯级水电站年发电量尽可能大，该目标旨在为电网提供尽可能多的水电发电量，以提高清洁可再生能源的发电利用水平，具体目标函数如下：

$$E=\max\sum_{i=1}^{N}\sum_{t=1}^{T}(A_{i,t}\cdot Q_{i,t}\cdot H_{i,t}\cdot M_t) \tag{2}$$

式中：E为梯级水电站的年发电量，10^4 kW·h；$A_{i,t}$为第i电站在第t时段的出力系数；$Q_{i,t}$为第i电站在第t时段发电流量，m^3/s；$H_{i,t}$为第i电站在第t时段的平均发电净水头，m；M_t为第t时段小时数，h；N为梯级水电站个数。

1.2　约束条件

1）水量平衡约束。具体表示为：

$$V_{i,t+1}=V_{i,t}+(q_{i,t}-Q_{i,t}-S_{i,t})\cdot\Delta t \tag{3}$$

式中：$V_{i,t+1}$为第i个电站第t时段末水库蓄水量，m^3；$V_{i,t}$为第i个电站第t时段初水库蓄水量，m^3；$q_{i,t}$为第i个电站第t时段入库流量，m^3/s；$S_{i,t}$为第i个电站第t时段弃水流量，m^3/s；Δt为计算时段长度。

2）水库水位约束。具体表示为：

$$\underline{Z}_{i,t}\le Z_{i,t}\le\overline{Z}_{i,t} \tag{4}$$

式中：$\underline{Z}_{i,t}$为第i个电站第t时段初的水位下限，m；$Z_{i,t}$为第i个电站第t时段初的水库水位，m；$\overline{Z}_{i,t}$为第i个电站第t时段初的水位上限，m。

3）水库发电流量约束。具体表示为：

$$Q_{it,\min}\le Q_{i,t}\le Q_{it,\max} \tag{5}$$

式中：$Q_{it,\min}$为考虑综合用水时第i个电站第t时段的最小下泄流量，m^3/s；$Q_{it,\max}$为第i个电站第t时段的最大过机流量，m^3/s。

4）电站出力约束。具体表示为：

$$N_{i,\min}\le A_{i,t}\cdot Q_{i,t}\cdot H_{i,t}\le N_{i,\max} \tag{6}$$

式中：$N_{i,\min}$为第i个电站允许的最小出力，10^4 kW；$N_{i,\max}$为第i个电站的装机容量，10^4 kW。

5）梯级电站水量联系约束。具体表示为：

$$q_{i,t}=Q_{i-1,t-1}+S_{i-1,t-1}+I_{i,t} \tag{7}$$

式中：$Q_{i-1,t-1}$为第$i-1$个电站（第i个电站的上游电站）第$t-1$时段（前一时段）的发电流量，m^3/s；$S_{i-1,t-1}$为第$i-1$个电站第$t-1$时段（前一时段）的弃水流量，m^3/s；$I_{i,t}$为第t时段第$i-1$个电站到第i个电站的区间平均入流，m^3/s。

6）非负条件约束

式（1）～（7）中所有变量均为非负变量（≥0）。

2　协同调度模型求解

本研究采用梯级水库群优化调度研究中常用的逐步优化算法（POA）进行金沙江下游水库群航运–发电多目标协同调度模型求解计算。POA算法是将多阶段的问题分解为多个两阶段问题，不同两阶段问题之间用状态变量来联系[24–28]；通过固定其他阶段的状态变量，对所选的两阶段决策变量进行寻优计算，实现两阶段问题的求解；在求解完该两阶段问题之后，再考虑下一个两阶段问题；最后，将上一次的计算结果作为下一次寻优计算的初始可行解，不断循环，直至收敛为

止。POA算法的主要求解流程具体如下：

1）初始化POA算法的参数，包括搜索步长、优化终止精度等。

2）确定初始轨迹。采用水利年6月上旬至10月下旬从死水位至汛限水位/正常蓄水位等水位差蓄水、12月上旬至次年4月下旬从正常蓄水位至死水位等水位差消落，5月和11月分别保持死水位和正常蓄水位运行的水位过程为初始轨迹。

3）依照电站从上至下的顺序，固定第i个电站的第0时段和第2时段的水位$Z_{i,0}$和$Z_{i,2}$不变，调整第1时段的水位$Z_{i,1}$（分别取原水位减1步长、原水位和原水位加1步长3个方案）。计算各方案的第0和1两时段的目标函数，选择目标函数最优的方案作为梯级各水电站在第1时段的新水位，继续寻优。

4）同理，依次对梯级水电站下一时刻进行寻优计算。固定第1、3时段的水位$Z_{i,1}$和$Z_{i,3}$不变，调整第2时段的水位$Z_{i,2}$，使第1、2两时段的目标函数最优，优化计算得各水电站第2时段的水位$Z_{i,2}$。

5）重复步骤4），直到遍历所有时段为止，完成一次循环，得到梯级各水电站在不同计算时段末的新水位。

6）判断是否满足终止条件（达到预设的计算次数或前后两次计算结果偏差很小），如不满足，则将本次求得的梯级各水电站水位过程作为下一次计算的初始轨迹，重新回到第3）步，则退出循环；最后一次循环得到的新水位即为优化计算的水位过程，与之对应的发电量和流量等结果，即为最终优化计算结果。

3 实例研究

长江干线川境段是长江黄金水道的重要组成部分，是四川和云南省优化沿江产业布局、调整国民经济结构、以新质生产力引领社会经济高质量发展的关键。随着三峡水运新通道建成后，川境段航道将受到三峡新通道运输的辐射影响，运量将大幅增加[29−31]，对川境段航道条件和通过能力提出了更高的要求。但受制于生态环保要求，单纯通过梯级渠化和深挖河槽、修筑整治建筑物的方式来提升长江川境段航道等级实施难度大。因此，本文结合《长江流域控制性水工程联合调度管理办法（试行）》[4]，开展面向航运的金沙江下游梯级水库群中长期多目标协同调度实例研究，验证本文所构建模型的可行性。

3.1 基础资料和特征参数

本文以金沙江下游乌东德、白鹤滩、溪洛渡、向家坝4座梯级水库群为实例研究，各水电站的基本参数如表1所示。其中，向家坝为日调节水库，在梯级水库群中长期航运−发电多目标协同调度模型计算时，不考虑其调节作用，仅统计其发电量。

表1 梯级各水库的特征参数

Tab. 1 Characteristic parameters for cascade reservoirs

电站名称	死水位/m	正常蓄水位/m	汛限水位/m	装机容量/(10^4 kW)	出力系数	最大过机流量/($m^3\cdot s^{-1}$)	最小下泄流量/($m^3\cdot s^{-1}$)	调节库容/(10^8 m^3)
乌东德	945	975	952	1 020	8.5	8 080.0	900	30.20
白鹤滩	765	825	785	1 600	8.7	8 764.8	1 160	104.36
溪洛渡	540	600	560	1 386	8.5	7 922.0	1 600	64.62
向家坝	370	380	370	600	8.5	7 056.0	1 600	9.03

通过对乌东德水电站的设计水文站（华弹水文站）实测年径流序列进行频率计算，分别选取1999、2003、1997年作为丰水年（25%）、平水年（50%）和枯水年（75%）。以金沙江下游梯级水库群最末一级向家坝水库的最小下泄流量为航运目标的控制对象，以水利年（6月上旬至次年5月下旬）为周期、以旬为计算时段，利用丰水年、平水年、枯水年金沙江下游梯级水库群的径流资料进行实例计算。其中，乌东德水库初、末水位均为945 m，白鹤滩水库初、末水位均为765 m，溪洛渡水库初、末水位均为540 m。

3.2 优化结果及分析

结合金沙江下游梯级水库群的实际资料，运用POA算法进行模型求解，得到丰水年、平水年、枯水年梯级水库群航运−发电多目标协同调度的计算结果。同时为便于对比分析计算结果，将以兼顾梯级枯水期最小出力的梯级总发电量最大为目标的优化调度模型（以下称模型2）进行计算，并与本文所建立的航运−发电多目标协同调度模型（以下称模型1）进行对比分析。图1为向家坝水库的下泄流量过程对比。图2为梯级水电站群的总发电量对比。图3为梯级水电站群的总发电出力对比。表2为不同水平年下各目标值。

由图1和表2可知：相较于模型2，模型1显著提高了枯水期11月至4月向家坝水库的最小下泄流量，丰水年、平水年、枯水年的最小旬平均流量增幅分别为43.97%、23.53%和19.48%，其中，平水年和枯水年的6月上旬，由于梯级各水库的入库流量较少且各水库水位均处于死水位，无法通过水库调节增大向家坝水库的下泄流量，其下泄流量分别为

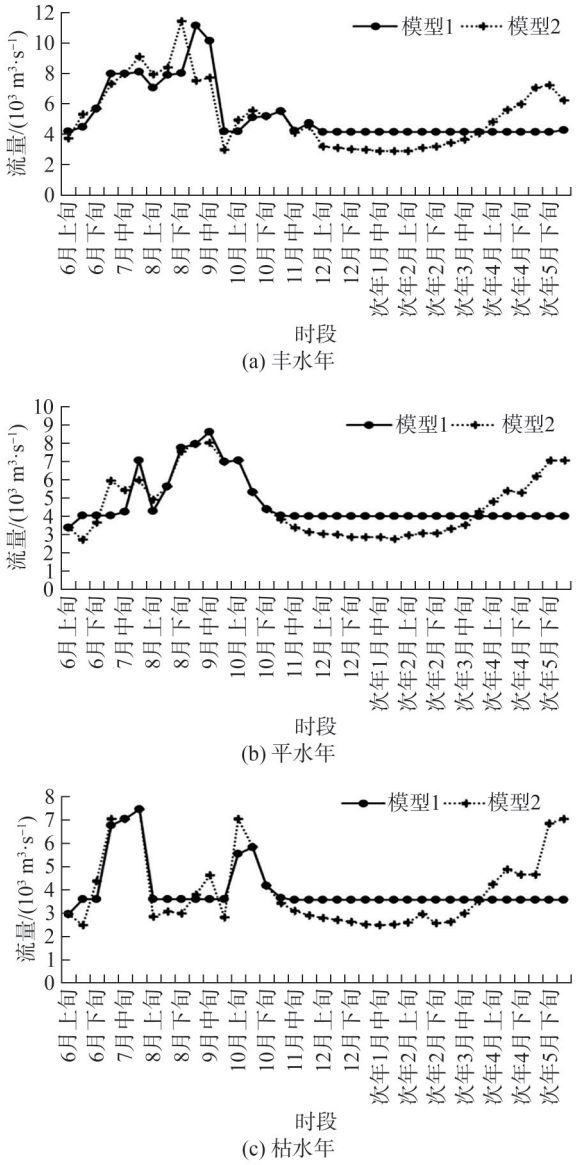


图1　向家坝水库的下泄流量过程对比

Fig. 1　Discharge processes comparison of Xiangjiaba Reservoir

3 391 m^3/s和2 969 m^3/s；其他各时段向家坝水库的最小下泄流量分别为4 005 m^3/s和3 570 m^3/s。由此可见，模型1在不同水平年下对枯水期最小下泄流量提升的效果明显，能够有效缓解枯水期河道航运压力。这主要是因为模型2为了增加发电量，让各水库在提高枯水期梯级最小出力的同时，尽可能保持高水头运行，在枯水期前几个时段尽可能少消落水库水位，利用梯级各水库较大的发电水头来确保梯级总发电出力，将水库蓄水量集中于枯水期末消落放水，导致枯水期前几个时段向家坝水库的下泄流量偏小，不利于保障下游河道航运用水需求。总体而言，在模型1中，梯级水库群的枯水期下泄流量得到均化，将水库群的蓄水量相对均匀地用于补给枯水期的河道流量，增加向家坝水库下游的河道通航水深，更有利于船舶通行。

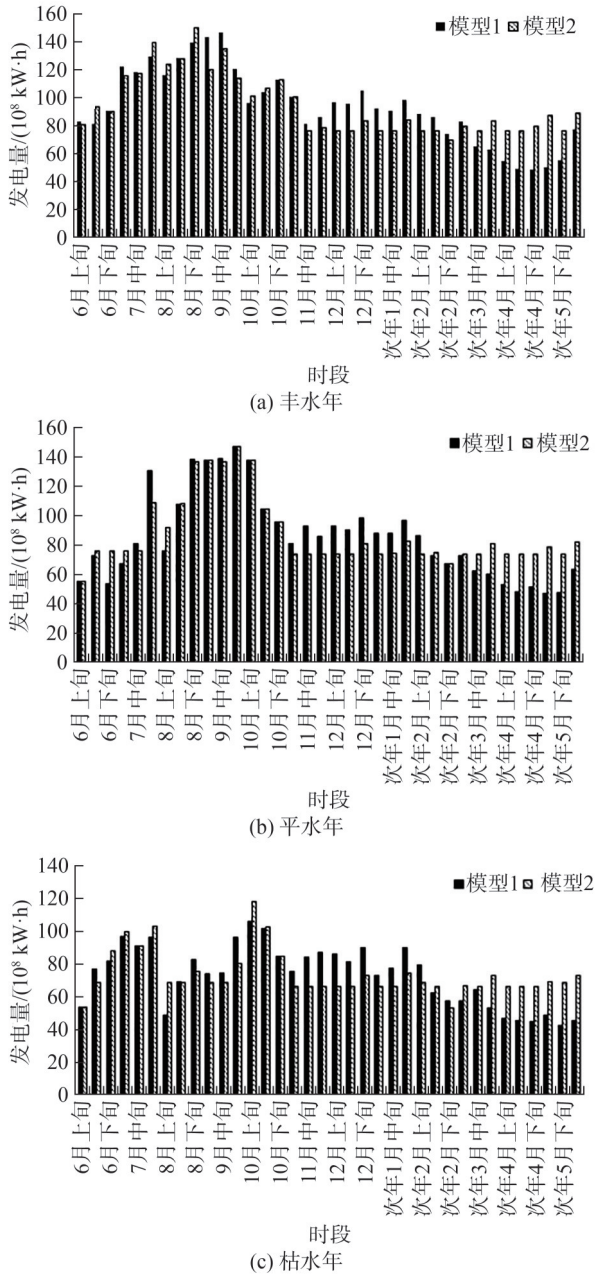


图2　梯级水电站群的总发电量过程对比

Fig. 2　Total power generation processes comparison of cascade hydropower stations

由图2和表2可知，相较于模型2，模型1丰水年、平水年和枯水年的全年梯级总发电量减幅分别为0.76%、1.72%和1.02%。由图3和表2可知，相较于模型2，模型1的枯水期梯级最小出力明显降低，减幅分别为36.32%、36.68%和38.03%。可见，模型1对梯级水库群的总发电量和梯级最小出力的影响主要集中在枯水期。总体来看，模型1能够以较小发电量损失（0.76%、1.72%、1.02%）实现对梯级水库群下游河道枯水期通航流量的较大提升（43.97%、22.20%、19.48%），但对枯水期的梯级最小出力影响较大，减幅分别为36.32%、36.68%和38.03%；考虑到在整个

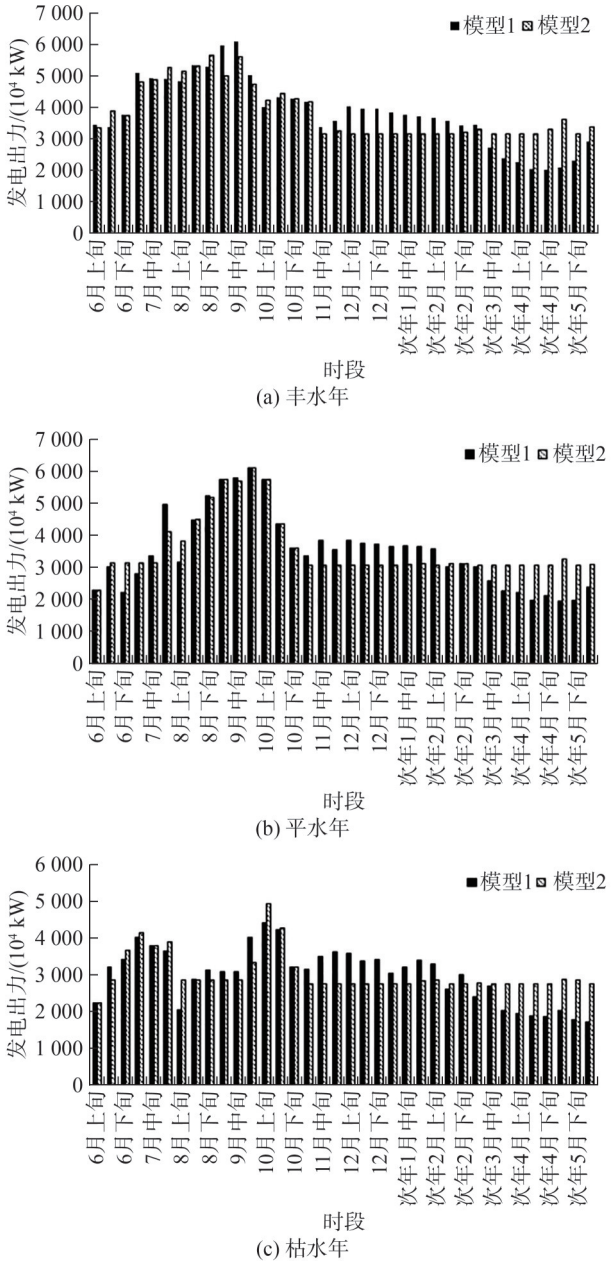


图3 梯级水电站群的总发电出力过程对比

Fig. 3 Total power generation output processes comparison of cascade hydropower stations

电力系统中,除金沙江下游梯级水电站群外,还有其他水电站和其他类型电源,金沙江下游梯级水电站群的枯水期总发电出力减幅对电网的影响相对有限,可由其他电源予以补充。综上所述,通过模型1的航运–发电协同调度能够兼顾梯级水库群的发电效益和航运效益,更好地发挥金沙江下游梯级水库群的综合利用效益。

为进一步剖析兼顾发电效益和航运效益目标下梯级水库群在丰水年、平水年、枯水年的运行调度方式,分别将模型1和2下乌东德、白鹤滩和向家坝水库不同水平年的水位过程进行对比分析,如图4所示。

由图4可知,模型1和模型2下金沙江下游梯级各水库水位变化过程的不同主要集中在枯水期,即在不同调度目标下梯级各水库枯水期的水位消落控制方式不同。总体来看,在同一模型下,丰水年、平水年、枯水年梯级各水库的水位变化趋势整体较为接近。模型2下,梯级各水库在枯水期尽可能保持高水位运行,以获得较大的水头效应,在兼顾梯级最小出力的同时,增加梯级总发电量,乌东德水库的水位从2～3月份开始消落、白鹤滩水库的水位从3～4月份开始消落、溪洛渡水库的水位从5月份开始消落;而模型1下,梯级各水库的水位消落时间整体提前,乌东德水库和白鹤滩水库的水位均从12月前后开始消落、溪洛渡水库的水位从4月份开始消落。

通过对比发现,丰水年、平水年、枯水年梯级各水库遵循先消落上游水库、后消落下游水库的水位消落顺序,这是因为根据梯级各水库之间流量自上而下传递的水力联系,在确保梯级最末一级水电站出库流量相同的情况下,先消落上游水库水位可以提高其下游水库的水头,使得梯级水库群的发电总水头增加,从而增加梯级总发电量。

由此可见,兼顾航运与发电的梯级水库群多目标协同调度,需结合流域梯级水库群的上下游关系、调节性能差异等要素,充分利用梯级水库群的调节库容,合理安排梯级各水库的水位消落次序,有效改善下游河道通航条件的同时,尽可能缓解枯水期航运补水需求与发电运行的矛盾。梯级各水库的水位消落起始时间和消落期长度反映了梯级上下游之间的水量

表2 不同水平年下各目标值

Tab.2 Target values comparison under different level years

水平年	年内最小下泄流量/($m^3 \cdot s^{-1}$)（航运目标）			全年梯级总发电量/(10^8 kW·h)（发电量目标）			枯水期梯级最小出力/(10^4 kW)（发电出力目标）		
	模型1	模型2	模型1的增幅/%	模型1	模型2	模型1的减幅/%	模型1	模型2	模型1的减幅/%
丰水年	4 165	2 893	43.97	3 373.93	3 399.82	0.76	2 018.68	3 170.02	36.32
平水年	4 005(其中6月上旬为3 391)	2 745	23.53	3 081.72	3 135.67	1.72	1 937.76	3 060.21	36.68
枯水年	3 570(其中6月上旬为2 969)	2 485	19.48	2 626.39	2 653.33	1.02	1 710.51	2 760.04	38.03

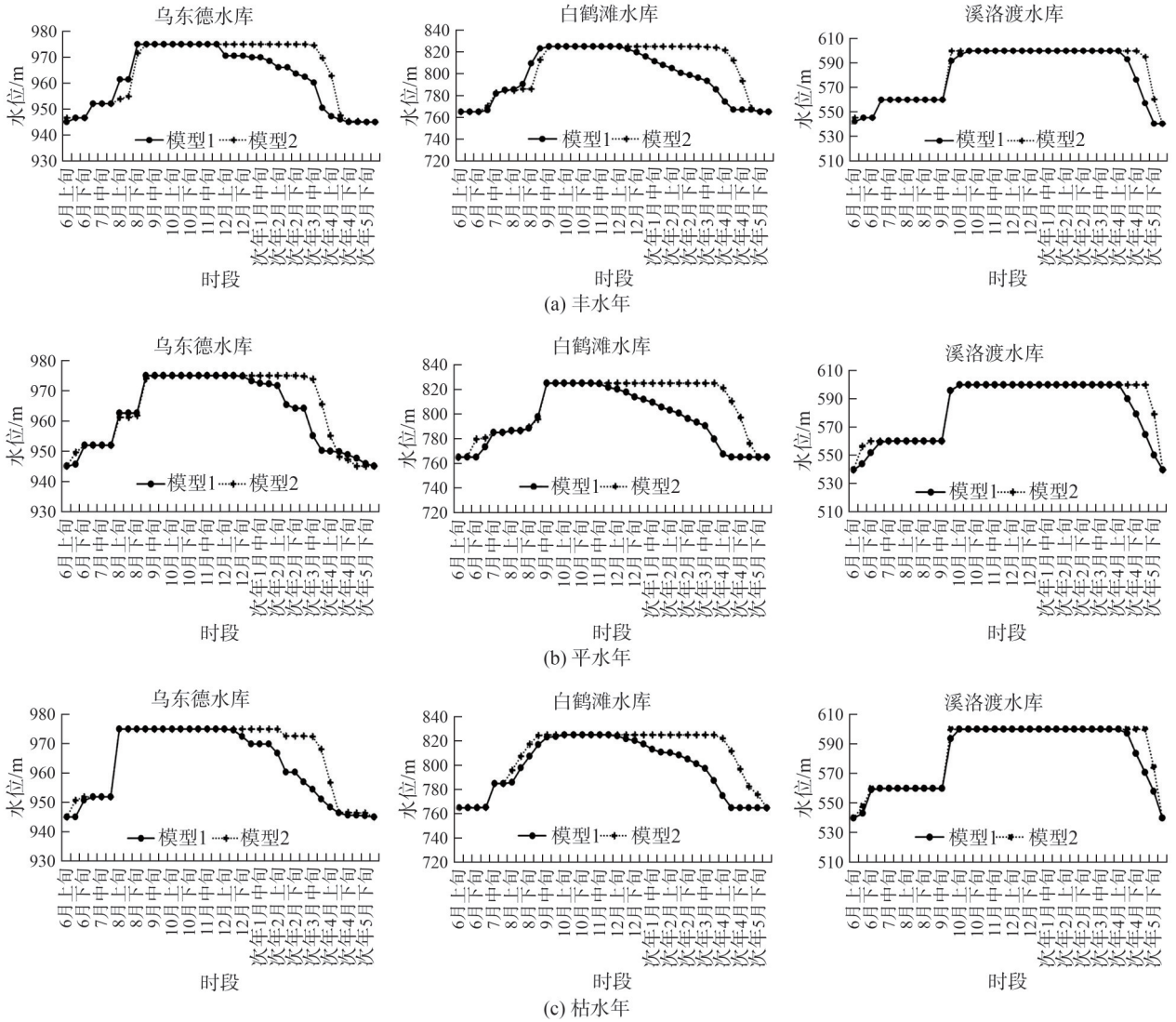


图4　两种模型下梯级各水库不同水平年水位过程对比

Fig. 4　Water level processes comparison in cascade reservoirs under different models

联系和水库的调节性能，进一步验证了航运–发电多目标协同调度方案的合理性。

4　结　论

面向长江川境段航运的补水需求，以充分发挥金沙江下游梯级水库群的发电和航运多目标综合利用效益为出发点，建立了以向家坝水电站最小下泄流量最大化和梯级总发电量最大化为目标的梯级水库群多目标协同调度模型，研究了多目标协同调度模型求解的POA算法，并通过丰水年、平水年和枯水年3个水平年对金沙江下游梯级水库群进行实例仿真计算，结果表明：在梯级水库群航运–发电多目标协同调度下，不同水平年梯级最末一级向家坝水库的最小出库流量分别为4 165、3 391和2 969 m^3/s，梯级水电站群全年总发电量分别为3 373.93×10^8、3 081.72×10^8和2 626.39×10^8 kW·h，与以兼顾枯水期最小出力的梯级总发电量最大为目标的优化调度模型计算结果相比，实现了梯级下游河道最小流量的显著增加，增幅分别为43.97%、23.53%和19.48%，而梯级总发电量的减幅分别为0.76%、1.72%和1.02%，枯水期梯级最小出力的减幅分别为36.32%、36.68%和38.03%，其对电网的发电影响相对有限，可由其他电源予以补充。

综上所述，本文所提模型和求解方法在提高水库群下游河道通航流量以满足航运需求的同时，又能较好地保障梯级水电站群的总发电量，得到的金沙江下游梯级水库群航运–发电多目标协同调度方案可为实际调度生产和航道等级提升方案决策提供参考。

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Medium- and Long-term Multi-objective Collaborative Scheduling of the Reservoirs Group in the lower Reaches of the Jinsha River for Navigation

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Abstract:

Objective With the construction of the new Three Gorges water transportation channel, the waterway in the Chuanjing section of the Yangtze River becomes a bottleneck between the downstream waterway of the Jinsha River and the Chongqing section of the upper reaches of the Yangtze River, restricting the full utilization of the transportation capacity of the Yangtze River's golden waterway. The upgrading of the waterway in the Chuanjing section of the Yangtze River is urgent, but traditional waterway improvement measures are difficult to implement due to environmental protection constraints. Therefore, this research explores the feasibility of utilizing the regulating and storage effects of cascade reservoirs in the lower reaches of the Jinsha River to increase the flow of the Yangtze River during the dry season and improve the waterway level by conducting a multi-objective collaborative scheduling study on medium-and long-term navigation and hydropower generation in the reservoir group.

Methods Firstly, based on the demand for navigation and water replenishment during the dry season of downstream rivers, this research aimed to improve the minimum discharge flow of Xiangjiaba Hydropower station as the navigation goal and to maximize the total power generation of cascade hydropower stations as the power generation goal. A multi-objective collaborative adjustment model for navigation and power generation of cascade reservoirs in the downstream of the Jinsha River was constructed, considering constraints such as water balance constraints, reservoir wa-

ter level constraints, reservoir power generation flow constraints, power plant output constraints, cascade power plant water connection constraints, and non-negative condition constraints. Secondly, this research adopted the commonly used progressive optimization algorithm (hereinafter referred to as “POA algorithm”) in the optimization scheduling research of cascade reservoir groups to calculate the multi-objective collaborative scheduling model of navigation and power generation of the cascade reservoirs in the lower reaches of the Jinsha River. The POA algorithm decomposed a multi-stage problem into multiple two-stage problems, with different two-stage problems connected by state variables. The two-stage problem was solved by fixing the state variables of other stages and performing optimization calculations on the selected two-stage decision variables. After solving these two-stage problems, the next two-stage problem was considered, and the previous calculation result was used as the initial feasible solution for the next optimization calculation. The process continued to loop until convergence. Finally, this research considered four cascade reservoirs in the lower reaches of the Jinsha River, including Wudongde, Baihetan, Xiluodu, and Xiangjiaba, as research objects and conducted case studies. This research calculated the hydrological frequency of the measured annual runoff series of the designed hydrological station (Huatan Hydrological Station) of the Wudongde Hydropower Station, and selected 1999, 2003, and 1997 as the years representing wet (25%), normal (50%), and dry (75%) conditions, respectively. Using the water conservancy year (from early June to late May of the following year) as the cycle and ten days as the calculation period, the runoff data of the cascade reservoirs in the lower reaches of the Jinsha River in wet years, normal years, and dry years were used for example calculations. At the same time, for the convenience of comparative analysis of calculation results, the optimization scheduling model (hereinafter referred to as “Model 2”) with the goal of maximizing the total power generation of the cascade while considering the minimum output during the dry season was calculated and compared to the multi-objective collaborative scheduling model for navigation and power generation established in this study (hereinafter referred to as “Model 1”.

Results and Discussions By compared to Model 2, Model 1 significantly increased the minimum discharge flow to the Jiaba Reservoir during the dry season from November to April. The minimum ten-day average flow in the wet year, normal year, and dry year increased from 2 893 $m^3 \cdot s^{-1}$, 2 745 $m^3 \cdot s^{-1}$, and 2 485 $m^3 \cdot s^{-1}$ in Model 2 to 4 165 $m^3 \cdot s^{-1}$, 3 391 $m^3 \cdot s^{-1}$, and 2 969 $m^3 \cdot s^{-1}$, respectively, with increases of 43.97%, 23.53%, and 19.48%, respectively. In Model 1, the discharge flow of the cascade reservoir group during the dry season was normalized, and the storage capacity of the reservoir group was relatively evenly utilized to supplement the river flow during the dry season, which increased the navigation depth of the river downstream of the Jiaba Reservoir and was more conducive to ship passage. The total annual cascade power generation of Model 2 was 339.982 billion kW·h, 31.567 billion kW·h, and 26.533 3 billion kW·h in wet years, normal years, and dry years, respectively. The total annual cascade power generation of Model 1 was 337.739 3, 30.817 2, and 26.263 9 billion kW·h, respectively. Compared to Model 2, the total annual cascade power generation of Model 1 decreased by 0.76%, 1.72%, and 1.02%, respectively. Compared to Model 2, the minimum output of the cascades in Model 1 during the dry season significantly decreased, from 31.702, 30.602 1, and 27.604 million kW in the wet year, normal year, and dry year, respectively, to 20.186 8 million kW, 19.377 6 million kW, and 17.105 1 million kW in Model 1, with reductions of 36.32%, 36.68%, and 38.03%, respectively. The impact of Model 1 on the total power generation and minimum output of cascade reservoirs was mainly concentrated in the dry season. Model 1 achieved a significant increase in the navigation flow of downstream channels of cascade reservoirs during the dry season (43.97%, 22.20%, 19.48%) with small power generation losses (0.76%, 1.72%, 1.02%). However, it had a significant impact on the minimum output of the cascade during the dry season, with reductions of 36.32%, 36.68%, and 38.03%, respectively. However, it was considered that within the entire power system, in addition to the cascade hydropower stations downstream of the Jinsha River, there were other hydropower stations and other types of power sources. Therefore, the impact of the total power output reduction during the dry season of the cascade hydropower stations downstream of the Jinsha River on the power grid was relatively limited and could be supplemented by other power sources. Accordingly, the coordinated scheduling of navigation and power generation through Model 1 balanced the power generation and navigation benefits of the cascade reservoir group and better leveraged the comprehensive utilization benefits of the downstream cascade reservoir group of the Jinsha River.

Conclusions The research results provide technical support and decision-making references for improving the waterway level of the Yangtze River through multi-objective collaborative scheduling of navigation and hydropower generation in the downstream cascade reservoirs of the Jinsha River. This contributes to the construction of the Yangtze River’s golden waterway and supports the implementation of the strategy to build a strong transportation system in China.

Key words: the reservoirs in the lower reaches of the Jinsha River; minimum discharge flow; medium- and long-term scheduling; multi-objective collaborative scheduling of navigation–hydropower generation; the total hydropower generation of hydropower stations

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