Study on Calculation Method of Water Resources Supply and Demand Balance in Plain River Network Area

WU Xia¹, Liu Lu Guang¹, Zhang Zu Lian¹, Guan Hong Lin¹, Dong Wei¹, Wang Jian¹

¹ Hubei Water Resources Research Institute, Wuhan, 430070, China

Abstract. After the impoundment of the Three Gorges reservoir, the middle and lower reaches of Yangtze River will have a long distance erosion in a long time, and in the conditions of the same flow, the water level of the three outlets along Jingjiang river reach (Songzi outlet, Taiping outlet, Ouchi outlet) will drop, which leads to the flow diversion reduction of three outlets. Undoubtedly, all these will have an impact on irrigation and water supply of river networks on south bank of Jingjiang river reach. The calculation of water resources supply and demand balance is the foundation of analyzing the influence of the Three Gorges Project on the river networks on south bank of Jingjiang river reach, clearing the key link of water shortage and allocating water resources. The calculation of water resources supply and demand balance in this area, however, has unique complexity of plain river network, which is caused by multi-water sources and multi-water intakes. To handle this problem, the water resources supply and demand balance model in plain water network with multi-water sources and multi-water intakes is established, which is based on the characteristics of plain river network. And this model is utilized to calculate and analyze the water resources supply and demand balance in river networks on south bank of Jingjiang river reach. Relevant research results provide new methods and thoughts for the calculation and analysis of water resources supply and demand balance in plain river network.

1. Introduction

Three outlets along Jingjiang river reach, namely Songzi outlet, Taiping outlet, and Ouchi outlet, is the main passage for Yangtze River to divide flow and sediment into Dongting Lake. After impoundment of the Three Gorges Reservoir, the middle and lower reaches of Yangtze River will have a long distance erosion in a long time, and the river bed will be cut down. In the same discharge, the water level along the course will decline to different degree. Especially, the decline of the water level at the three outlet gates, will make the split flow of three outlets to reduce[1-2]. Undoubtedly, the reduce of split flow has certain influence on irrigation and water supply in this area (Hereinafter referred to as "Jing Nan river network area"). The calculation of water resources supply and demand balance is the foundation of analyzing the influence of the Three Gorges Project on the Jingnan river network area, clearing the key link of water shortage and allocating water resources[3]. At present, in calculation of water resources supply and demand balance[4-6], the calculation unit is usually administrative area, irrigation area or river basin, and careless or unreasonable division of the calculation unit easily lead to some parts of the water shortage links being covered. In addition, in areas where rivers are used as water sources, the influence of upstream water users’ getting water from the river on downstream water users is not considered, and the bendway of the river after river blanking is also not taken into account. Jingnan river network area has features of multi-water users (refer to water for agriculture, industry, construction industry, the tertiary industry, life and ecology, etc.), multi-water source (refer
to Yangtze River, Jingjiang river, reservoirs, lakes, deep trenches, river bends, groundwater and ponds, etc.), and multi-water intakes (refer to the diversion culverts, pumping stations, and intakes of water works, etc.). These features lead to the calculation of water resources supply and demand balance in this area having the unique complexity of plain river network. Therefore, traditional calculation methods and thoughts are not very applicable, and cannot really reflect the water shortage links in this area. In order to overcome all these obstacles, the water resources supply and demand balance model in plain water network with multi-water sources and multi-water intakes is set up, which is based on the characteristics of plain river network. And this model is utilized to calculate and analyze the water resources supply and demand balance in river networks on south bank of Jingjiang river reach. Relevant research results have important reference value in calculation and analysis of water resources supply and demand balance in plain river network.

2. Basic information of river networks on south bank of Jingjiang river reach in Hubei
Jingnan River network area is located in the south of the province of Hubei, involving Songzi City (7 villages), Jingzhou District (Mishi Town), Gong'an County and Shishou City (10 villages) and so forth. There are 21 irrigated areas in this network area, which consists of 2 large irrigation districts, 18 medium-sized irrigation districts and 1 small irrigation areas. Its designed irrigation area is 2.9905 million mu, and the present irrigation area is 2.2223 million mu. And in this area, water storage projects include 31 reservoirs, 25 lakes, 269 deep trenches, 6318 ponds, 33 deep sinks, rivers mainly include the Songzi River, the Hudu River and the Ouchi River (hereinafter referred to as "Three rivers in JingNan"). What's more, there are 112 water diversion works (sluices). Water diversion capacity is 593.9m³/s. There are 76 living water supply projects. Corresponding water supply scale is 6.40m³/s. and there are 11 main industrial water intakes. Corresponding water supply scale is 3.89m³/s.

3. The general idea of the water resources supply and demand balance
The water users in Jingnan river network mainly include water for agriculture, industry, construction

Fig.1 The geographical position of Jingnan River network area and irrigation districts
Note: the name of irrigation districts and abbreviation are in Fig.1

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industry, life, the tertiary industry and off-stream ecology, and the water sources mainly include the Yangtze River, three rivers in Jingnan, reservoirs, lakes, deep trenches, groundwater and ponds, etc. Industrial water and construction water generally have independent water intakes. Most water users get water from Yangtze River and underground water, whereas a small amount get water from reservoirs and three rivers in Jingnan. For those enterprises whose water resources cannot be guaranteed, they are usually equipped with groundwater backup water sources. The residents' living water, the tertiary industrial water and the off-stream ecological water are mostly provided by the waterworks, which mainly get water from the Yangtze River, the three rivers in Jingnan, the underground water, the reservoirs and the lakes. The waterworks that take three rivers in Jingnan as water source, can basically meet the demand of domestic water, because the water intake is generally located in the deep channel of the rivers, though the three rivers in Jingnan may break in the dry season. To those waterworks that cannot meet the water demands, some of them have also been equipped with groundwater back water source. Agricultural water users get water from Yangtze River, three rivers in Jingnan, lakes, reservoirs, ponds and deep canals. The agricultural users, which take three river in Jingnan, lakes and reservoirs as water sources, are inevitably influenced by industrial water and domestic water intakes, which should be considered together. Based on these situations of water use and water sources, the general idea of water resources supply and demand balance in Jingnan River network is as follows:

1) Calculate and predict the water demand of agriculture, industry, construction, the third industry, the residents' living and off-stream ecology.

2) According to the situation of water intake and water use, partition computational subareas and compute units. Among those water users, which take Yangtze River as water source, the industrial water and domestic water are guaranteed, and the agricultural water intakes require supply-demand balance calculation. As to the water users with the three rivers in Jingnan as water source, the supply-demand balance are calculated in terms of intakes (including agriculture, industry and life water). And those water users with the reservoirs or lakes as the water source, we use reservoirs or lakes as calculation units.

3) The sequence of water source supplying water: the ponds and deep trenches are prior, such as the Yangtze River, rivers, reservoirs and lakes. The sequence of water users getting water: calculate the supply-demand balance of the water users, which take the three rivers in Jingnan as the water source, from upstream to downstream according to the location of the intakes; and when the three rivers in Jingnan break and water is supplied only by deep sinks, the sequence of water supply is that the water supply for living and industry is prior, followed by water for agriculture. While the reservoirs and the lakes are water source, the sequence of water supply is that: life, industry, construction industry, and agriculture.

4) The newly added or expanded pump stations that have been determined to be implemented are regarded as current water supply projects while calculating.

4 The construction of water resources supply and demand balance model

4.1 Calculation partitions, calculation units, and analysis units

4.1.1 Calculation partitions
According to the main water source for irrigation in Jingnan river network, the study area is divided into four subareas: Three rivers subarea (three rivers in Jingnan is the main water source, hereinafter referred to as "TRS"), Yangtze River subarea (Yangtze River is the main water source, hereinafter referred to as "YRS"), Lake subarea (lakes are the main water source, hereinafter referred to as "LS") and reservoir subarea (reservoirs are the main water source, hereinafter referred to as "RS").

4.1.2 Calculation units
In the reservoir subarea and lake subarea, every single reservoir and lake is a calculation unit. In the
Yangtze River subarea and three rivers subarea, the calculation nodes are corresponding calculation units. In this paper, the computation nodes are divided into 3 types: the water level-flow control point, the water level point and the water flow point. Furthermore, the computation nodes are defined as mentioned below and the generalization of these nodes is shown in figure 2.

① The water level-flow control point is the starting and terminal point of the calculation of river reach. The attributes of this point include the every ten days water level, the every ten days flow rate and the rating curve of the section where this point locates. If the node is a branch point or a confluence point, it contains relevant attribute information such as the split ratio and the confluence ratio.

② The water level point is the independent sluice or auxiliary water source project for the sluice gate station in calculating river reach (except the starting and terminal point), and this point attributes include the every ten days water level and the every ten days flow rate.

③ The flow point is the independent pumping station water source project in calculating river reach (except the starting point and the terminal point), and the node attributes only include the every ten days flow rate. Irrigation pump stations (separated), waterwork intakes and industrial water intakes are all recorded as flow points.

There are 31 reservoirs and 25 lakes in the study area. Therefore, there are 56 calculation units in the reservoir subarea and the lake subarea in total. According to the definition of calculation node, there are 118 calculation nodes in the three rivers subarea, including 18 water flow points, 65 water level points and 35 water level-flow control points. And there are 34 calculation nodes in the Yangtze River subarea, including 7 water flow points, 16 water level points and 11 water level-flow control points.

4.1.3 Analysis units
The agricultural water supply and demand balance is analyzed by irrigated area element, and the irrigation water requirement, water supply and water shortage are collected. Then the calculation and analysis of water deficient ratio and irrigation guarantee rate are carried out. The results of non-agricultural supply and demand are statistically analyzed by water intake element.

4.2 Calculation process and train of thoughts

4.2.1 Three rivers subarea
① Take ten days as a calculation interval, and calculate by every ten days.
② Take the calculation nodes as the calculation units, and calculate by every river reach and every calculation node.
③ Distinguish the types of calculation nodes (water level-flow control point, water flow point, water level point). Read the relationship between water level and discharge, the length of river reach, slope of river reach, split ratio and some other calculation factors. Then figure out the water level and water flow of the calculation nodes.

④ While considering the water consumption of industry and living in the three rivers, it is necessary to distinguish the types of water intakes, including two categories, namely industry and life intake and irrigation intake.

⑤ If the water intake is the industry or life water intake, the available water supply can be determined by comparing the water inflow and the design flow of the water intake. And then the actual water supply can be figured out by comparing the available water supply with the industry and life water demand. Finally, the next calculation node flow can be obtained by subtracting actual water supply from water inflow.

⑥ While calculating the water balance of irrigation intakes, the irrigation area and gross irrigation quota and other attributes factors should be read firstly, then the irrigation water requirement (the irrigation water requirement after deducting the water supply of ponds and deep trenches) can be calculated. Afterwards, distinguish the type of water project of the calculation nodes, and the project types mainly include water level point (independent sluice gate, gate station matching project) and flow point (independent pump station). Finally, different calculation methods are used to calculate the supply-demand balance according to the node types. More specifically, the discharge capacity of sluice gate is calculated in accordance with the broad crested weir and that of sluice (circular) is calculated in accordance with pressure or non-pressure short hole. When calculate the supply-demand balance of the gate and station supporting project, water supply-demand balance is firstly calculated, and supply water through the pump station when the water demand cannot be satisfied.

⑦ Since the deep sinks have water supply function while watercourse is dry up, they should be treated as special ponds (or reservoirs) strung on river reach, which only have volume and no water level. When using deep sinks to supply water, it should be confirmed that only the pump station can supply water and the sluice gate cannot.

⑧ Finally, irrigation (non-agriculture) water demand, available water supply, actual water supply and water shortage of every calculation unit will be obtained and summarized on the analysis unit.

4.2.2 Calculation principle of deep sink

It is assumed that the maximum water storage in deep water sink is \(W_{\text{max}}\), the storage capacity is \(W_0\) at the beginning of the ten day period, and the water storage is \(W_1\) at the end of the ten day period:

① When \(W_{\text{in}} \geq W_d\), namely the amount of water inflow \((W_{\text{in}})\) is greater than or equal to the water demand \((W_d)\):
   - if \(W_{\text{in}}-W_d+W_0 > W_{\text{max}}\), then \(W_1=W_{\text{max}}\), after deducting the water demand and the water storage of the deep sink, the remaining water quantity is taken as the inflow of next calculation node, and the water amount in deep sink is the maximum water storage in the deep sink;
   - if \(W_{\text{in}}-W_d+W_0 \leq W_{\text{max}}\), then \(W_1=W_{\text{in}}-W_d+W_0\), after the water demand is deducted, the remaining water is all stored in the deep sink, so the inflow of next calculating node is 0.

② When \(W_{\text{in}} < W_d\), namely the amount of water inflow is less than water demand:
   - if \(W_{\text{in}}-W_d+W_0 > 0\), then \(W_1=W_0-(W_d-W_{\text{in}})\), the water inflow is less than the water demand, whereas the sum of the inflow water and the water in the deep sink meets the requirement of water demand, then the water in the deep sink reduce, and the inflow of next calculating node is 0.
   - if \(W_{\text{in}}-W_d+W_0 \leq 0\), then \(W_1=0\), the sum of inflow and water in the deep sink cannot meet the irrigation demand, then the water in the deep sink is reduced to 0, and inflow of the next calculation node is 0.

4.2.3 Yangtze River subarea
The calculation process and thought of Yangtze River subarea are similar to that of three rivers subarea. More specifically, they all take ten days as a calculation interval and calculate by every river reach and every calculation node. On the other hand, the inflow of calculation node has nothing to do with the water consumption of upstream node and the available water supply depends on the water capacity of corresponding water source project, which is because the water supply capacity of Yangtze River is sufficient.

4.2.4 Lake subarea and reservoir subarea
① Calculate the water balance of every lake and reservoir by every ten days.
② While calculating the available water supply of lakes, the water supply capacity of pump station (intake) requires to be take into account, since the lake supply water for irrigation by pump.

4.3 Main calculation parameters

4.3.1 Calculation and determination of water quota
Use the daily observation data from 1971 to 2000 of 4 meteorological stations (Gongan County, Shishou City, Songzi City and Jingzhou District) as meteorological data, and determine the reference crop requirement by Penman-Montieth method. Based on these, the actual crop requirement can be calculated. Then, the irrigation norm of rice (early season, middle-season, late), vegetables, wheat and cotton is calculated through water balance.

The industrial, construction industrial, the tertiary industrial, domestic and ecological water quota should be determined by comprehensively referring to the 《Jingzhou official report on water resources (2014)》, tough water management measures, 《Hubei province water quota》.

4.3.2 Utilization coefficient of irrigation water
The coefficient of status quo year is determined by the situation of current projects in irrigation area, whereas that of the planning year should be determined by 《modern development program of irrigation in Hubei province》, efficiency index in tough water management measures, and 《the design specifications of irrigation and drainage project》. And since the irrigation areas in Jingnan river network area have multi scattered water sources and more diversion and lifting projects, the utilization coefficient of irrigation water in this area is a bit higher than the other similar irrigation area in Hubei province. After comprehensive consideration, the utilization coefficient of irrigation water of different water sources in status quo year are determined as follows: ponds are 0.75, deep canals are 0.75, lakes are 0.55~0.7, reservoirs are 0.5~0.7, sluice stations are 0.5~0.7; and in the planning year, the corresponding coefficients are determined as follows: ponds are 0.8, deep canals are 0.8, lakes are 0.6~0.75, reservoirs are 0.6~0.75, sluice stations are 0.6~0.75.

4.3.3 Water inflow
The Lake River network 1-D sedimentation mathematical model, which aim to research the river reach from Yichang to Datong of Yangtze River main stream, three outlets along Jingjiang river reach, Dongting Lake and Poyang Lake, was constructed. And this model adopts the three stage solution of river network, and uses measured data of 2003-2009 years to calibration and validate the flow and sediment deposition rate[7]. Afterwards, this model was utilized to simulate the everyday water level and flow at the water level-flow control point in status quo year and planning year (2022, 2032, 2042, 2052).

Generally, the lake (reservoir) inflow is calculated according to water balance. However, due to the lack of measured data, the inflow should be calculated through the method of runoff coefficient, and the runoff coefficient can be determined by referring to 《feasibility study report of continue auxiliary and water-saving improvement projects of the Weishui River irrigation area》.

The calculation of water supply of ponds and deep trenches adopts SCS method. The water supply
time of the ponds is the wet period (May ~October), and the water supply time of deep trenches is dry period (November ~ April in next year). Pond re-storage times is 2 in high flow years, 1.5 in normal flow years, 1 in low level years, and 0.75 in dry years, whereas canal re-storage times is 0.75 in every year.

4.3.4 Average water level gradient at every river reach in different level years
According to the prediction results of water level at different water level-flow control points in different level year, the average water level gradient at every river reach in different level years is determined.

4.3.5 Rating curve of water level-flow control points
According to the prediction results of water level at different water level-flow control points in different level year, imitative effect of the stage-discharge relation at water level-flow control point is good (typical stage-discharge relation is shown in Figure 3), so it can be used for model calculation. Then, use quartic polynomial to fit the rating curve of water level-flow control points.

4.3.6 Split ratio
Because the split ratio is affected by many factors, the fitting relation between the flow rate of the main stream and the split ratio is not good, and the long series of split ratio is adopted to improve the calculation accuracy.

4.3.7 Water level and flow of every station
Water level and discharge at three outlets are simulated by one-dimensional water sediment model, and the flow of each calculation node is equal to the flow of the last calculation node deduct the actual water supply (if there're deep sinks in the river reach, the water storage in sinks should also be deducted). Furthermore, the water level at the water level-flow control points can be determined by the relation between water level and flow, and the water level of calculation nodes between the two water level-flow control points can be calculated in terms of the water level gradient.

5 Analysis of calculation results
By using the constructed water resources supply and demand balance mode, the water supply and
demand balance of Jingnan river network was calculated, and the change rule of every irrigated area’
water shortage rate and probability of irrigation were analyzed.

5.1 The water shortage rate of different irrigation districts in different level years
The water shortage ratio of Paifangkou irrigation district (PFKID), Babao irrigation district(BBID),
Dongfengzha irrigation district (DFZID), Nanhaiyuan irrigation district (NHYID), Donggangyuan
irrigation district(DGYID), Caouzi irrigation district (CZID), Xingxueyuan irrigation district (XXYID),
Guanjiapu irrigation district (GJPID) and the Lianxinyuan irrigation district (LXYID) is low, but that
of other irrigation districts is all high. And the water shortage rate of all the irrigation districts (except
the Paifangkou irrigation district (PFKID)) show an increasing trend over time, which mainly due to
the development of irrigation technique, the increase of utilization coefficient of irrigation water and
the change of river water level and flow. Furthermore, the downstream of the Ouchi River, the Songzi
River and the Hudu River are the main water shortage area, and the water shortage in Ouci River is
especially serious.

5.2 Irrigation guarantee rate of irrigation districts in different level years
① In general, the irrigation guarantee rate of Paifangkou irrigation district (PFKID), Lianxinyuan
irrigation district (LXYID) and Nanhaiyuan irrigation district (NHYID) is relatively high. The
irrigation guarantee rate of other irrigation districts, however, is too low to meet the demand of
irrigation.

② The irrigation guarantee rate of Babao irrigation district (BBID), Dongfengzha irrigation
district (DFZID), Donggangyuan irrigation district (DGYID), Mishi irrigation district (MSID),
Jingjiang irrigation district (JJID), Nanwuzhou irrigation district (NWZID), Guanjiapu irrigation
district (GJPID) and Diaodong irrigation district (DDID) in status quo year is high, whereas that in
planning year is low. And the irrigation guarantee rate of other irrigation districts, both in the status
quo and planning years, is low, which cannot meet the irrigation demand.

③ The trend of irrigation guarantee rate’s changing with time: because of the implement of
water-saving reform of irrigation districts, the irrigation guarantee rate of Paifangkou irrigated
district(PFKID), Lianxinyuan irrigation district(LXYID) and Nanhaiyuan irrigation district(NHYID) is relatively high. The
irrigation guarantee rate of other irrigation district s, however, is too low to meet the demand of
irrigation.

④ The irrigation guarantee rate is generally calculated by the unit of irrigation district. But for the
irrigation districts with multi-water sources, the irrigation guarantee rate of the whole irrigation area
cannot reflect the problems of a certain water source or water source project. To handle this problem,
the irrigation guarantee rate of irrigated subarea with different water sources in a irrigation district was
determined (Table 1). Table 1 shows that the Paifangkou irrigation district(PFKID), Donggangyuan
irrigation district(DGYID), and Diaodong irrigation district(DDID) mainly exist the problem of
insufficient water supply of reservoir, and other irrigated areas mainly exist the problem of insufficient
water supply and engineering shortage of the intake at three rivers in Jingnan. This method figures out
the shortage link of every irrigation district, and it has important guiding significance to not only the
construction of continue auxiliary projects and water-saving reform of the irrigation districts but also
water resources allocation.
Fig. 4 The water shortage rate of different irrigation districts in different level years

Table 1. The irrigated guarantee rate of irrigation districts in different years

| Level year | 2018 | 2022 | 2032 | 2042 | 2052 |
|------------|------|------|------|------|------|
|             | TRS  | YRS  | LS   | RS   | total |
| PKJ          | 96.8 | 96.8 | 96.8 | 71.0 | 74.2  |
| HZY          | 88.2 | 87.1 | 93.5 | 71.0 | 80.6  |
| BBI          | 96.8 | 96.8 | 96.8 | 71.0 | 88.1  |
| HSY          | 96.8 | 96.8 | 96.8 | 71.0 | 96.8  |
| DGY          | 96.8 | 96.8 | 96.8 | 71.0 | 96.8  |
| CJI          | 96.8 | 96.8 | 96.8 | 71.0 | 96.8  |
| HYI          | 96.8 | 96.8 | 96.8 | 71.0 | 96.8  |
| MSJ          | 96.8 | 96.8 | 96.8 | 71.0 | 96.8  |
| SSY          | 96.8 | 96.8 | 96.8 | 71.0 | 96.8  |
| JJJ          | 96.8 | 96.8 | 96.8 | 71.0 | 96.8  |
| ZHI          | 96.8 | 96.8 | 96.8 | 71.0 | 96.8  |
| MDY          | 96.8 | 96.8 | 96.8 | 71.0 | 96.8  |
| NWZ          | 96.8 | 96.8 | 96.8 | 71.0 | 96.8  |
| JFY          | 96.8 | 96.8 | 96.8 | 71.0 | 96.8  |
| WFX          | 96.8 | 96.8 | 96.8 | 71.0 | 96.8  |

6 Conclusion

(1) The water resources supply and demand balance model at plain river network region with multi-water sources and multi-node is constructed. When calculating the water supply and demand balance of Three rivers subarea and Yangtze River subarea, take the control area of water source project as calculation unit, and calculate by every ten days, every river reach and every node. In the Reservoir subarea and the Lake subarea, the control area of a single reservoir and a single lake is taken as the calculation unit, and the storage and transportation calculation is carried out. It provide a new method to the calculation of water resources supply and demand balance in plain river network area, especially the handling method of the river reach at three rivers in Jingnan has important significance.
to that river reach whose intake discharge cannot be ignored to the total inflow of this river reach.

(2) The irrigation guarantee rate of each irrigation district is analyzed by taking the irrigation
district as analytical unit. Generally speaking, the irrigation guarantee rate of irrigation district taking
the Yangtze River as the main water source is high, and since the irrigation district with three rivers in
Jingnan as the main water source is affected by the decrease of split flow, the irrigation guarantee rate
shows a downward trend with time. In the meantime, analyzes the water shortage rate and irrigation
guarantee rate of every irrigation area by taking each calculated subarea as a unit, and clarifies the
water shortage link of irrigation districts. Thus, it provides a new idea for the analysis of water supply
and demand balance in multi-water source irrigation districts.

(3) The generalized treatment of the calculation nodes and deep sink is valuable for the analysis of
water supply and demand balance and the allocation of water resources for regions like plain river
network area.

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