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Study on integrated calculation of ecological water demand for basin system

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The operation of reservoir(s) has a certain impact on the downstream hydrologic regime, and even endangers the ecological water safety of river corridor and ecosystems which interact with river system. Therefore, ecological operation needs to be carried out in order to ensure ecological water use of downstream zone. The key technological support is the estimation and integrated calculation of ecological water demand. The connotation of the integrated calculation on ecological water demand lies on that the ecological water demand of different ecosystems is integrated to meet the requirements of water allocation and operation on watershed scale in terms of hydrological cycle. Considering the practical requirement of ecological operation of reservoir(s), this study proposed an integrated calculation approach of ecological water demand according to the ecological water demand in various ecosystems as well as the hydraulic connection among them; it established an integrated calculation model of regional ecological water demand by means of the distributed hydrological model, and studied the integrated calculation in Yalong River basin which is the source area of the west route of South-North Water Transfer Project as an example. The results indicated that the integrated calculation model more effectively combined the ecological water demand and hydraulic connection of ecosystems in time and space, compared with the lumped water balance analysis, since the former conquered the defect of insufficient ecological water source and supplement on multiple spatial and temporal scales, and met the demand of ecological operation of reservoir(s).

ecological operation of reservoir, ecological water demand, integrated calculation, distributed hydrological model, west route of South-North Water Transfer Project in Yalong River source area

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The scientific estimation of the ecological water demand on a regional multi-temporal and spatial scale is the key to ecological water allocation and ecological operation of reservoir(s) [1–4]. Because of the differences between the ecological water demand estimation and water resources allocation/operation on a temporal and spatial scale, plus the differences existing in the estimation approaches and the characteristics of water demand of various ecosystems, integrated calculation needs to be carried out on the ecological water demand of the region, in order to avoid double counting of the water demand of various ecosystems and overcome the ecological water shortage on a multi-temporal and spatial scale. The integrated calculation of ecological water demand has become the cutting-edge frontier of the research on the hydrology and water resources.

Currently, there are mainly three models of the integrated

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calculation of regional ecological water demand: one model is based on the macro-analysis of water balance [5], that is, placing large-scale regional macro-allocation demand of water resources as the target and aggregating various ecological water demand within the unit of hydrological water resources; the second model is the integrated calculation model that is based on the differences in hydrological characteristics [6–8], that is, dividing ecological water demand into different integrated types and units according to hydrological characteristics, for example, the ecological water demand within the region could be integrated into slope ecological water demand (ecological water demand outside riverways) and river ecological flow (ecological water demand inside riverways); the third model is the integrated calculation model that is based on the hydrological process [9, 10], that is, taking regional precipitation-runoff flows and flow concentration on the slope as the main line, and integrating the regional ecological water demand into the threshold value of runoff process for the allocation/operation units and nodes. By contrast, the hydrological mechanism of the third integrated calculation model is more express, and can meet the requirements of the estimation of ecological water demand on a multi-spatial and temporal scale during the allocation and operation of regional water resources. However, the research is still in its infancy; that is to say, the current stage is mainly to meet the requirements of water resources allocation.

An integrated calculation pattern of ecological water demand has been established in this study according to the practical requirements of the ecological operation of reservoir(s), and the distributed hydrological model (WEP) is employed to support the development of an integrated calculation model. On this basis, a study on integrated calculation of ecological water demand has been conducted on the downstream zone affected by the West Route of South-to-North Water Transfer Project in Yalong River Basin, with a view to provide theoretical and technical support to the comprehensive ecological operation of the project.

1 Content, characteristics and models of the integrated calculation of ecological water demand for basin system

1.1 Basic content of the integrated calculation of ecological water demand

Within certain temporal and spatial scales, socio-economic water has diverted ecological water, which has led to ecological degradation and threatened ecological security and harmonious development within the region. Consequently, rational allocation and operation of ecological water is needed, so as to bring the benefit of regional water resources into full play in terms of socio-economy and eco-environment. Regional water circulation and accompanying water ecological process possess multi-directional feedback function, and have experienced integral evolution under the dual drive of “natural and artificial” forces. Focused on the temporal and spatial need of water allocation and operation, the integrated calculation of ecological water demand is to integrate various ecological water demand of different regional units into the units and nodes of water allocation/operation, following the main line of water circulation and accompanying water ecological process.

It should be noted that the indicators of ecological water demand differ due to the hydraulic interaction within the units and nodes of allocation/operation during the water circulation process. Thus, it is difficult to obtain the total volume of the ecological water demand of all the regions simply by direct calculation. For instance, as for slope ecological water demand, the focus is to estimate the water demand of vegetation and the necessity to maintain suitable living conditions, that is, mainly assessing the “stock” of water; whereas, as for river ecological water demand, the target is to mainly estimate the water level and flow of ecological water control, that is, mainly assessing the “flux” of water. Meanwhile, there exists water runoff and water loss among the nodes of allocation/ operation along each river. Thus, the integrated calculation of ecological water demand needs to be conducted on regional slopes and river confluence. Otherwise, it will be difficult to meet the requirements of ecological water demand of all the river sections and the entire river.

1.2 Characteristics and requirements of the integrated calculation of ecological water demand

The operation of reservoir(s) will influence the hydrological regime of the downstream river of the dam(s). Moreover, the impact will be gradually decreased with the increase of inflow. The influence of reservoir(s) operation on the ecological environment of the downstream regions will change as hydrological conditions change. In order to guarantee ecological water demand of the downstream regions along with the river sections and maintain their eco-environmental health, various factors (such as flood control, eco-environmental protection, water conservancy project, etc.) need to be comprehensively considered and ecological operation of reservoir(s) should be implemented. During the current ecological operation of reservoir(s), the key consideration is the influence on the eco-environment of near-dam downstream regions [2]. That is to say, the overall ecological water demand of the downstream regions should be further taken into account [11].

In terms of the allocation of water resources, the focus is to conduct the integral calculation on the ecological water demand, i.e. the “stock” of water. The water requirement of allocation node is to control the runoff volume through the node, and the volume is integrated according to the hydrological process per month in the typical years of historical sequence. Whereas in terms of the operation of water resources, the water requirements in the format of “stock” need to be integrated into the water requirements in the format of "flux". Besides, the actual hydrological process and forecast on a smaller temporal scale should be integrated. Therefore, the eco-hydrological mechanism of small-scale river basin or region should be systematically analyzed.

1.3 Basic models and key supporting technologies of the integrated calculation of ecological water demand for basin system

The integrated calculation of ecological water demand for basin system should follow the main line of the water circulation and the accompanying ecological process, and should be based on the model of "total-sub-total". First of all, the overall ecological function zoning and ecological protection goals of the downstream area of the dam should be taken into consideration. Besides, the spatial distribution of water circulation, the operation nodes of water resources and ecological partition should be determined. And then the units and ecological goals of ecological water demand should be established to identify the eco-hydrological mechanisms of each calculation unit and to estimate the ecological water demand of each type within each unit. The runoff processes of each operation node under different ecological conditions should be obtained through the slope flow and river confluence tracing calculation (see Figure 1).

According to hydrological and ecological spatial distribution, regions or watersheds can be divided into slope system and river corridor system. In terms of the water origins of slope ecosystems, there are two subsystems—slope runoff supply system and slope-river runoff combination supply system. The ecological water demand of the former mainly contains loss from river sections caused by slope consumption; the ecological water demand of the latter contains the water supply from river runoff besides the loss from river sections caused by slope consumption. The river corridor system mainly includes river aquatic ecosystem, riverside wetland ecosystem and estuarine ecosystem. During the integrated calculation, the ecological water demand of the previously stated subsystems should be respectively estimated in order to check whether they accord with the temporal scale of the ecological operation. Besides, water circulation and hydraulic factors should be considered to further integrate the ecological water demand of those subsystems into that of operation nodes.

The distributed hydrological simulation technology, with physical mechanism included, can be used to objectively describe the temporal-spatial differences of the basin/river water circulation, the linkage among multi-temporal and spatial water circulation processes and the spatial continuity features, and meet the requirements of integrating ecological water demand of various subsystems into the runoff processes of operation nodes. Therefore, the distributed hydrological model is adopted in this study as the technical support for the integrated calculation.

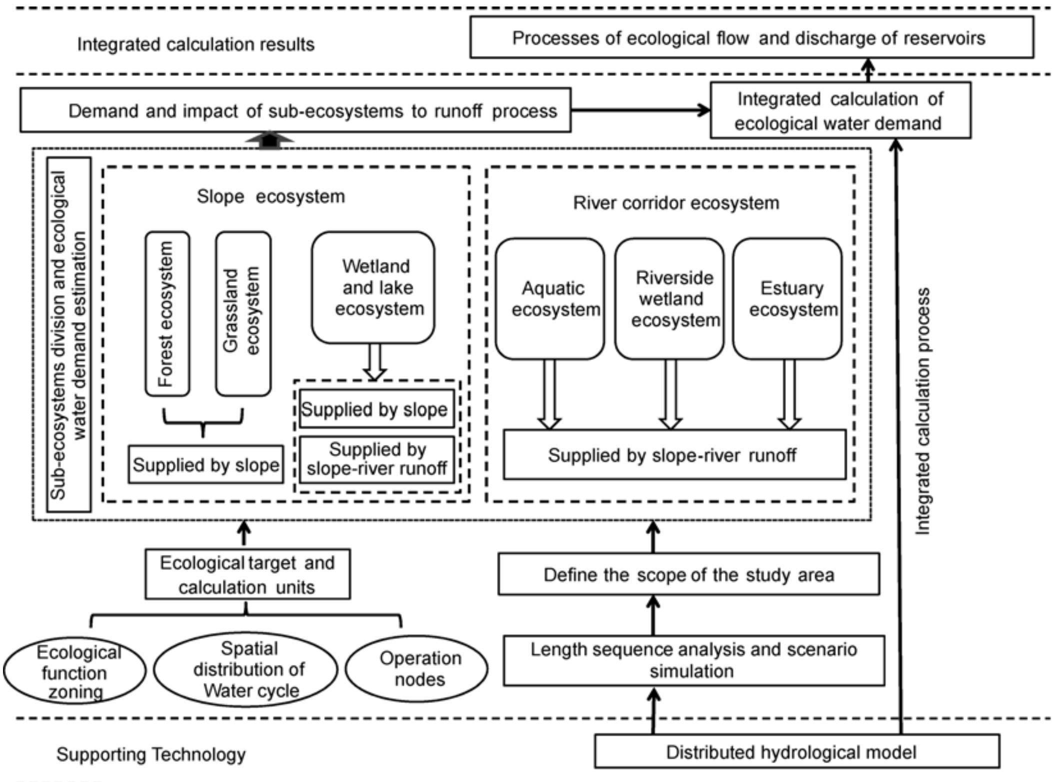

Figure 1 Frame diagram of integrated calculation models concerning ecological water demand.

2 Estimation methods of ecological water demand for subsystems

According to the above-mentioned integrated calculation model, estimation of ecological water demand for each subsystem in a certain basin/region should be conducted at first.

2.1 Ecological water demand of slope system

Natural slope ecosystem mainly includes forest ecosystem, grassland ecosystem and lake and wetland ecosystem. Ecological water demand of forest and grassland ecosystems mainly comes from slope runoff. While there are two types of recharge sources for lake and wetland ecosystems; one is slope runoff and the other is slope-river runoff. Estimation methods of the two types of ecological water demand for lake and wetland ecosystems are similar, and will be expounded in the following section. In addition, an artificial ecosystem also exists on the slope, including urban ecosystem and farmland ecosystem. Ecological water demands of these ecosystems are not considered in the integrated calculation, as they are social economical water use objects in the water resources management.

Ecological water demand of the natural slope ecosystem primarily comprises evaporation, evapotranspiration and seepage [9].

$$W_p^t = W_w^t + W_T^t + W_u^t,$$

where W_w^t, W_T^t, W_u^t are water consumption of evaporation, evapotranspiration and seepage of the natural slope ecosystem. They are obtained from the distributed hydrological model, and their effects on river runoff process are analyzed via rainfall-runoff calculation.

2.2 Ecological water demand of river corridor

2.2.1 Aquatic sub-ecosystem

Ecological water demand of the aquatic ecosystem includes consumptive water demand and non-consumptive water demand. The former denotes water consumption of surface evaporation, vegetation transpiration and river bed seepage, while the latter means ecological flow that can realize and maintain the ecological function, like sediments transporting, biological habitats and migration channels. The integrated calculation should make sure that runoff can meet the requirement of non-consumptive water demand after the runoff has been cut down by consumptive water demand in order to maintain ecosystem health.

Ecological water demand of the aquatic ecosystem can be calculated by the following equation:

$$W_r^t = W_{\mathrm{C}}^t + W_{\mathrm{NC}}^t = (W_w^t + W_T^t + W_u^t) + Q_t \Delta t,$$

where W_r^t is total ecological water demand of the aquatic ecosystem at t; W_w^t, W_T^t, W_u^t are water consumption of surface evaporation, vegetation transpiration and river bed seepage at t; Q_t is ecological flow of the river subsystem; Δt is time step size.

Nowadays, a great number of methods for ecological flow calculation have been proposed both at home and abroad [12, 13], such as hydrological method (Tennant [14] and Texas [15]), hydraulic method (wet perimeter method [16] and R2-Cross method [17]), hydrological-biological analysis method (Basque method [18]), habitat simulation method (IFIM/PHABSIM method [19]) and synthesis method (BBM method [20]). The most suitable method could be chosen for calculation on the basis of river ecological characteristics and gathered information, and parameters of the non-consumptive water demand could be obtained using the distributed hydrological model.

2.2.2 Lake and riverside wetland sub-ecosystem

Eco-environmental water consumption of the lake and riverside wetland is to maintain its structure and function. Ignoring the relationship between water income and consumption of the wetlands may result in wetlands shrinking and bad water quality [9]. Cui and Yang believe that the generalized wetland ecological water demand is the water required to maintain wetland ecological balance and normal development and to protect the hydrological and environmental functions. In a narrow sense, wetland ecological water demand is the water consumption for ecology and environment on a certain spatial and temporal scale [21, 22].

From the perspective of engineering, taking the narrow sense, this study calculates the ecological water demand of wetland processes according to the following formula:

$$W_l^t = W_w^t + W_T^t + W_u^t,$$

where W_l^t is the total amount of wetland ecological water demand at t; W_w^t, W_T^t, W_u^t are evaporation, transpiration and wetlands seepage, respectively [9].

Reservoir (s) operation will affect the river hydrological regime of downstream area of a dam, thus endangering the ecological water safety of the wetlands and riverside. For wetland protection goals, apart from natural recharge, artificial water diversion from river will be needed to supplement wetland water consumption. Therefore, total river flow demand is

$$\begin{aligned} Q_w^t &= Q_{\mathrm{N}}^t + \mathrm{Q}_{\mathrm{A}}^t = (W_l^t - W_s^t)/\Delta t \\ &= [(W_w^t + W_T^t + W_u^t) - (W_p^t + W_c^t)]/\Delta t, \end{aligned}$$

where Q_w^t is total river flow demand of lake and riverside wetland whose recharge source is slope-river runoff at period t; W_l^t is the total amount of wetland ecological water demand at period t; W_s^t is water supplement from the slope flow; W_p^t and W_c^t are water supplement from precipitation and converging water. If $W_l^t \leqslant W_s^t$, Q_w^t would be defined as 0.

2.2.3 Estuary sub-ecosystem

Estuary subsystem is affected by both river runoff and sea tide whose hydrological situation is extremely complex. Flow of the coastal river needs not only to satisfy ecological water consumption of the estuary subsystem, but also maintain a certain degree of sea traffic for ensuring stable hydrological situation and preventing sea water encroachment [23]. Water demand of the estuary subsystem is calculated according to the following formula:

$$\begin{aligned} W_e^t &= W_{\mathrm{C}}^{\mathrm{t}} + W_{\mathrm{NC}}^{\mathrm{t}} \\ &= (W_w^t + W_T^t + W_u^t) + \max(Q_e, Q_s, Q_n) \times \Delta t, \end{aligned}$$

where W_e^t is total amount of ecological water demand of estuary subsystem at period t; W_w^t, W_T^t, W_u^t are evaporation, transpiration and water consumption of seepage of the estuary subsystem respectively; Q_e, Q_s, Q_n are the flow for maintaining habitats, salt balance and sediment transport. Similar to river aquatic ecosystem, the integrated calculation should make sure that runoff can meet the requirement of non-consumptive water demand after the runoff has been cut down by consumptive water demand.

3 Integrated calculation methods of ecological water demand

The integrated calculation of ecological water demand includes consolidation of different types of ecological water demand and ecological water demand in different regions.

3.1 Integrated calculation method for different types of ecological water demand

Ecological water demand can be divided into consumptive water demand and non-consumptive water demand. The integration of different types of ecological water demand aims to transform various ecological water demands into river flow process or influence. Specifically, (1) consumptive ecological water demand of the river aquatic eco-subsystem and estuary subsystem will reduce river runoff, thus this part of consumption needs to be deducted in the integrated calculation; (2) ecological water demand of lake and riverside wetland whose recharge source is slope-river runoff is mainly classified as consumptive water demand. In the integrated calculation, this part needs to be deducted appropriately according to objectives and measures of the ecological protection; (3) lake, wetland, woodland, grassland and other slope ecosystems which are supplied by slope runoff intercept rainfall and reduce water during a certain interval. Their ecological water demand is classified as consumptive water demand. In the integrated calculation, their evaporation, transpiration and seepage are calculated using the distributed hydrological model. Their effects on river flow are analyzed through rainfall runoff calculation.

3.2 Integrated calculation method of ecological water demand for different regions

In the integrated calculation, ecological water demand in different regions is integrated based on convergence modules of the distributed hydrological model. Through integrated calculation, upper and lower reaches of river flow are jointed. According to the characteristics of river, the integrated calculation can be divided into single river ecological flow integrated calculation and complex river network ecological flow integrated calculation (Figure 2).

Ecological flow integrated calculation for single riverway is shown in Figure 2(a), where R is the reservoir; A-A, B-B, C-C are river control sections. Requirements of the upper and lower reaches of the river of the ecological system on the reservoir discharge process are as follows: ecological water demand of the dam section A-A should be met; the ecological water demand at sections B-B and C-C should also be met after various types of water consumption. More reservoir discharge is needed when the above requirements are not satisfied. On the basis of the distributed hydrological model, integrated calculation of the various control sections is completed by reverse passing loop algorithm. Steps of the loop algorithm are as follows:

Step 1. Data and parameters input of the river confluence calculation.

Step 2. Confluence calculation.

Step 3. Sections judgment of the confluence calculation. Once dam cross section appears, define the flow as their month ecological flow at the dam site section. And then go to the calculation of the next section.

Step 4. Sections judgment of the confluence calculation. Once control section appears, compare the confluence in calculation with the monthly ecological flow of the section. If the former value is greater, proceed to the next river confluence calculation. Conversely, flow correction value is

$$\Delta Q = \xi(Q_{\mathrm{eco}} - Q_{\mathrm{cal}}),$$

where $\zeta \in (0\text{–}1)$, and this parameter reflects nonlinear characteristics of the river confluence calculation.

Step 5. Return to Step 2, recalculate the river confluence.

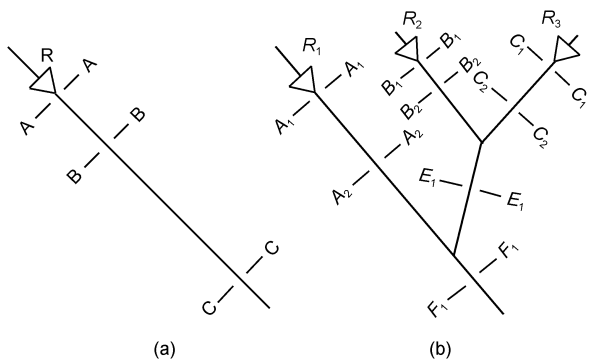

Figure 2 Integrated calculation of ecological flow

When calculation runs to the cross section of the dam, define the flow as the sum of the monthly ecological flow at the dam site and flow correction value. Repeat it until the flow of this section is greater than the value of ecological flow or the difference is small between the two values. One more section will be integrated when such a cycle is finished.

Step 6. End calculation when the integrated calculation of all sections has been completed.

Ecological flow integrated calculation for complex river network is shown in Figure 2(b), where $R_1 \ldots R_3$ are reservoirs, A_1-A_1, A_2-A_2,…,F_1-F_1 are river control sections. Being different from single riverway, multiple reservoirs and numbers of streams often appear in complex river network integrated calculation. Reservoir discharge process should not only meet the ecological water demand at the cross section of dam and each river control section, but also be able to satisfy ecological water demand of more advanced river after main stream and tributary confluence. In Figure 2(b), reservoir discharge of R_2 and R_3 needs to satisfy the ecological water demand of section E_1-E_1; reservoir discharge of R_1, R_2, R_3 needs to meet ecological water demand of section F_1-F_1.

Ecological flow integrated calculation of complex river network is also based on the reverse passing loop algorithm. Compared with the calculation for single riverway, the greatest difficulty in complex river network loop calculation is the distribution of ecological flow correction values at dam sites. If the discharge flow of reservoirs R_1, R_2, R_3 fails to meet the ecological water demand of section F_1-F_1 after convergence in the basin (Figure 2(b)), reservoir discharge of R_1, R_2, R_3 needs to be increased. However, combinations that meet the ecological water demand of section F_1-F_1 are numerous. In this study, the ratio has been predetermined according to runoff series over years and water supply requirements to resolve this problem.

4 Case study

4.1 Study area

The Yalong River basin, a plateau climate zone, is located in the southeast of Tibetan Plateau, between Jinsha River and Dadu River. The first stage project of the west route of the South-to-North Water Transfer Project is positioned on the Ganzi section of Yalong River and the upper reaches of Xianshui River which is a branch of Yalong River (see Figure 3). Water of 4.2, 0.7 and 0.75 billion m^3 is transferred from Reba, A'an and Renda dams per year, respectively.

Due to the impacts of interval inflow, the variation of hydrological conditions of the downstream area after the water transfer will become little with the increasing distance to the dam. The Lianghekou Reservoir is being built at the lower reaches about 3 km from the junction of Yalong River and Xianshui River. After the water transfer project, the change of hydrological conditions at the dam is the most obvious. Considering the operation function of Lianghekou Reservoir, it could be indicated that the water transfer from Yalong River through the first stage project of the west route of the South-to-North Water Transfer Project has weak effects on the eco-hydrological processes of the downstream region of Lianghekou Reservoir. Thus, the region between water diversion dams to Lianghekou Dam has been selected as the study area.

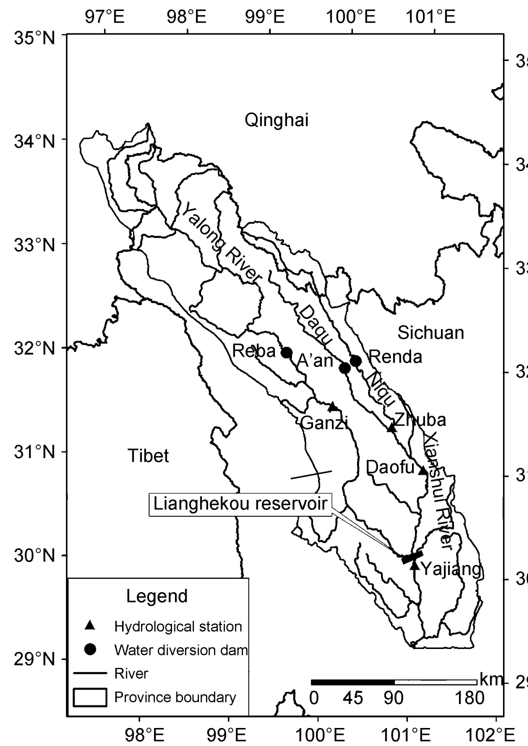

Figure 3 Location of study area.

After the implementation of the first stage project of the west route of the South-to-North Water Transfer Project, the decrease of runoff at the downstream region of water diversion dams had influences on the ecosystem of rivers [24]. The health of river ecosystem is an important goal of ecological protection in the affected region of water transfer projects. The elevation of this region ranges from 3500 to 4000 m, and it is a transition region from plateau to mountain canyon. Fish species in the river includes *schizothorax wangchiachii* (Fang), *ptychobarbus kaznakovi* Nikolsky, *gymnodiptychus pachycheilus* Herzenstein, *euchiloglanis davidi* (Sauvage) etc. [25].

Except rivers, the eco-hydrological processes of partial wetlands and nature reserves were affected by the project, especially the Kasha Lake, which was the key protection goal of this region.

4.2 Technological support of integrated calculation

To estimate the ecological water demand of different ecosystems, the hydraulic relationships of subsystems should be considered to avoid the repeated calculation of ecological water demand. The integrated calculation of ecological water demand for basin system is supported by the distributed hydrological models. In this study, the WEP Model [26] has been chosen, and its theory and function of major modules are listed in Table 1.

4.3 Ecological water demand of each sub-ecosystem

Based on the above classification and estimation methods on ecological water demand and the integrated calculation model of regional ecological water demand, the ecological water demand in this region which is divided into 10 aquatic ecosystems units (river section), 76 forest units, 54 grass units, and 22 slope wetland units according to the investigation data has been evaluated. The results are shown below.

4.3.1 Ecological water demand of slope system

Slope system consists of forest, grassland and wetland ecosystems. Considering the joint supplement of slope and river, the ecological water demand for this kind of wetland will be calculated by additional method. Only the ecological water demand of forest, grassland and wetland with the exclusive supply from slope has been estimated in this section.

According to the long-term simulation by the WEP model, the ecological water demand of the whole slope system has been obtained by counting the evaporation, transpiration and seepage of each calculation unit (Table 2).

4.3.2 Ecological water demand of river ecosystem

To estimate the ecological water demand of aquatic ecosystems accurately, it is necessary to divide the river into many sections and calculate the ecological water demand of each section. The following factors will be considered: (1) the distribution of biological species (mainly fish); (2) confluence of river; (3) geomorphology of riverbed. In addition, due to the significant changes of hydrological conditions in river sections close to dam, the ecological water demand of those sections will be calculated separately (see Table 3).

Table 1 The function and theory of major modules in the WEP model

Module	Function and theory
SURSOIL	This module was used to simulate the vertical water-heat process, and the evapotranspiration and infiltration amounts were calculated in this module by Penman or Penman-Monteith formula and Green-Ampt model, respectively.
OVERLAND	The concentration process of overland flow was simulated by the kinematic wave equation.
RIVER	According to practical background, the kinematic wave equation or dynamical wave equation was adopted to simulate the flow concentration of river channels.
GWATER	The Bousinessq equation was used to describe the movement of ground water.
SNOW	The snow and snowmelt process was simulated by the Degree-day Method.

Table 2 Ecological water demand of slope system

Month	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Annual
Ecological water demand (10^8 m^3)	5.21	5.96	8.75	9.78	10.80	9.41	9.87	9.31	7.73	6.33	5.21	4.84	93.21

Table 3 The river subsections and control cross sections

River	River section	Cross section	Geomorphological features
Yalong River	Reba Dam—the boundary of Dege and Ganzi counties	Reba Dam	The upper reaches of Yalong River is a mountain zone with V-shaped deep valleys and intensive and fast flow.
Yalong River	the boundary of Dege and Ganzi counties—Ganzi hydrological station	the boundary of Dege and Ganzi counties	
Yalong River	Ganzi hydrological station—Xinlong County	Ganzi hydrological station	The middle reaches of the river is a mass of canyons and steep slope. The shape of river is V-shaped and U-shaped.
Yalong River	Xinlong County—Lianghekou	Xinlong County	
Daqu	A'an Dam—the boundary of Ganzi and Luhuo counties	A'an Dam	hummocky plateau form with the deep valleys, floodplains and valleys
Daqu	the boundary of Ganzi and Luhuo counties—estuary of Daqu	the boundary of Ganzi and Luhuo counties	
Niqu	Renda Dam—the boundary of Ganzi and Luhuo counties	Renda Dam	The fractured rocks are distributed along the river with the fast water flow in the straight riverway.
Niqu	the boundary of Ganzi and Luhuo counties—estuary of Niqu	Zhuba hydrological station	
Xianshui River	the connection of Daqu and Niqu—Daofu hydrological station	the boundary of Daofu and Luhuo counties	Due to the shallow depths of valley, the hummocky undulating plateau and wide-shallow valley are formed in this region with rift basin and gully occasionally.
Xianshui River	Daofu hydrological station—estuary of Xianshui River	Daofu hydrological station	

At present, many researchers have analyzed the ecological flow of Yalong River in the first stage project of the west route of the South-to-North Water Transfer Project by different methods [25, 27–29]. Due to excessive sections involved in this study, it is difficult to collect hydraulic parameters of all sections. In this study, the ecological flow of each section has been calculated by the Tennant Method, in which a certain percentage of average annual flow is taken as the ecological flow. The calculation standard is shown in Table 4 [9].

In the Tennant Method, the proposed flow of "General" grade is considered as the minimum of ecological flow to ensure no degradation occurring in the downstream region of the Yalong River water transfer project [30]. In this study, this standard is selected to calculate the ecological flow of each section of Yalong River in the first stage project of the west route of the South-to-North Water Transfer Project, and the results are listed in Table 5.

4.3.3 Ecological water demand of riverside wetlands

The ecological water demand of riverside wetlands includes evaporation, transpiration and seepage. The estimation method introduced in Section 2.2.2 is used to estimate and count the processes of ecological water demand of the 10 riverside wetland units. The result is shown in Table 6.

4.3.4 Ecological water demand of the wetlands jointly supplied by slope and river

There is complex hydraulic linkage between rivers and the wetlands which are jointly supplied by slope and river. Accordingly, Kasha Lake is the only one large-scale wetland which has been considered as an important object of protection. It is located at Zhuwo Town, Luhuo County, Ganzi, Tibetan Autonomous Prefecture, Sichuan Province, with an altitude of 3520 m. Kasha Lake has an east-west rectangular shape. The water area of the lake is about 109 hm^2 in the dry period, 130 hm^2 in the wet period, and 120 hm^2 in the normal period. In the east of the lake, there is an herbaceous swamp with an area of 18 hm^2. The deepest depth of the lake is 17 m [31].

The ecological water demand of Kasha Lake consists of two parts, one is seepage amount, and the other is net evaporation of the lake. Since supplement balance exists between the surface water and groundwater of Kasha Lake due to the relatively small impact of human activities, the seepage amount of the wetland could be ignored.

In the study, the precipitation and evaporation of Kasha Lake in the normal year (P=50%) and dry year (P=75%) have been described by the data of Luhuo weather station. The ecological water demand of Kasha Lake during different years has been calculated based on the weather data and the water area in the normal year or dry year. The result is shown in Table 7.

4.4 Integrated calculation of the ecological water demand

According to the integrated calculation methods discussed in Section 3, a module (ECOWATER) has been developed based on the RIVER module of WEP model (Table 1) to integrate the ecological water demand of each subsystem. The module is called for before the RIVER module, and the result could be used as the boundary conditions of the RIVER module.

With the WEP model taken as a computing platform, the integrated calculation has been conducted in combination with the ecological water demand of each ecosystem in the downstream zone affected by water transfer project in Yalong River Basin. For easy analysis, the integrated calculation has been conducted on dams and cross sections. Since the interval inflow is taken into account, the result would be unequal in different years. The hydrological process simulation and integrated calculation have been completed for 1960 to 2000 in this study, and the annual average is considered as the result (Table 8).

Comparing Tables 5 and 8, we have found that the ecological flow of cross sections increases with different magnitudes except the last cross sections (Xinlong County in Yalong River and Daofu hydrological station in Xianshui River). Among all the dams, the ecological flow of Reba Dam which is located at the main stream of Yalong River has undergone a significant change, especially in April and May. The ecological flow of cross sections in Daqu and Niqu has changed greatly, especially in April, May and September.

The discharge processes of the water transfer dams after the project have been analyzed in this study according to the preliminary results on the planning stage of the first stage project of west route of South-to-North Water Transfer Project. The result is shown in Figure 4.

Figure 4 shows that although the annual water quantity is enough, the discharge processes of dams could not meet the ecological water demand, especially in April, May and June when it is clear that discharge quantity is much less than

Table 4 Proposed standard of ecological flow in the Tennant Method

Proposed flow	Stage	Max	Optimal	Excellent	Very good	Good	General	Poor	Very poor
Percentages of average annual flow (%)	general period (Oct. to Mar. next year)	200	60–100	40	30	20	10	10	0–10
	spawning period (Apr. to Sept.)	200	60–100	60	50	40	30	10	0–10

Table 5 Ecological flow of river sections in the downstream region affected by the water transfer project in Yalong River Basin

River	River section	Cross section	Ecological flow ($m^3 s^{-1}$)	
			general period (Oct.–Mar.)	spawning period (Apr.–Sept.)
Yalong River	Reba Dam—the boundary of Dege and Ganzi counties	Reba Dam	19.3	57.8
Yalong River	the boundary of Dege and Ganzi counties-Ganzi hydrological station	the boundary of Dege and Ganzi counties	20.4	61.1
Yalong River	Ganzi hydrological station—Xinlong County	Ganzi hydrological station	27.3	81.8
Yalong River	Xinlong County—Lianghekou	Xinlong County	30.2	90.4
Daqu	A'an Dam—the boundary of Ganzi and Luhuo counties	A'an Dam	3.3	9.8
Daqu	the boundary of Ganzi and Luhuo counties—estuary of Daqu	the boundary of Ganzi and Luhuo counties	3.7	11.2
Niqu	Renda Dam—the boundary of Ganzi and Luhuo counties	Renda Dam	3.6	10.9
Niqu	the boundary of Ganzi and Luhuo counties—estuary of Niqu	Zhuba hydrological station	6.4	19.1
Xianshui River	the connection of Daqu and Niqu-Daofu hydrological station	the boundary of Daofu and Luhuo counties	12.3	36.8
Xianshui River	Daofu hydrological station—estuary of Xianshui River	Daofu hydrological station	14.4	43.2

Table 6 Ecological water demand of riverside wetland

Month	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Annual
Ecological water demand ($10^4 m^3$)	101.5	118.1	173.4	193.7	212.2	186.3	193.7	184.5	153.1	125.5	101.5	95.9	1839.5

Table 7 Ecological water demand of Kasha Lake

Typical year	Ecological water demand (10^4 m^3)												
	Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
Normal year (P=50%)	8.99	11.66	18.56	18.74	24.37	−3.76	−1.18	11.84	−0.69	11.79	9.81	8.30	118.43
Dry year (P=75%)	8.28	11.18	17.78	19.35	12.63	8.21	7.42	13.13	0.31	4.85	9.37	7.21	119.72

Negative number means the precipitation is greater than the evaporation.

Table 8 Results of integrated calculation for ecological water demand in the downstream region affected by water transfer project in Yalong River Basin

River	Cross section	Ecological flow ($m^3 s^{-1}$)											
		Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
Yalong River	Reba Dam	20.07	22.05	21.85	65.07	66.33	62.05	63.23	62.94	65.85	22.2	19.3	19.3
Yalong River	the boundary of Dege and Ganzi counties	21.17	22.82	22.35	66.22	70.95	65.64	66.93	66.61	68.86	23.54	20.4	20.4
Yalong River	Ganzi hydrological station	28.11	28.29	28.21	83.7	84.13	82.84	83.32	83.35	83.65	28.14	27.3	27.96
Yalong River	Xinlong County	30.2	30.2	30.2	90.4	90.4	90.4	90.4	90.4	90.4	30.2	30.2	30.2
Daqu	A'an Dam	3.61	3.44	3.62	10.34	12.13	10.86	11.25	11.2	11.55	4.17	3.3	3.39
Daqu	the boundary of Ganzi and Luhuo counties	4.19	3.8	3.75	11.74	13.02	11.96	12.36	12.32	12.52	4.43	3.7	4.01
Niqu	Renda Dam	3.75	3.6	3.67	11.27	15.61	13.5	13.99	13.65	15.29	5.5	3.6	3.6
Niqu	Zhuba hydrological station	8.14	6.95	6.53	19.65	21.6	20.54	20.75	20.83	21.32	7.57	6.4	7.25
Xianshui River	the boundary of Daofu and Luhuo counties	12.58	12.3	12.3	36.8	39.76	38.76	38.87	39.25	39.33	13.57	12.3	12.54
Xianshui River	Daofu hydrological station	14.4	14.4	14.4	43.2	43.2	43.2	43.2	43.2	43.2	14.4	14.4	14.4

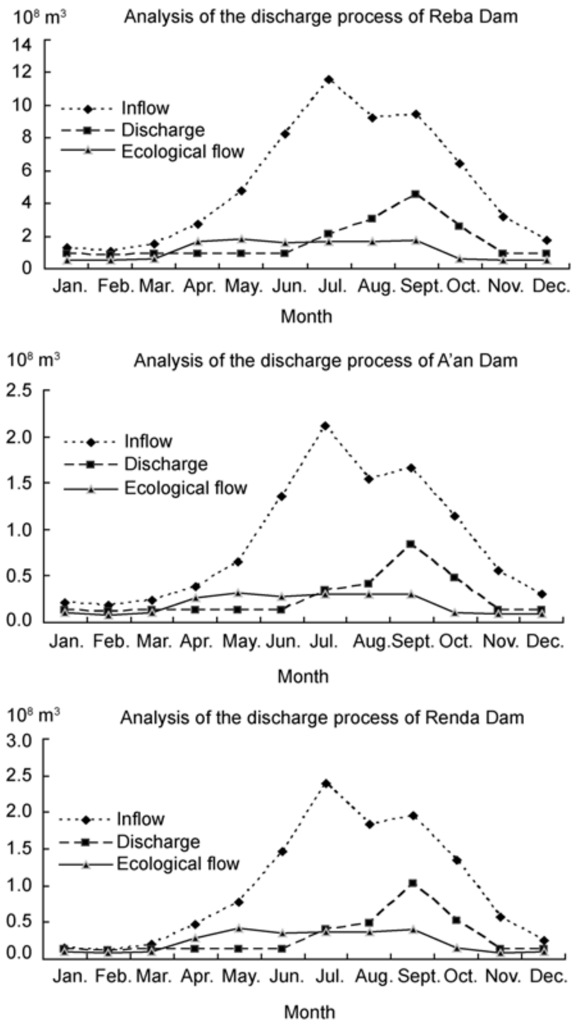

Figure 4 Analysis on the discharge process of water transfer dams in Yalong River basin.

ecological water demand of the downstream region. The reason is that fish is experiencing laying, hatching and nursing while regional water confluence amount is small in this period. Therefore, it is necessary to increase the discharge quantity in order to satisfy the requirements of water level and flow rate for fish laying.

5 Conclusions

(1) An integrated calculation pattern of ecological water demand for basin system has been developed in this study according to the practical requirements of dams' ecological operation. In this pattern, water cycle and its accompanying ecological processes are taken as a main line, with ecological water demand processes and hydraulic linkage of different ecosystems as the basis. Besides, it possesses the physical mechanism. Furthermore, it could satisfy the demand that the ecological water demand of subsystems is integrated into the runoff processes of the operation nodes.

(2) Supported by the aforesaid theory and methods, an integrated calculation model of regional ecologic water demand has been developed in this study based on the WEP distributed hydrological model. The downstream area affected by water transfer project in Yalong River Basin is taken as an example. The result shows that the ecological flow at different water transfer sites is different before and after the calculation, especially in the dry months during spawning periods. The ecological water demand of the downstream area could be met if the dams are operated according to the ecological flow after the integrated calculation.

(3) In the integrated calculation of ecological flow for complex river network, a static method which presets ratios according to the runoff series and water demand is used to allocate the correction values of ecological flow for each dam in this study. A dynamic model will be developed in future based on the theory and methods of reservoir optimal operation.

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