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A general multi-objective programming model for minimum ecological flow or water level of inland water bodies

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Abstract: Assessment of ecological flow or water level for water bodies is important for the protection of degraded or degrading ecosystems caused by water shortage in arid regions, and it has become a key issue in water resources planning. In the past several decades, many methods have been proposed to assess ecological flow for rivers and ecological water level for lakes or wetlands. To balance water uses by human and ecosystems, we proposed a general multi-objective programming model to determine minimum ecological flow or water level for inland water bodies, where two objectives are water index for human and habitat index for ecosystems, respectively. Using the weighted sum method for multi-objective optimization, minimum ecological flow or water level can be determined from the breakpoint in the water index–habitat index curve, which is similar to the slope method to determine minimum ecological flow from wetted perimeter–discharge curve. However, the general multi-objective programming model is superior to the slope method in its physical meaning and calculation method. This model provides a general analysis method for ecological water uses of different inland water bodies, and can be used to define minimum ecological flow or water level by choosing appropriate water and habitat indices. Several commonly used flow or water level assessment methods were found to be special cases of the general model, including the wetted perimeter method and the multi-objective physical habitat simulation method for ecological river flow, the inundated forest width method for regeneration flow of floodplain forest and the lake surface area method for ecological lake level. These methods were applied to determine minimum ecological flow or water level for two representative rivers and a lake in northern Xinjiang of China, including minimum ecological flow for the Ertix River, minimum regeneration flow for floodplain forest along the midstream of Kaxgar River, and minimum ecological lake level for the Ebinur Lake. The results illustrated the versatility of the general model, and can provide references for water resources planning and ecosystem protection for these rivers and lake.

Keywords: minimum ecological flow; minimum ecological water level; wetted perimeter method; physical habitat simulation method; inundated forest width method; lake surface area method

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Inland water bodies, such as rivers and lakes, provide habitats for inland aquatic ecosystems, and also serve as important water sources for human. In the past several decades, water abstraction from water bodies have been increasing rapidly due to rapid increase of domestic, agricultural and industrial water requirements. In many parts of the world, especially in arid regions and during dry seasons, over-abstraction of water from water bodies for human uses leads to significant decrease of water available for ecosystems, and eventually results in degradation of ecosystems dependent on water bodies (Sun et al., 2008). To protect these degraded or degrading ecosystems, many methods had been proposed to assess ecological flow

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for rivers and ecological water level for lakes and wetlands in the past several decades (Beca, 2008). The ecological flow or water level assessment mainly concerns the ecological integrity within water bodies and their margin, which is a part of the environmental flow or water level assessment considering ecological, cultural, recreational, landscape and other values of water bodies (Beca, 2008).

For rivers, ecological flow provides a certain level of protection for river ecosystems. During the past several decades, over 200 river flow assessment methods have been proposed (Tharme, 2003; Jain, 2012). These methods were usually classified into hydrological (Tennant, 1976), hydraulic rating (Gippel and Stewardson, 1998), habitat simulation (Bovee, 1982; Waddle, 2001), holistic (King and Louw, 1998), combination and other methodologies (Tharme, 2003). They differ in their data requirements, methods to specify the ecological flow requirement, and ecological assumptions (Jowett, 1997).

In some ecological flow assessment methods, flow requirement of floodplain forest was also considered. The regeneration of floodplain forest requires appropriate sites and suitable moisture conditions for seedling emergence provided by overbank floods or regeneration flow (Hughes and Rood, 2003). Methods to estimate the flow necessary for the protection of floodplain forest include spatial and temporal comparisons (Braatne et al., 2003), the recruitment box model (Mahoney and Rood, 1998) and the dynamic simulation model (Ahn et al., 2007). However, these methods usually require a large amount of data that are difficult to obtain, which limit their applicability in the practice of floodplain forest protection.

For lakes or wetlands, minimum ecological water level provides a certain level of protection for lake or wetland ecosystems. Different from many methods for river flow assessment, only limited number of lake level assessment methods have been proposed to define a minimum ecological lake level, including historical lake level method, lake morphology analysis, lake surface area method, water balance analysis, water quality modeling, habitat analysis and species- environment models (Xu et al., 2004; Beca, 2008; Shang, 2013). Similar methods have also been used in wetland level assessment (Beca, 2008; Li et al., 2009; Tan et al., 2012).

In summary, most river flow or water level assessment methods are only applicable to a specified water body, such as river or lake. Many of these methods did not consider the trade-off between water uses by human and ecosystems, and considered only part factors influencing ecosystems dependent on water bodies, such as hydrological, hydraulic or habitat factors. In fact, issues of ecological flow or water level for inland water bodies originate from the conflict of water uses by human and ecosystems. Therefore, the trade-off between water uses by human and ecosystems should be considered in determining ecological flow or water level, which can be described by multi-objective programming model considering both human and ecosystem water uses. In our previous studies, multi-objective programming models had been proposed to assess ecological flow (Hao and Shang, 2008; Shang, 2008), regeneration flow for floodplain forest (Shang and Mao, 2010), and ecological lake level and storage (Shang, 2013). These models are similar in form, but each model considers only a specified assessment objective.

The main objective of this study is to propose a general multi-objective programming model to determine minimum ecological flow or water level for inland water bodies. The relationships between this model and several commonly used flow or water level assessment methods were analyzed.

1 General multi-objective programming model for minimum ecological flow or water level

For determining minimum ecological flow or water level, the trade-off between water uses by human and ecosystems can be described by the following multi-objective programming model:

$$\begin{cases}\min\ Z_1 = F(X), \\ \max Z_2 = G(X), \\ \text{s.t.}\ \ X_l \leqslant X \leqslant X_u.\end{cases} \tag{1}$$

Where X is the state variable of water bodies (discharge or water level) ranging from X_l to X_u; F and G are water index and habitat index of water bodies dependent on X, respectively; and Z_1 and Z_2 are two objective functions. The first objective represents the minimization of water index so as to supply more water for human, while the second objective represents the maximization of habitat index so as to provide more habitats for the aquatic ecosystem. Therefore, this model aims at providing more habitats with less water.

In general, two objectives in model 1 (Eq. 1) are incommensurable. For the convenience of solving model 1, variables and objective functions were firstly converted to dimensionless variables or functions with Eqs. 2–4:

$$x = (X - X_l)/(X_u - X_l)\,. \tag{2}$$

$$f = (F - F_l)/(F_u - F_l)\,. \tag{3}$$

$$g = (G - G_l)/(G_u - G_l)\,. \tag{4}$$

Where x, f and g are dimensionless state variables, water index and habitat index, respectively; F_l and F_u are limits of F corresponding to X_l and X_u, respectively; and G_l and G_u are limits of G corresponding to X_l and X_u, respectively. Using these conversions, x, f and g are all rescaled to [0, 1]. Then model 1 can be rewritten as:

$$\begin{cases} \min\ z_1 = f(x), \\ \min\ z_2 = 1 - g(x), \\ \text{s.t.}\quad 0 \leqslant x \leqslant 1. \end{cases} \tag{5}$$

Where z_1 and z_2 are two dimensionless objective functions, respectively.

Model 5 (Eq. 5) can be solved with the weighted sum method or the ideal point method with the scaling coefficient of 1 for multi-objective optimization (Shang, 2006), which results in the following optimization model of one objective:

$$\min\ d(x) = \lambda_1 f(x) + \lambda_2[1 - g(x)]\,. \tag{6}$$

Where $d(x)$ is the evaluation function, λ_1 and λ_2 are non-negative weights for two objectives that meet $\lambda_1+\lambda_2=1$. Different combinations of weights represent different considerations on the relative priority of human and ecosystem water uses, and greater value of λ_2 means more consideration for habitat index.

The minimization of $d(x)$ results in a Pareto solution of model 5, which expresses the trade-off between water uses by human and ecosystems. This Pareto solution is defined as the dimensionless minimum ecological flow or level x_e.

$$\frac{\mathrm{d}g}{\mathrm{d}f}\bigg|_{x=x_e} = \frac{\lambda_1}{\lambda_2}\,. \tag{7}$$

Using the α-method or λ-method (Shang, 2006), the weights are determined to be $\lambda_1=\lambda_2=0.5$. Of course, other combinations of weights can also be used to reflect the preference of decision makers. For equal weights, Eq. 7 can be written as:

$$\frac{\mathrm{d}g}{\mathrm{d}f}\bigg|_{f=f_e} = 1 \quad \text{or} \quad \frac{\mathrm{d}G}{\mathrm{d}F}\bigg|_{F=F_e} = \frac{G_u - G_l}{F_u - F_l}\,. \tag{8}$$

Where f_e and F_e are the dimensionless water index and water index corresponding to minimum ecological flow or level (x_e or X_e), respectively.

The left and right part of Eq. 8 are marginal and average benefits of habitat output to water input, respectively. Therefore, Eq. 8 defines minimum ecological flow or water level as the point where the marginal benefit equals to the average benefit. More specifically, f_e and F_e can be defined as the breakpoints of the f–g and F–G curves, where the curve slopes are 1 for the f–g curve and the ratio of maximum habitat index increment to maximum water index increment for the F–G curve (Fig. 1), respectively. This definition is similar to the slope method to determine minimum ecological flow from the wetted perimeter–discharge curve (Gippel and Stewardson, 1998). In other words, model 1 is a generalization of the slope method. Besides the wetted perimeter method, the slope method can also be used to determine minimum ecological flow or water level when choosing appropriate water and habitat indices for inland water bodies.

In general, the F–G relationship is available as scattered data pairs. If this relationship can be expressed as simple functions, the ecological flow or water level can be calculated analytically from Eq. 8. Otherwise, the ecological flow or water level can be calculated by numerical optimization of the evaluation function $d(x)$. For all available scattered data pairs of (F_i, G_i), i=1, 2, …, n, we calculate d_i from Eq. 6, and find out minimum value d_k=min{d_i, i=1, 2, …, n} and corresponding F_k. Then minimum ecological water index (F_e) can be estimated with the parabolic interpolation method for univariate optimization (Shang, 2006), which is:

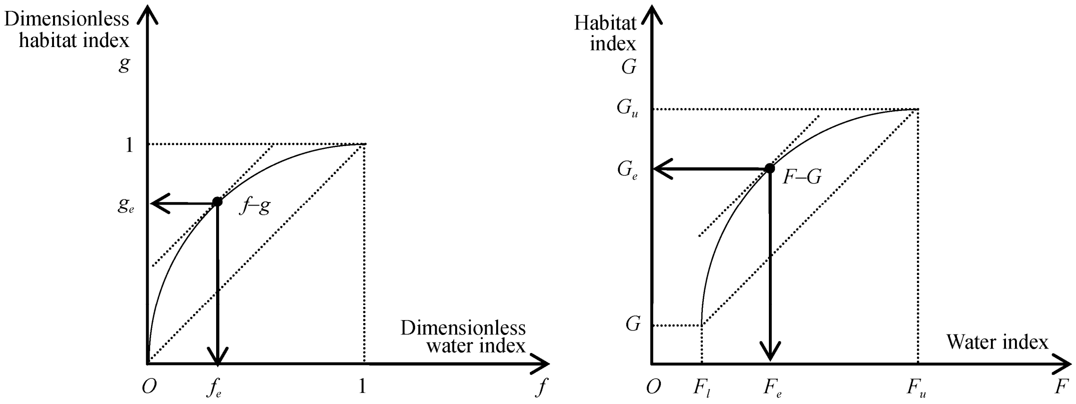

Fig. 1 Sketch of the general model to estimate ecological water (f_e, F_e) and habitat (g_e, G_e) indices corresponding to minimum ecological flow or water level (X_e) from water index (f, F)–habitat index (g, G) curve

$$F_e = \frac{1}{2}\frac{d_{k-1}(F_k^2 - F_{k+1}^2) + d_k(F_{k+1}^2 - F_{k-1}^2) + d_{k+1}(F_{k-1}^2 - F_k^2)}{d_{k-1}(F_k - F_{k+1}) + d_k(F_{k+1} - F_{k-1}) + d_{k+1}(F_{k-1} - F_k)}. \tag{9}$$

The numerical estimation of minimum ecological water index using Eq. 9 can avoid the estimation of the first derivative of the *F–G* curve, which is very useful when the *F–G* curve cannot be expressed as simple function.

2 Some methods deduced from the general model

The general model 1 provides a general analysis framework to determine minimum flow or water level for river, floodplain, lake and wetland ecosystems. This model considers the trade-off between water uses by human and ecosystems, and aims at providing more habitat for ecosystems with less water. With appropriate water and habitat indices, the general model can be used to determine ecological flow for river ecosystems, regeneration flow for floodplain forest and ecological water level for lake ecosystems (Table 1). Other appropriate water and habitat indices can also be used to develop new methods to define minimum ecological flow or water level for inland water bodies.

2.1 Wetted perimeter method

Wetted perimeter method is the most widely used method among hydraulic rating methods for minimum ecological flow. In this method, minimum ecological flow is defined as the discharge at the breakpoint of the wetted perimeter–discharge curve, and the breakpoint is usually determined by the slope method where the curve slope equals to a specified value (usually 1) or the curvature method where the curvature reaches the maximum (Gippel and Stewardson, 1998). However, results of these two methods are usually different (Gippel and Stewardson, 1998; Liu et al., 2006), and it is not clear which method better defines minimum environmental flow.

Taking the river discharge (*Q*) as water index and wetted perimeter (*P*) as habitat index, model 1 can be written (Shang, 2008) as:

Table 1 Some methods that can be deduced from the general model for ecological flow or water level

Method	Water body	State variable	Water index	Habitat index	Result
Wetted perimeter method (Shang, 2008)	River	Discharge	Discharge	Wetted perimeter	Ecological river flow
Multi-objective PHABSIM method (Hao and Shang, 2008)	River	Discharge	Discharge	Weighted usable area	Ecological river flow
Inundated forest width method (Shang and Mao, 2010)	River	Flood level	Flood level	Inundated forest width	Ecological flow for floodplain forests
Lake surface area method (Shang, 2013)	Lake or wetland	Lake level	Lake storage	Lake surface area	Ecological lake level and storage

$$\begin{cases}\min\ Z_1 = Q,\\ \max Z_2 = P(Q),\\ \text{s.t.}\quad 0 \leqslant Q \leqslant Q_m.\end{cases} \tag{10}$$

Where Q_m usually takes the value of annual mean discharge. From Eqs. 8 and 10, minimum ecological flow (q_e or Q_e) can be calculated from:

$$\frac{\mathrm{d}p}{\mathrm{d}q}\Big|_{q=q_e} = 1,\ \text{or}\ \frac{\mathrm{d}P}{\mathrm{d}Q}\Big|_{Q=Q_e} = \frac{P_m}{Q_m}. \tag{11}$$

Where $p=P/P_m$ and $q=Q/Q_m$ are dimensionless wetted perimeter and discharge, respectively; P_m is the wetted perimeter corresponding to Q_m.

Equation 11 is the same as the slope method. Therefore, the slope method to determine minimum ecological flow from Q–P curve is a special case of the general model for ecological flow or water level. Meanwhile, the slope method is more reliable to define minimum ecological flow from Q–P curve than the curvature method, as demonstrated by theoretical analysis and case studies (Shang, 2008).

If the derivative of the wetted perimeter–discharge curve ($\mathrm{d}P/\mathrm{d}Q$) is difficult to calculate analytically when the curve cannot be expressed as simple functions, minimum ecological flow can be estimated directly from Eq. 9, and evaluation function is:

$$\min\ d(Q) = 1 + Q/Q_m - P/P_m. \tag{12}$$

2.2 Multi-objective physical habitat simulation method

In the physical habitat simulation (PHABSIM) model (Waddle, 2001), weighted usable area (WUA) is used as the habitat index for target aquatic species and life stages. Considering habitat suitability criteria of water depth, velocity, and channel index for chosen target species and life stages, WUA–discharge (Q) relationship can be obtained from the habitat modeling process in PHABSIM. River flow at the peak of the WUA–Q curve is generally considered to provide the most suitable habitat for target species. However, the above determined flow considered only ecological water use, and may be irrational as ecological flow because the flow may be too large compared with flow records under some circumstances (Waddle, 2001). Therefore, the WUA–Q curve is usually incorporated in the instream flow incremental methodology (IFIM) (Bovee, 1982) to assess the impact of flow variation on habitat.

Taking the river discharge (Q) as water index and WUA as habitat index, model 1 can be written (Hao and Shang, 2008) as:

$$\begin{cases}\min\ Z_1 = Q,\\ \max Z_2 = \mathrm{WUA}(Q),\\ \text{s.t.}\quad 0 \leqslant Q \leqslant Q_p.\end{cases} \tag{13}$$

Where the upper limit of discharge is set to the peak flow of the WUA–Q curve (Q_p). From Eqs. 8 and 13, minimum ecological flow (Q_e) can be calculated from:

$$\frac{\mathrm{dWUA}}{\mathrm{d}Q}\Big|_{Q=Q_e} = \frac{\mathrm{WUA}_p}{Q_p}. \tag{14}$$

Where WUA_p is the peak value of WUA.

It can be clearly seen from model 13 that only the ecological objective (Z_2) is considered in defining Q_p as the ecological flow. To balance water uses by human and ecosystems, a certain proportion of WUA_p is usually used to define minimum ecological flow. Since WUA does not necessarily increase with Q, the slope method is considered to be inapplicable to determine minimum ecological flow from the WUA– Q curve (Gippel and Stewardson, 1998). However, the general multi-objective programming model and the slope method are also applicable if the discharge is restricted in the range from 0 to Q_p, as expressed in Eqs. 13 and 14.

Usually the WUA–Q curve cannot be expressed as simple analytical functions, and minimum ecological flow can also be estimated directly from Eq. 9, where the water index (F) is the river discharge (Q), and evaluation function is:

$$\min\ d(Q) = 1 + Q/Q_p - \mathrm{WUA}/\mathrm{WUA}_p. \tag{15}$$

2.3 Inundated forest width method

As an analogue to the wetted perimeter method to determine minimum ecological flow for river ecosystems (Gippel and Stewardson, 1998), the inundated forest width method defines minimum regeneration flow for floodplain forest from the inundated forest width–water level curve (Shang and Mao, 2010). In the inundated forest width method, water and habitat indices are flood level and inundated forest width, respectively. Using these two indices, model 1 can be written as:

$$\begin{cases}\min\ Z_1 = H, \\ \max Z_2 = \mathrm{IFW}(H), \\ \text{s.t.}\ \ H_0 \leqslant H \leqslant H_m.\end{cases} \tag{16}$$

Where H is the water level ranging from H_0 to H_m, H_0 is the minimum level that can inundate the forest, H_m is the maximum level that can inundate the whole forest, and IFW is the inundated forest width corresponding to H along selected section. From Eqs. 8 and 16, minimum regeneration flood level (H_r) can be calculated from:

$$\frac{\mathrm{d\,IFW}}{\mathrm{d}H}\Big|_{H=H_r} = \frac{\mathrm{IFW}_m}{H_m - H_0}. \tag{17}$$

Where IFW_m is the maximum forest width along selected section.

If the IFW–H curve cannot be expressed as simple analytical functions, minimum regeneration level can also be estimated directly from Eq. 9, where the water index is the water level (H), and evaluation function is:

$$\min\ d(H) = 1 + \frac{H - H_0}{H_{\max} - H_0} - \frac{\mathrm{IFW}(H)}{\mathrm{IFW}_{\max}}. \tag{18}$$

Therefore, the inundated forest width method defines minimum regeneration flow for floodplain forest from the flow at the breakpoint of the inundated forest width–water level curve, where the curve slope equals to the ratio of maximum inundated forest width to maximum water depth (Shang and Mao, 2010). This minimum regeneration flow considers the balance between flood to inundate the forest and flow diverted for human uses, and can provide appropriate overbank floods for the regeneration of floodplain forest. Compared with other methods for regeneration flow, the inundated forest width method requires less data and is easy to use.

2.4 Lake surface area method

In lakes, lake surface area or lake bed area provide possible habitat for lake ecosystems. Taking lake surface area (S) and storage (V) as the habitat and water indices, respectively, model 1 can be expressed (Shang, 2013) as:

$$\begin{cases}\min\ Z_1 = V, \\ \max Z_2 = S(V), \\ \text{s.t.}\ \ 0 \leqslant V \leqslant Vm.\end{cases} \tag{19}$$

Where V_m is the maximum lake storage. From Eqs. 8 and 19, minimum ecological lake level can be calculated from:

$$\frac{\mathrm{d}S}{\mathrm{d}V}\Big|_{V=V_e} = \frac{S_m}{V_m}. \tag{20}$$

Where V_e is minimum ecological lake storage, and Q_m is the maximum lake surface area. Then minimum ecological lake level corresponding to V_e can be determined from lake level–storage curve.

If the V–S curve cannot be expressed as simple analytical functions, minimum ecological lake level can also be estimated directly from Eq. 9, where the water index is the lake storage (V), and evaluation function is:

$$\min\ d(V) = 1 + V / V_{\max} - S(V) / S_{\max}. \tag{21}$$

Therefore, the lake surface area method defines minimum ecological lake storage as the lake storage at the breakpoint of the lake surface area–storage curve, where the curve slope equals to the ratio of maximum lake surface area to maximum lake storage. This method can also be applied to wetland.

3 Applications of methods deduced from the general model

Methods deduced from the general model was used in two representative rivers and a lake in northern Xinjiang of China. The typical arid plain area of northern Xinjiang is characterized by little precipitation and strong potential evaporation rate. Agricultural and industrial water uses in the plain area rely heavily on river runoff originated from mountain regions. With the rapid increase of agricultural and industrial water uses in recent years, river flow decreased significantly, which has resulted in severe ecological issues in some rivers and related lakes. For protecting the ecosystems dependent on river flow, minimum ecological flow for the Ertix River, minimum regeneration flow for floodplain forest along the Kaxgar River and minimum ecological lake level for the Ebinur Lake were determined using corresponding methods in Table 1.

3.1 Minimum ecological flow for the Ertix River

The Ertix River is the second largest river in Xinjiang. For meeting the increasing water demand for agriculture and industry, several reservoirs have been built in its upstream to regulate river flow. The annual mean flow downstream the reservoirs is about 105 m^3/s. A major branch with an annual mean flow of 135 m^3/s, the Burqin River, flows into the main stream 210 km downstream the reservoir (Li, 1999). Flow regime from the reservoir to the confluence of the Burqin River and main stream will change significantly due to water abstraction from reservoirs and the main stream (Fig. 2).

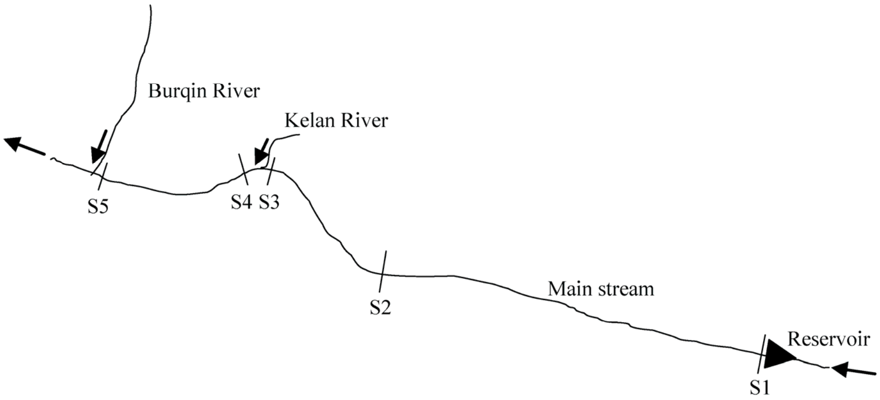

Fig. 2 Sketch of the studied river reach and controlling sections (S1 to S5)

For protecting the river ecosystem in this river reach, minimum ecological flows during the fish breeding period and non-breeding period were determined using multi-objective PHABSIM method (Hao and Shang, 2008) and wetted perimeter method (Shang, 2008), respectively. Five controlling sections, S1 to S5, were selected in the studied river reach (Fig. 2), and the channel geometry and bed slope of each section were surveyed (Shang, 2008).

In the non-breeding period, the wetted perimeter method was used, with the wetted perimeter and discharge at different water levels estimated from the channel geometry and the Manning equation (Shang, 2008). As an example, Figs. 3a and b show the channel geometry at section S4 and the relative wetted perimeter (p)–discharge (q) curve. The relationship between p and q can be expressed as $p=q^{0.478}$, with a correlation coefficient of $R^2=0.996$. From Eq. 11, minimum ecological flow at section S4 can be estimated to be 24% of the annual mean flow, or 25.2 m^3/s. Minimum ecological flow at other sections can be similarly estimated. The results for all five sections are from 19% to 24% of the annual mean flow. Their average value, 21% of the annual mean flow (22 m^3/s), was recommended as minimum ecological flow (Shang, 2008). Following the standard of Tennant (1976), this flow can offer fair habitat conditions during non-breeding periods. At this recommended minimum ecological flow, the average water depth varies from 0.47 to 0.90 m, and average water flow velocity from 0.47 to 0.79 m/s, (Shang, 2008), which are both in the good to optimum range for aquatic organisms by Tennant (1976).

For the fish breeding period, taimen (*Hucho taimen* Pallas) was selected as the indicator species in habitat simulation. Considering habitat suitability indices of flow velocity and water depth, weighted usable areas (WUA) of controlling sections at different discharge (Q) can be calculated (Hao and Shang, 2008). The WUA–Q curve of section S4 shown in Fig. 3c peaks at $Q_p=74$ m^3/s and $WUA_p=41$ m^2. Using the multi-objective physical habitat simulation method, minimum ecological flow can be estimated to be 63 m^3/s (Hao and Shang, 2008). For all sections used, minimum ecological flow ranged from 63 to 112 m^3/s, and the average value of 83 m^3/s was recommended as minimum ecological flow in the fish breeding period (Hao and Shang, 2008). The recommended ecological flow is about 79% of the annual mean flow, which is in the optimal range of ecological flow following the standard of the Tennant (1976) method.

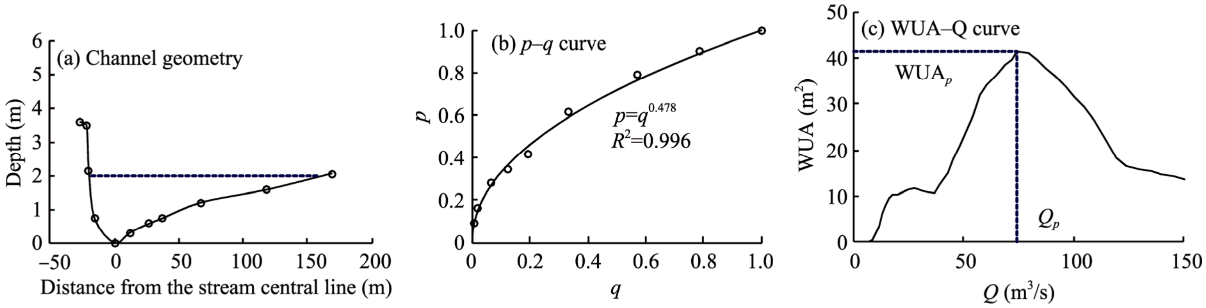

Fig. 3 Channel geometry and relationships of p–q and WUA–Q for section S4

By integrating the results of the multi-objective physical habitat simulation method for fish breeding period (83 m^3/s) and wetted perimeter method for the other seasons (22 m^3/s), the monthly ecological flow requirement can be obtained (Fig. 4). This ecological flow process can provide essential protection for river ecosystems, and is the base for water resources allocation considering both economical and ecological water uses.

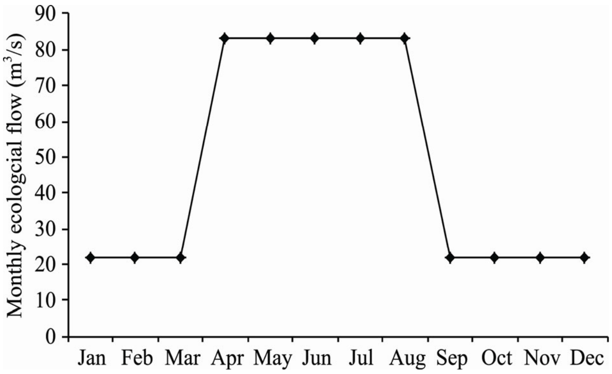

Fig. 4 Monthly ecological flow for the study reach of Ertix River

3.2 Minimum regeneration flow for floodplain forest of the Kaxgar River

The studied floodplain forest grows along the midstream floodplain of the Kaxgar River, the second largest branch of the Ili River in northern Xinjiang. The area of the floodplain forest is about 45.5 km^2. The constructive species of the floodplain forest is the dense-leaf poplar (*Populus talassica* Kom.). The seed dispersal and seedling emergence of the dense-leaf poplar are closely related with flooding. However, flood flow reduced significantly due to regulation of upstream reservoirs, which may threaten the regeneration of the midstream floodplain forests. Therefore, it is urgent to determine minimum flood flow for the regeneration of floodplain forest.

For determining minimum regeneration flow, topography, forest distribution, historical flood stage and discharge-stage relationship at seven representative sections (S1 to S7) were surveyed by the local Hydrology and Water Resources Survey Bureau from August 2006 to July 2007 (Shang and Mao, 2010). Figure 5a shows the topography and forest distribution along section S7. Forest width at this section is 1132 m, the widest among the seven sections. Using the surveyed data, inundated forest width at different flood levels can be estimated (Fig. 5b), which was then used to determine minimum regeneration flood level at section S7 based on Eq. 18. The result is 15.36 m, and the corresponding minimum regeneration flow is 346 m^3/s (Shang and Mao, 2010). At this flow, 98% of the forest along this section can be inundated. For all seven sections, minimum regeneration flow was estimated to be from 306 to 393 m^3/s (Shang and Mao, 2010), and their maximum (393 m^3/s) was recommended as minimum regeneration flow for the midstream forest. At this flood flow, about 80% of the floodplain forests can be inundated. The recommended flood flow can be used in the reservoir regulation to protect the floodplain forest.

3.3 Minimum ecological lake level for the Ebinur Lake

With a drainage area of 5.06×10^4 km^2, the Ebinur Lake is the largest saltwater lake in Xinjiang. It is an endorheic lake mainly recharged by Bortala, Jing and Kuntun rivers. From the 1950s to 1970s, the lake surface area shrank rapidly from about 1,200 to

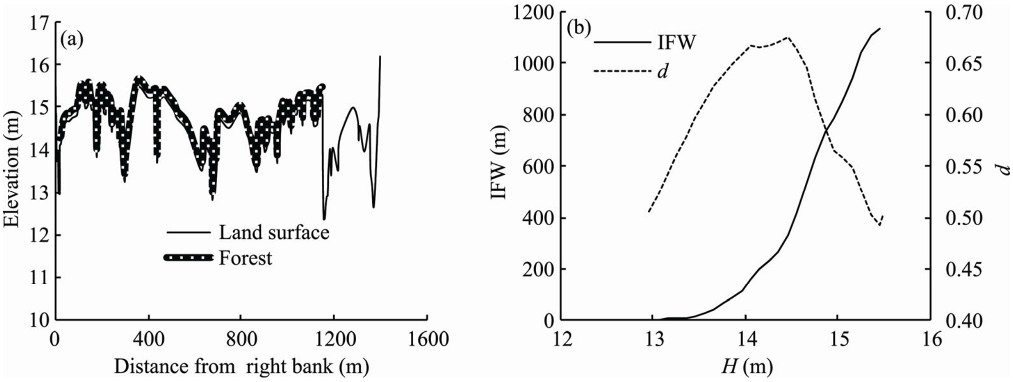

Fig. 5 Calculation of minimum regeneration flood level for section S7. (a), topography and forest distribution; (b), inundated forest width (IFW)–water level (*H*) curve and *d*(*H*) in Eq. 18.

500 km^2 due to decreasing water inflow and strong evaporation. The lake level remained lower during the 1980s, and fluctuated with climate since the 1990s (Jia et al., 2006). The lake shrinkage has led to severe ecological and environmental disasters, such as ecosystem degradation, desertification, and sandstorms (Liu et al., 2011). For protecting the ecosystems and environments in the Ebinur Lake Basin, water from a neighboring river will be diverted to the Ebinur Lake Basin, according to official plans. Determination of minimum ecological water level for the Ebinur Lake is the base of water resources planning for the ecology and environment protection projects in the Ebinur Lake Basin.

The lake storage (*V*)–area (*S*) curve of the Ebinur Lake (Liu et al., 2008) cannot be expressed as simple functions (Fig. 6a). Therefore, evaluation function in Eq. 21 was calculated and shown in Fig. 6b, then minimum ecological lake level was determined numerically with Eq. 9. The calculated minimum ecological lake water storage for the Ebinur Lake is 8.06×10^8 m^3, and the corresponding lake surface area and water level are 571 km^2 and 191.2 m, respectively (Shang, 2013). This minimum ecological lake level is very close to the integrated results of three other methods (Liu et al., 2008). At this level, 24% of the maximum lake storage provides 54% of the maximum lake surface area.

The above determined minimum ecological lake level and area provide essential habitat for lake ecosystems. Besides, water area required for the environment protection (such as wind erosion control (Bao et al., 2006)) can also be determined. A rational lake surface area can then be determined considering both ecological and environmental requirements for lake surface area, and can be used to calculate the required water inflow to the lake to compensate lake evaporation and seepage losses.

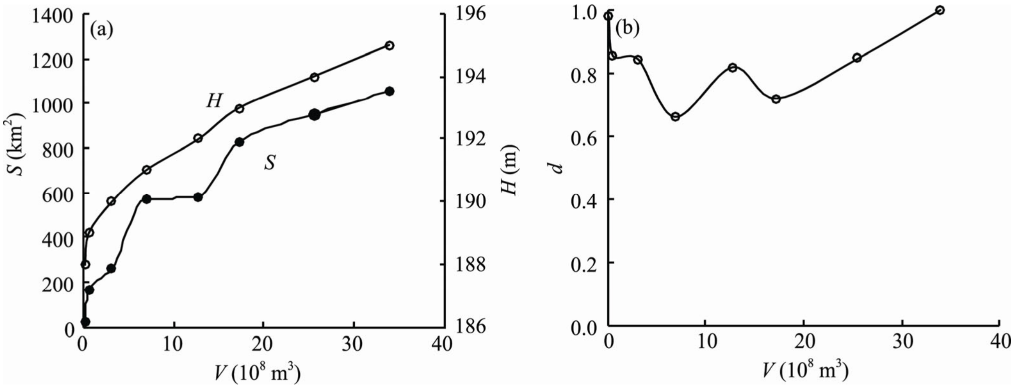

Fig. 6 Relationship between water level (*H*), surface area (*S*) and storage (*V*) and evaluation function (*d*) in Eq. 21 for the Ebinur Lake. (a), *H*–*S*–*V* relationship (Liu et al., 2008); (b), *d*–*V*.

4 Conclusions

Considering the trade-off between water uses by human and ecosystems, a general multi-objective programming model was proposed to determine minimum ecological flow or water level for inland water bodies. Using the weighted sum method for multi-objective optimization, minimum ecological flow or water level can be determined from the point where the marginal benefit equals to the average benefit, which is similar to the slope method to determine minimum ecological flow from the wetted perimeter–discharge curve. However, the general multi-objective programming model is superior to the slope method in its physical meaning and calculation method. This model provides a general analysis framework for ecological water uses of different inland water bodies.

The general model can be used to define minimum ecological flow or water level by choosing appropriate water and habitat indices. Several previously developed flow or water level assessment methods are found to be special cases of the general model, includeing the wetted perimeter method and the multi-objective physical habitat simulation method for ecological river flow, the inundated forest width method for regeneration flow of floodplain forests and the lake surface area method for ecological lake level.

Methods deduced from the general model were used in two representative rivers and a lake in northern Xinjiang of China. For the studied reach of the Ertix River, minimum ecological flow was determined to be 83 m^3/s during fish breeding season and 22 m^3/s for the other seasons. For the midstream floodplain forest along the Kaxgar River, the recommended minimum regeneration flow was calculated to be 393 m^3/s. For the Ebinur Lake, minimum ecological lake level was estimated to be 191.2 m. These results illustrated the versatility of the general model, and can provide references for water resources planning and ecosystem protection in the studied rivers and lake.

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