An ecological hydraulic radius approach to estimate the instream ecological water requirement*

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Abstract This essay defines the concepts of ecological flow velocity as well as ecological hydraulic radius (EHR) and proposes an ecological hydraulic radius approach (EHRA) which considers both the watercourse information (including hydraulic radius, roughness coefficient and hydraulic gradient) and the required stream velocity necessary for maintenance of certain ecological functions all together. The key parameter of EHRA is to fix the watercourse cross-sectional flow area corresponding to EHR, by which the relation between parabola shaped cross-sectional flow area and hydraulic radius is deduced. The EHRA not only meets the requirement of flow velocity for adequate fish spawning migration, but also is applicable to the ecological flows in regard with other ecological issues (such as the calculation of the instream flow requirements for transporting sediment and for pollution self-purification, etc.). This essay has illuminated the computational process taking the estimation of ecological water requirement of Zhuba Hydrologyical Station watercourse in Niqu branch of the Yalong River as an example. Additionally, we compare EHRA with Tennant approach. The result shows that the Zhuba Hydrological Station ecological water requirement calculated by EHRA lies between the minimum and favorable ecological water requirement calculated by the Tennant approach. This is due to the fact that the ecological flow velocity (such as the fish spawning migration flow velocity) was taken into consideration, producing results applicable to the practical situation.

Keywords: **ecological flow, flow velocity, cross-sectional flow area, ecological hydraulic radius (HER), instream ecological water requirement.**

More and more attention has been paid to the ecological (environmental) water requirement with global climatic changes, the gradual deterioration of eco-environment as well as the increasing water resources shortage. We also realize that the only way to protect the living environment and to make the water resources be sustainably utilized is to harmonize the relationship among production, life and ecology. Hence the study on ecological (environmental) water requirement has stepped into a flourishing period. Till now, the theory on ecological water requirement is still at the establishment stage, and in some documentation it is also called environmental water utilization or ecological and environmental water utilization. As yet, there is no exact definition[1].

The main purpose to study ecological (environment) water requirement is to actualize the harmony between human society and nature, to avoid human life and production from occupying the ecosystem water requirement and to implement the optimized allocation of water resources in a river basin, and then to provide scientific bases for the realization of sustainable development of ecosystem in the basin. Generally, the basin ecological water requirement is divided into instream and outstream uses for further study, and this essay mainly focuses on the study of instream ecological water requirement.

1 Estimation approaches for instream ecological water requirement

Currently the approaches to calculate the instream ecological water requirement are mainly classified into the following four types.

(1) Hydrology approach: This approach fixes the minimum flow standard to protect river flow right. It is an off-site style approach, which deduces the recommended value of river flow based on the historical data of the flow rather than the on-site sur-

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veyed data. It mainly includes the Tennant approach (or Montana approach)[2], 7Q10 approach[3] and Texas approach[4]. The advantages of hydrology approach are the simple calculation, easy handling and low demand of the data. However, this approach has oversimplified the practical situation of the river and has not considered biological parameter and its interactions directly[5]. At the same time, a river is also influenced by the climate and man-made pollution etc. Thus, the practical situation of river ecological water requirement is not fully reflected. The hydrology approach is only applicable for low priority stream segment or as a rough inspection for other approaches.

(2) Hydraulics approach: With wetted perimeter approach[6,7] and R2-CROSS approach[8] as its examples, this approach determines river flow requirement based on hydraulic parameter (such as breadth, depth, flow velocity, wetted perimeter, etc.). The required hydraulic parameter can be obtained from actual measurement or from the Manning formula calculation. The advantage of this approach is that only simple field survey is required, the detailed data on species-habitat relationship is not necessary, so the data is easy to obtain. Hydraulics approach cannot reflect the seasonal variations of ecological flows, so it is unavailable to confirm the flow rate of seasonal stream. However, the hydraulics approach can provide a hydraulics basis for other approaches, which allow its use in conjunction with other approaches[9].

(3) Habitat approach: With IFIM approach[10,11] as its typical example, this approach needs to study the fixed hydraulic condition and relevant fish habitat parameter of hydrologic series. The advantage of this approach is that it could combine the biological information with river flow data. However, the emphasis of traditional IFIM approach is on the target species rather than the river ecosystem as a whole. Thus, the results from the IFIM approach are not applicable to the whole river management planning[12]. The quantitative biological information is difficult to obtain, which limits usage of this approach[13].

(4) Holistic approach: With the BBM (Building Block Methodology) as its typical representation, this approach has obtained a relatively extensive application in South Africa[12,14,15]. The BBM approach focuses on impact analysis of flow variation on river ecology and environment, necessitating year-round flow magnitude changes and the corresponding river ecosystem observation. For this approach, the definition for different flow is very important and the whole process needs the participation of multidisciplinary groups including an aquatic ecologist, a hydraulician, etc. It is comparatively complex and challenging deploy.

Chinese scholars have made an extensive study on refined cleansing water required for diluting contamination[16—18], the sediment transport water requirement, the minimum instream water requirement[19] to prevent seawater encroachment and the ecological water requirement of surface evaporation[20], and they have proposed some relevant calculation approaches. Since most studies on river ecological water requirement in China are based on hydrologic data and water quality data, they are lopsided on macroscopic scale and the calculation approaches are not perfect yet.

To a given river, the ideal ecological water requirement calculation approach shall be able to quantify all the parameters and could reflect the interaction among the parameters. So far, such approach does not exist. All the approaches are established on a certain specific river or region, therefore, we must make a careful evaluation when applying any existing approach. Similarity of natural environment and biology plays a very important role for successful application of the approach. Though the sensibility having similar geologic condition and basin area towards low water of two adjacent catchments may differ greatly[21], abundant data source support is another requirement for the success of the study.

Based on the above questions, this essay submits the EHRA to estimate instream ecological water requirement taking full advantage of aquatic biological information (fish spawning migration flow velocity) and watercourse information (including water level, flow velocity, roughness coefficient, etc.).

2 EHRA to estimate instream ecological water requirement

2.1 Proposal and definition of relevant concepts

2.1.1 Ecological flow velocity

The instream current flow velocity[22] refers to the displacement distance of water particle in unit time (m/s). The ecological flow velocity submitted in this essay ($v_{ecology}$) refers to the minimum stream flow velocity to maintain certain ecological targets, namely to let the watercourse ecosystem keep its elementary ecological functions. The ecological targets include: ① flow velocity demand of aquatic biology and fish, such as the flow velocity of fish spawning migration, and flow velocity necessary for the fish to live on its habitat; ② flow velocity to keep balance between erosion and sedimentation for watercourse sediment transportation; ③ self-purification flow velocity to prevent the watercourse from pollution; ④ if the river flows to the sea, the flow velocity is needed to keep a certain amount of water running into the sea for ecologic equilibrium.

2.1.2 EHR

As an important parameter in hydraulics, the hydraulic radius (R) refers to the ratio between watercourse cross-sectional flow area and its wetted perimeter. The EHR in this essay refers to the hydraulic radius corresponding to ecological flow velocity and it is represented by $R_{ecology}$.

2.2 Assumed preconditions

EHRA and its proposal are mainly aiming at the ecological flow of a certain watercourse cross-section of a natural channel, which is a comparatively macroscopic physical variable, leading to two assumed preconditions: the first one is that the fluid state of natural channel belongs to the uniform flow of an open channel; the second is that the flow velocity adopts the average discharge of watercourse cross-section, in order to eliminate the impact of different velocity distribution to watercourse wetted perimeter[23,24].

2.3 The rationale

Based on the above two assumptions and the relational concepts, the rationale for submitting EHRA to estimate instream ecological water requirement will be listed in the following essay.

According to the open channel uniform stream formulae[25], the relationship among hydraulic radius R, average flow velocity of cross-section $\bar{v}$, hydraulic gradient J and roughness coefficient n can be obtained:

$$R = n^{3/2}\bar{v}^{3/2}J^{-3/4}, \quad (1)$$

where the roughness coefficient (n) and the hydraulic gradient (J) are watercourse hydraulics parameter (namely watercourse information).

If the average flow velocity of cross-section is endued with biological meaning, i. e., the aforementioned ecological flow velocity as the flow velocity of fish migrating for propagation $v_{ecology}$ is treated as the average flow velocity of cross-section, the hydraulic radius possesses the ecological meaning (namely the EHR) $R_{ecology}$, and then we can calculate the flow of cross-section that satisfies the ecological water requirement for the maintenance of a certain ecological function of the river, such as the fish spawning migration.

2.4 EHRA and ecological flow determination

Taking the calculation of ecological water requirement that meets the requirement of aquatic biology and fish spawning migration as an example, the basic process to calculate watercourse ecological water requirement using EHRA is introduced.

Firstly, determine the flow velocity $v_{ecology}$ that meets the requirement of aquatic biology (according to the living habit and breeding season of the fish as well as the river scale, it is generally 0.4—2.5 m/s[25—27]). Utilizing n, J to figure out the ecological hydraulic radius $R_{ecology}$ of watercourse across-section and then using $R_{ecology}$ to calculate the cross-sectional flow area A, we can obtain the relationship between A and R and calculate the ecological water requirement ($Q_{ecology}$) of a certain watercourse cross-section in certain time through the flow calculated by $Q = n^{-1}R^{2/3}AJ^{1/2}$, namely the ecological flow containing aquatic biology and watercourse cross-section information, then determine the migration period ($T_{ecology}$) and calculate the ecological flow and runoff.

2.5 Relationship between different A and R

From the aforementioned calculation to estimate ecological water requirement by EHRA, it can be found out that $v_{ecology}$ (the aquatic biological required flow velocity, such as fish migrating, etc.) could be used to calculate $R_{ecology}$ of a certain watercourse cross-section. How to deduce A through $R_{ecology}$ becomes the key point to deduce the ecological flow of this watercourse cross-section. The following essay will use several different geometric shaped watercourse cross-sections to analyze the relationship between A and R.

2.5.1 Regular geometric watercourse cross sections

The shapes of manual structured watercourse cross sections mainly include circle shape (conduit), culvert shape, trapezia shape, V shape, etc. They can refer to professional documentations[28,29] on "Hydraulics" for relationship among all the channel cross-sectional flow areas, wetted perimeter and hydraulic radius, which will not be explained in this essay.

2.5.2 Cross-section of natural watercourse

The cross-section of natural watercourse usually does not have the same regular shape as the manual structured watercourses. The surveyed cross sections of the hydrologic stations at Yalong River as well as branches of Dadu River are shown in Fig. 1.

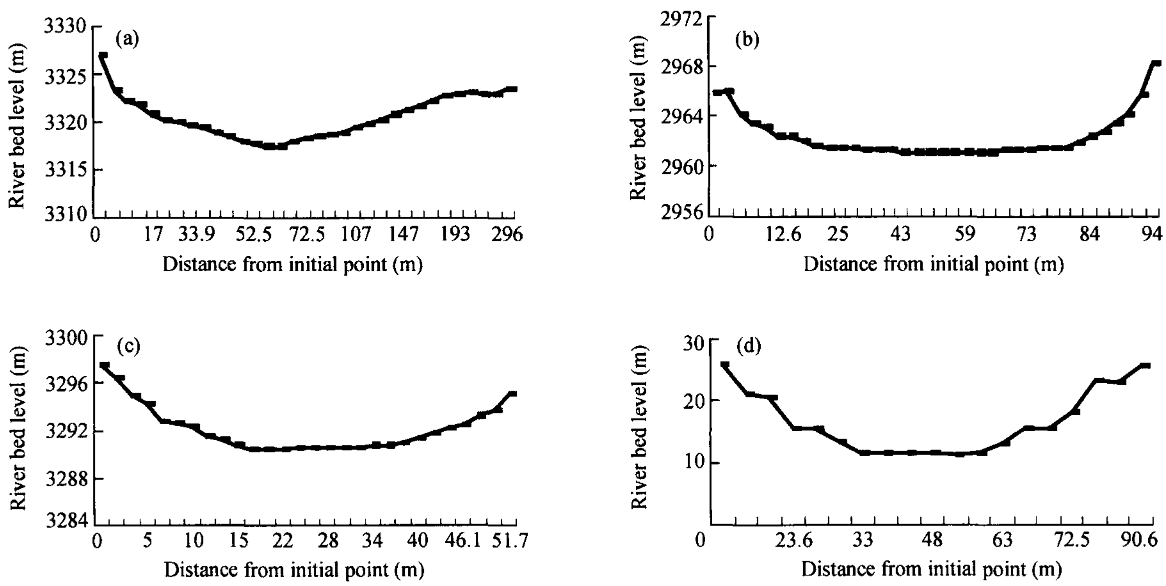

Fig. 1. The surveyed hydrological station cross-section of natural watercourse. (a) Ganzi Station at Yalong River (1970); (b) Daofu Station at Xianshui River (1970); (c) Zhuba Station at Niqu River (1980); (d) Zumuzu Station at Zumuzu River (1980).

It is observed from Fig. 1 that the water-carrying section of cross-section of natural watercourse usually presents parabola shape; moreover, the authors have investigated more than 80 valleys and discovered that most cross-sections of natural watercourse present parabola shape. Consequently, most cross-sections of natural watercourse could be generalized as parabola shape. The following essay will focus on the relationship between parabola shaped discharge area and hydraulic radius.

2.5.3 Parabola shaped watercourse cross-section

Cross-section of natural watercourse can be generalized as parabola as has been mentioned before. (Fig. 2)

From Fig. 2 we can see that the water breadth is

$$B = b_1 h^{\delta} \quad \text{or} \quad B = 2\alpha h^{\delta}, \qquad (2)$$

here h is the water depth, B is the water breadth corresponding to h, b_1 is water breadth when the water depth is $h_1 = 1$ m, α is the diffusion coefficient of the cross-section, which is obviously a half of water breadth when the water depth is h_1, namely $b_1 = 2\alpha$. Taking $\delta \approx 1/2$, which is obtained by the fieldwork, we may reach the following conclusion: $B = b_1 h^{1/2}$ or $B = 2\alpha h^{1/2}$.

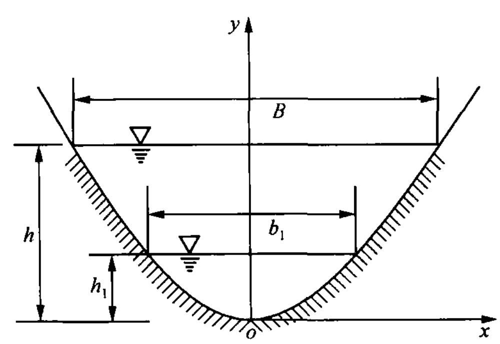

Fig. 2. Sketch for parabola shaped watercourse cross-section.

According to the coordinate system, it is easy to obtain: $x = \frac{b_1}{2} y^{1/2}$, namely $y = \frac{4x^2}{b_1^2}$. Obviously, cross-sectional flow area $A = 2\int_0^y x \mathrm{d}y$, when $y = h$, $A = \frac{2}{3} Bh$. From Fig. 2, wetted perimeter P is

$$P = 2\int_0^x \sqrt{1 + \frac{64x^2}{b_1^4}}\,dx. \quad (3)$$

Wetted perimeter P after integral calculus is

$$P = 2h^{1/2}\sqrt{h + \frac{b_1^2}{16}} + 0.125b_1^2 \ln \frac{4h^{1/2} + 4\sqrt{h + \frac{b_1^2}{16}}}{b_1}. \quad (4)$$

The aforementioned formula is about the relationship between P and h, when the parameter of parabola shaped cross-section is b_1. Obviously, we could calculate the P based on h and twofold section diffusion coefficient b_1. According to a large amount of checking calculation, if the water breadth is $b_1 =$ 3—50 m, water depth is within $h = 1$—4 m range, the calculation of P could be reduced to

$$P = (b_1 + 2)h^{1/2}. \quad (5)$$

The inaccuracy of Eq. (5) shortcut calculation is around 11.4%. According to hydraulic radius $R = \frac{A}{P}$, we could obtain the hydraulic radius of parabola shaped cross-section as

$$R = \frac{Bh}{3h^{1/2}\sqrt{h + \frac{b_1^2}{16}} + 0.1875b_1^2 \ln \frac{4h^{1/2} + 4\sqrt{h + \frac{b_1^2}{16}}}{b_1}}. \quad (6)$$

2.6 Characteristic of the EHRA

The usage of the approach proposed in this essay is to determine R_{ecology} corresponding to v_{ecology} through Manning formula[29] and then estimate ecological water requirement to meet certain ecological objects using the relationship between Q and R. By doing this, we could avoid determining the critical point at the relation curve between P and Q by the wetted perimeter approach[6,7]. It is obvious that the EHRA proposed in this paper to estimate instream ecological water requirement is the integration of hydrology (including the information on cross-section, flow, water level, etc.) and hydraulics (Manning formula). The following essay will take hydrologic stations in the water transferring region of the west line scheme planned by the South-North Water Transfer Project[30,31] as an example to illuminate the application process of the EHRA.

3 Application example

The following case analysis over the computational process of using EHRA is to estimate instream ecological water requirement. Being the only hydrologic station in water transfer river Niqu River, Zhuba Station locates at 100°41′E, 31°26′N. The Zhuba Station, founded in 1959, has a catchment area of 6860 km^2 and has survey data started from May 1960 (data on water level, flow, cross-section, etc.).

3.1 Selection of basic data

The basic parameters (including the calculation of A, P as well as others) are necessary for applying EHRA to calculate the instream ecological water requirement. Consequently, only a fixed number of years possessing data on surveyed cross-section information, flow Q, water level Z are applicable for using this approach to calculate instream ecological water requirement. In this case, the 15 years data of Zhuba Station from 1972 to 1987 (excluding 1982 for lacking of actual surveyed cross-section information) are chosen to calculate the instream ecological water requirement of Zhuba Station each year, and the chosen data includes hydrologic data of actual surveyed cross-section information, mean monthly water level, monthly maximum water level, monthly lowest water level, mean monthly discharge, monthly maximum discharge, monthly minimum discharge, etc. This essay will take 1980 as an example to illuminate the process of applying EHRA to estimate the instream ecological water requirement.

3.2 Calculation process

3.2.1 Calculate EHR

According to the above-mentioned calculation procedures, we will first determine v_{ecology} which will satisfy the life and habitation requirement of the instream aquatic biology. According to the fieldwork and bibliographic information[25—27], the fishes in this river are primarily *Schizotorax* (*Racoma*), *Nemachelus*, *and Euchiloglantis kishinouyei* Kimura. Furthermore, the Niqu River belongs to a third-order branch[30,31] of Yalong River, v_{ecology} is 0.6 m/s. The watercourse roughness coefficient n is chosen as 0.031 and watercourse hydraulic gradient J is taken as 4/1000. The R_{ecology} of watercourse cross-section can be figured out as $R_{\text{ecology}} = n^{3/2}\bar{v}_{\text{ecology}}^{3/2}J^{-3/4} =$ 0.9 m.

3.2.2 Determine the relationship between Q and R

Utilizing actual surveyed cross-section information (actual surveyed cross-section of Niqu Zhuba Station in 1980 at Fig. 2), and water level data, we could calculate the hydraulic radius of watercourse cross-section under different water level conditions (see Fig. 3).

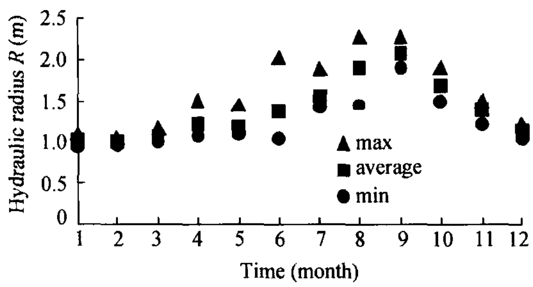

Fig. 3. Hydraulic radius of watercourse cross-section Station of Niqu (1980).

According to the flow series (see Fig. 4) and aforementioned calculated hydraulic radius, we can calculate the relationship between Q and R (see Fig. 5).

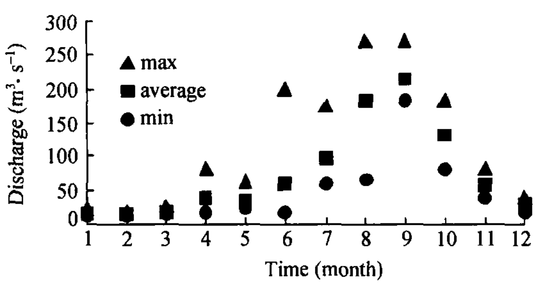

Fig. 4. Flow in Zhuba in Zhuba Station of Niqu (1980).

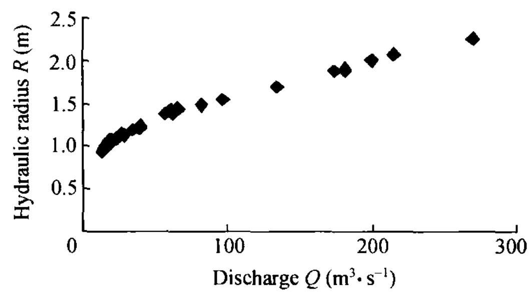

Fig. 5. Relationship between Q and R of Zhuba Hydrologic Station (1980).

Utilizing the power function to proceed matching, we can calculate the functional relationship between Q and R, i.e. $Q = 16.774R^{3.6331}$, and correlation coefficient is 0.99.

3.2.3 Calculate ecological water requirement

According to the calculated $R_{ecology} = 0.9$ m, and $Q = 16.774R^{3.6331}$, we can get the ecological required water flow of Zhuba Station in 1980 $Q_{ecology} = 16.774 \times 0.9^{3.6331} = 11.44$ m^3/s.

Utilizing the EHRA which is used for calculating the instream ecological water requirement mentioned in the above essay, we calculated the yearly ecological water requirement of Niqu Zhuba Station from 1972 to 1987 that may satisfy the living and habitation requirement of aquatic biology (see Table 1).

Table 1. The percentage of ecological flow occupying annual mean discharge in Zhuba Station

Year	Average annual flow (m^3·s^{-1})	Ecological hydraulic radius approach		Tennant approach	
		Ecological flow (m^3·s^{-1})	Ecological flow/ annual mean flow (%)	Ecological flow (m^3·s^{-1})	Ecological flow/ annual mean flow (%)
1972	57.8	13.43	23.2	11.30—17.05	19.6—29.5
1973	43.5	12.48	28.7	7.57—11.91	17.4—27.4
1974	64.8	14.27	22.0	10.99—17.45	17.0—26.9
1975	68.5	13.96	20.4	12.82—19.63	18.7—28.7
1976	69.6	13.46	19.3	11.96—18.89	17.2—27.1
1977	54.4	12.80	23.5	10.36—15.77	19.0—29.0
1978	46.4	11.71	25.2	7.48—12.11	16.1—26.1
1979	78.1	12.14	15.5	12.06—19.82	15.4—25.4
1980	75.6	11.44	15.1	10.77—18.30	14.2—24.2
1981	66.1	11.03	16.7	11.37—17.96	17.2—27.2
1983	54.5	11.70	21.5	10.13—15.55	18.6—28.5
1984	44.4	12.13	27.3	9.09—13.50	20.5—30.4
1985	77.4	12.18	15.7	13.52—21.22	17.5—27.4
1986	39.8	8.82	22.2	6.52—10.50	16.4—26.4
1987	54.4	14.76	27.1	9.53—14.93	17.5—27.5

3.3 Discussion and analysis

To verify whether the calculation of EHRA confirms with the practical situation, we adopt Tennant approach[32] to calculate the instream ecological water requirement of Zhuba Station synchronous with the time period of what EHRA has calculated.

According to the Tennant approach computing standard[32], the instream minimum ecological water requirement was calculated. During the general-purpose water usage period (from August to April of the next year), it takes 10% of the average monthly discharge for years as instream minimum ecological water requirement. During the fish spawning and rearing period (from May to July), it takes 30% of the average monthly discharge for years as instream minimum ecological water requirement. The instream favorable ecological water requirement was also calculated. During the general-purpose water usage period (from August to April of the next year), it takes 20% of the average monthly discharge for years as instream favorable ecological water requirement. During the fish spawning and rearing period (from May to July), it takes 40% of the average monthly discharge for years as instream favorable ecological water requirement.

From Table 1, basically the yearly instream ecological water requirement of Zhuba Station (1972—1987) calculated by EHRA lies between the minimum and favorable amounts of ecological water requirement set by Tennant approach, among which the ecological water requirement in 1973 calculated by EHRA is 0.57 m^3/s bigger than the favorable ecological water requirement calculated by Tennant approach; while the ecological water requirements of 1981 and 1985 are 0.34 m^3/s and 1.34 m^3/s, respectively, smaller than the minimum ecological water requirement calculated by Tennant approach. Focusing primarily on the living habit of the local aquatic creature and the climate features, the computing standard of Tennant approach in this essay is corresponding to the local river ecological and environmental condition. In summary, the result of applying EHRA to calculate instream ecological water requirement has been verified by Tennant approach, while its quantitative estimates is more object than Tennant approach and it avoids the artificial setting of the computing standard of Tennant approach.

4 Conclusion

This paper has proposed the concepts of v_{ecology} and R_{ecology} and provided a new instrument for the EHRA, which was used for estimation of instream ecological water requirement. Based on the characteristics of river ecological water requirement and the requirement of fixed parameter, the EHRA, which has considered the watercourse information (including hydraulic radius, roughness coefficient and hydraulic gradient) and the required flow velocity necessary for the maintenance of river ecological function, has been proposed. The cross-sectional shape of natural river course has been generalized as parabola. Through deduction of the relationship between cross-sectional flow areas of parabola shaped watercourse and hydraulic radius, the method for applying EHRA to calculate ecological water requirement suitable for the natural watercourse cross-section is proposed. The instream ecological water requirement during a certain period of time of the river course can be determined by checking Q from the relation curve between Q and R at the fixed R_{ecology}.

We have used the newly proposed EHRA to carry out the estimation of 15 years annual ecological flow of Zhuba Station at Niqu Branch of Yalong River from 1972 to 1987 (excluding 1982). The results show that the Zhuba Station ecological flow calculated by EHRA lies between the minimum and favorable ecological water requirement set by Tennant approach. The main reason is that it has considered the requirement of fish towards the flow velocity, so the result is corresponding to the practical situation of the planned Western Line of the South-to-north Water Transfer region. EHRA is the integration of hydrology (including the information on cross-section, flow, water level, etc.) and hydraulics (Manning formula), so it avoids the uncertainty of wetted perimeter approach caused by defining the critical point[33].

The new approach proposed is not only applicable for the analysis of flow velocity suitable for aquatic systems such as fish habitat, but also available to determine the water flow velocity of sediment transport water requirement and refined cleansing water required for diluting contamination, which is the extrusive characteristic of the EHRA.

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