A review of environmental flow assessment: methodologies and application in the Qianhe River

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Abstract. Environmental flow is of great significance for maintenance of ecological services in the riverine ecosystem. The paper reviews present methodologies for environmental flow assessment on the basis of three classifications, including the Hydrological Index Methodologies, the Hydraulic Rating Methodologies and the Habitat Simulation Methodologies. Both advantages and disadvantages of each classification are fully analysed, as well as applicable conditions. Moreover, representative methods of different classifications are applied to prescribe environmental flow in the Qianhe River of north China with consideration of hydrological series, hydraulic characteristics and habitat suitability of targeted species. The results of environment flow by the Montana Method, Wetted Perimeter Method and Physical Habitat Simulation System are 1.23 m³/s, 2.07 m³/s and 0.52 m³/s for the Qianyang section in middle reach of the Qianhe River. In view of seasonal variation of the Qianhe River, the paper recommends 1.23 m³/s as the minimum runoff in the dry season and 2.07 m³/s in the wet season. For further improvement of environmental flow assessment, studies of quantitative correspondence relationship between each component of instream flow and its ecological functions of riverine ecosystem, and the development of Holistic Methodologies by combination of various methodologies and multi-disciplinary information have great potential.

1. Introduction

In recent years, rapid socio-economic development and accompanying intensive interruption of the local water cycle have brought about severe ecological environmental problems in many places. The protection and restoration of regional ecological environments draw more and more attention, and environmental flow assessment comes to a focus of study both in China and abroad. Generally, the ecological environment system consists of rivers, lakes, wetlands, forests and so on. The paper focuses on the environmental flow of riverine ecosystem, by investigating and summarizing different ways to work out how much water a river needs to maintain its ecological functions.

Environmental flow, the quantity and corresponding processes of instream flow for preset target of ecological functions in the context of specific hydrological and ecological conditions, serves as the most fundamental element in riverine ecosystem for its balances of heat, sediment, salinity and water. The environmental flow assessment requires multidisciplinary study and integrated application of hydrology, hydraulics, river geomorphology, environmental science, biology, and so on. Flow regime, altered by socio-economic water use and dam constructions in many rivers, is believed to be the key
point of environmental flow as the master variable of fluvial geomorphology and aquatic community evolution, as well as mass and energy exchanging between streamway and floodplain area [1-2], and advanced hydraulic models provide powerful tools for numeric simulation of hydrological processes in regional water cycle [3].

Current methodologies of environmental flow assessment could be grouped into three categories, including Hydrological Index Methodologies, Hydraulic Rating Methodologies and Habitat Simulation Methodologies. Different methods of environmental flow assessment should be adopted in water resources management of given basins according to data collection, technical skills and research budgets. The paper completes environmental flow assessment of Qianhe River in China on the basis of application and comparison of different methodologies.

2. Methodologies
Hydrological Index Methodologies, which generally assume that riverine ecosystem goes well under natural status, simply set some percentage of simulated or monitor runoff as necessary eco-environment water for the studied river. Hydraulic Rating Methodologies take selected hydraulic indexes as reasonable representation of integrated functions in the riverine ecosystem, so corresponding runoff in accordance with appropriate hydraulic indexes needs to be satisfied. Habitat Simulation Methodologies focus on the specific requirement of species of concern in the riverine ecosystem and evaluate environmental flow by establishing a quantitative relationship between biological suitability of certain species and hydrological and hydraulic factors.

2.1. Hydrological Index Methodologies
The basis of Hydrological Index Methodologies is historical runoff series. Environmental flow assessment of the studied river is carried out by selected characteristic parameters of hydrological data and proper ratio. The historical hydrological runoff of a specific river section, either simulated or monitored data, is the only necessary input data, which means widely applicable capacity and very few calculations. Since lacking of clear mechanism linkage on hydrological variation and ecological response, Hydrological Index Methodologies are adopted only for rivers with lower priority or very rough approximations in river planning and management. Several common methods of this classification include Montana Method, Range of Variability Approach, etc.

2.1.1. Montana Method. Montana Method, also known as Tennant Method named after its presenter, proposed by American scientist Don Tennant in 1976 and first applied in the middle and western parts of the United States [4], has been widely used in many places in the world since the early stages of environmental flow assessment. Minimum environmental flow of the river section concerned is converted on the basis of annual average natural runoff by different ratios according to wet season and dry season, varying from 10% to 200%. The advantage of the Montana Method is its simplicity, but it ignores the daily or seasonal variation characteristics of a runoff data series. In some cases, recommended minimum environmental flow is even larger than natural instream runoff, especially in a dry season. Hence, it’s not suitable for seasonal rivers and other rivers with apparent temporal fluctuation of runoff. The method has been improved by ecologists and hydrologists, who set more detailed options of ratios according to a requirement of key protected targets in different stages [5]. Environmental flow assessment by the Montana Method needs a natural runoff series of more than 30 years by numerical simulations or restored data based on observations.

2.1.2. Range of Variability Approach. Range of Variability Approach, or RVA for short, deriving from aquatic ecology theory concerning the critical value of hydrological variability, is a method for environmental flow assessment and eco-hydrological variation evaluation on the basis of Indicators of Hydrologic Alteration (IHA for short) index system [6-7]. The IHA index system consists of five classifications of runoff characteristics to represent ecologically related hydrological processes, including: scale, timing, frequency, duration and rates of change [8]. In general, each hydrologic indicator values between one standard deviation from the mean, or range of values variation between 25% and 75% (or 33% and 67%) frequency according to natural runoff series, are considered to be
acceptable for conservation of local biological diversity, following the principle of Intermediate
Disturbance Hypothesis [9]. The comparisons between hydraulic indicators of a natural runoff series
before intensive disturbance and those of natural-artificial water cycle [10] are carried out to evaluate
the variation of hydrological characteristics and corresponding impacts on the riverine ecosystem at
different stages. RVA just provides possible integrated impacts on the riverine ecosystem by flow
alteration, instead of detailed responses of hydro-ecological factors and processes.

2.2. Hydraulic Rating Methodologies
Hydraulic Rating Methodologies believe that aquatic habitat availability is closely related with certain
hydraulic indexes, such as: river width, average depth, flow velocity, wetted perimeter and hydraulic
radius. Correlative curves between runoff and selected hydraulic indexes are obtained from long-term
data series of a hydrologic monitoring system or a hydraulic computation on the basis of theoretical
formulae. The turning points or specific characteristic values of studied rivers are regarded as
environmental flow for the local riverine ecosystem. Although river channel characteristics,
transsection shapes and longitudinal slope for instance, are considered by Hydraulic Rating
Methodologies, direct and well-defined effects of river runoff on specific ecosystem functions and
seasonal variations are still not reflected. The representative method of this classification is Wetted
Perimeter Method.

The Wetted Perimeter Method [11] evaluates environmental flow on the basis of one-to-one
correspondence between wetted perimeter of river transection and runoff. The roughness of river
channel, transection shapes and riverbed gradient, obtained from field surveys or hydrological
yearbook, are necessary parameters. The wetted perimeter is the line length of the wetted part of
selected river cross section under water level. According to the relation curve of wetted perimeter and
corresponding runoff, the inflection point is considered to be representative for the basic riverine
ecological state. The ecological functions of the riverine ecosystem for both of instream living beings
and riparian regions would be significantly damaged if stream flow falls below critical runoff. There
are various ways to recognize the critical point on wetted perimeter-runoff curve. Maximum curvature
principle, and slope coefficient of 1, is the most popular method. When the Wetted Perimeter Method
is used for environmental flow assessment, fitting functions are often introduced. Fitting functions of
wetted perimeter-runoff curves vary with different transection shapes. Power function is suitable for
fitting of triangle, U shaped or parabola transections, while exponential function is used for
rectangular or trapezoid transections.

2.3. Habitat Simulation Methodologies
Habitat Simulation Methodologies, the most complex way to compute environmental flow, set up
experiential or physical relationships between the stream flow and the habitat requirement of aquatic
organisms in a certain living period [12]. Hydraulic data and biological information are collectively
considered to establish the direct and indirect response of available habitat for protected species on the
depth and velocity of river flow, channel slope and section configuration of river channel, roughness
and overburden of riverbed, as well as water temperature and water quality. Integrated applications of
Habitat Simulation Methodologies need both quantitative correspondence of steam flow and habitat
suitability, and explicit relationship between habitat suitability and species individual amount.
Hydraulic model, habitat simulation model and hydrological series analysis model are essential
components to support comprehensive environmental flow assessment. Moreover, not only single
recommended environmental flow, but also dynamic habitat improvement or degradation for targeted
species with environmental flow variation, are realized by Habitat Simulation Methodologies to
provide meaningful decision-making reference for a river administrator, as long as protected species
are decided. Since the relationship curve between habitat suitability and hydraulic indexes are
empirical at present, it’s still not transplantable in different rivers, even for similar species. A large
number of surveys and experiments are required to establish the explicit relationship curve. In addition,
complicated technique and high budget prevent the wide application of the Habitat Simulation
Methodologies. The most representative one of this classification is Instream Flow Incremental
Methodology.
Instream Flow Incremental Methodology (IFIM for short), involving hydrodynamic, water quality, hydrological and ecological models, is a theoretical system of environmental flow assessment to provide alternative analysis and decision support in integrated planning and scientific management of river basins [13]. Generally, fish are selected as targeted species by IFIM as the top of the food chain in freshwater biomes. Macrohabitat and microhabitat are all considered by IFIM to demonstrate available habitat area in different periods of fish life, such as the spawning period, the nursing period and the mature period. Factors of macrohabitat include river morphology, water quality, temperature, turbidity and transparency, while those of microhabitat include water depth, velocity, riverbed base and surface coverage. One of the representative methods of microhabitat simulation is Physical Habitat Simulation System (PHABSIM for short) developed by US Fish and Wildlife Service [14]. River channel characteristics and relationship curve of habitat suitability index for specific fish are input into the hydraulic model in microhabitat simulation, and responsive value of weighted usable area (short for WUA) in accordance with instream runoff are calculated. The inflection point of WUA-runoff curve is considered as minimum environmental flow, and the peak point represents the best status of the targeted species. While in macrohabitat simulation, SSTEMP model and QUAL2E model are popularly used concerning water temperature, dissolved oxygen, ammonia nitrogen and other harmful materials.

3. Study area
Qianhe River, a tributary of the Weihe River in the Yellow River Basin in north China, originates from Shimiaoliang of Gansu province and flows from the northwest to the southeast. The length of Qianhe River is 129.6 km with the catchment area of 3493 km$^2$. The altitude of the upstream basin is between 1500m and 2000m, 1000m-1500m in the middle reach and below 1000m in the downstream basin. There are three reservoirs located at the main stream of the Qianhe River, Duanjiaxia reservoir, Fengjiashan reservoir and Wangjiaya reservoir from upstream to downstream, and one national aquatic germ plasm resources conservation zone along the middle and lower reach, as is shown in figure 1. The study of environmental flow of Qianhe River is essential for regional ecological environment conservation.

Qianyang hydrometric station, located in the middle reach of Qianhe River near the end of conservation zone, is selected as a representative section for environmental flow assessment. Data collections and preparations for environmental flow assessment of the Qianyang section are completed as following: (1) Data series of meteorological stations including precipitation, air temperature, humidity, wind velocity, and sunshine duration, underlying surface information including DEM, agrotype, land use and vegetation cover, water resources system networks including river network and diversion projects, water use and drainage data, as well as monthly hydrological series of instream flow of Qianyang section from 1973 to 2010, are collected and processed for the establishment and validation of the hydraulic model to simulate natural runoff of study area [15]. (2) River channel characteristics including transection shape, riverbed roughness and longitudinal slope are collected from hydrologic yearbooks of the Yellow River Basin in China for hydraulic indexes computation of selected section. The transection shape of Qianyang section is shown in figure 2.

![Figure 1. Overview of Qianhe River basin.](image1)

![Figure 2. Transection shape of Qianyang section.](image2)
4. Results and discussions

4.1. Environmental flow assessment by Hydrological Index Methodologies
For natural runoff process simulation of the Qianhe River, distributed hydrological model WEP (Water and Energy transfer Processes) based on physical mechanism is adopted to analyze variation of runoff yield and convergence. The WEP model was developed on the basis of Physically-Based Spatially Distributed (PBSD) models and Soil Vegetation Atmosphere Transfer (SVAT) models. It is capable of hydrological processes simulation under changing environment. The model was encoded in Fortran Language. It’s suitable for both a personal computer and a giant server to run the model. The structure of the model consists of horizontal subdivisions of contour bands, intersecting small sub-watersheds and vertical composition of 9 layers. The modelling approaches and establishment of the WEP model are referred to in published papers and reports [3, 15, 16].

The comparison of simulated and measured average annual runoff in Qianyang section is shown in figure 3. The relative error of runoff simulation is 4.5%, and the Nash Efficiency Coefficient of yearly runoff simulation is 0.78, with monthly runoff simulation of 0.56, indicating a satisfactory accuracy. On this basis, monthly and annual natural runoff of Qianyang section are simulated. The average annual runoff of long series in Qianyang section is 12.28 m$^3$/s. According to the Montana Method, 10 percent of average annual runoff regarded as base flow is the minimum water requirement for the riverine ecosystem. Hence, the basic line of environmental flow for Qianyang section of the Qianhe River is 1.23 m$^3$/s by Hydrological Index Methodologies.

![Figure 3. Validation of runoff simulation in Qianyang section.](image)

4.2. Environmental flow assessment by Hydraulic Rating Methodologies
The paper collects hydraulic indexes of Qianyang section by field research and literature investigation, including river channel roughness, transection shape and longitudinal slope. The relationship of wetted perimeter and water depth is obtained according to the transection shape of Qianyang section. Fitting curve of wetted perimeter and runoff by power function is shown in Figure 4. To eliminate the influence of coordinate scale, relative values of each factor, derived from ratio of actual value and maximum value of overall series, are presented in the figure.

Runoff of Qianyang section is 2.07 m$^3$/s in accordance with slope coefficient of fitting curve as 1. The calculated runoff is supposed to be the critical point of the riverine ecosystem functions. Basic ecological services may be interrupted when instream flow falls below this value.

4.3. Environmental flow assessment by Habitat Simulation Methodologies
The weighted usable area (WUA) is a key factor of Habitat Simulation Methodologies to represent suitability of stream communities. The paper selects ephemeroptera benthos, one of the most common riverine benthos in Qianhe River, as an aquatic indicator species. Velocity and depth of instream flow are considered to be the key hydraulic indexes. The relationship curve between habitat suitability of ephemeroptera benthos and hydraulic indexes are referred to in former achievements [17]. Manning's
formula is adopted to demonstrate the correspondence relationship between WUA and runoff according to river channel roughness, transection shape and longitudinal slope of the Qianyang section. Variation of WUA with runoff of Qianyang section is shown in figure 5. As is shown in the figure, the value of WUA rises up with increasing instream flow at the beginning. The peak of curve represents the maximum usable habitat for ephemeroptera benthos, and corresponding runoff of the Qianyang section is 0.52 m$^3$/s. After that, the WUA falls down and becomes zero when the runoff is about 0.9 m$^3$/s.

Figure 4. Fitting curve of wetted perimeter and runoff of Qianyang section.  
Figure 5. Variation of WUA with runoff of Qianyang section.

5. Conclusions

There are three kinds of methodologies for environmental flow assessment: the Hydrological Index Methodologies, Hydraulic Rating Methodologies and Habitat Simulation Methodologies. The paper summarizes the advantages and disadvantages of different methodologies, as well as their applicable conditions. Generally, the Hydrological Index Methodologies are based on hydrological statistics without consideration of specific characteristics of different sections and rivers. The Hydraulic Rating Methodologies reflects the influence of river channel characteristics, but detailed correspondences of ecological functions and each component of environmental flow are not embodied. The Habitat Simulation Methodologies quantitatively presents the habitat suitability of targeted species by weighted usable area, but ignores other ecological services in integrated management of the river basin.

Besides, the applications of the representative methods of each classification are carried out in the Qianyang section of the Qianhe River in north China. The results of environment flow by the Hydrological Index Methodologies, Hydraulic Rating Methodologies and Habitat Simulation Methodologies are 1.23 m$^3$/s, 2.07 m$^3$/s and 0.52 m$^3$/s. It’s worth noting that the minimum result of 0.52 m$^3$/s by the Habitat Simulation Methodologies can just meet the requirement of the targeted species, ephemeroptera benthos. The maximum result of 2.07 m$^3$/s by the Hydraulic Rating Methodologies is regarded as the critical point of the instream flow for effective survival environment of the riverine ecosystem. The mediate result of 1.23 m$^3$/s by the Hydrological Index Methodologies represents the base flow of the Qianhe River for fundamental requirements of river continuum and self-purification. In view of seasonal variation of the Qianhe River, like most rivers in north China, the paper suggests that the base flow of 1.23 m$^3$/s is set to be the minimum runoff for a dry season while the critical flow of 2.07 m$^3$/s for a wet season.

The results of this study put forward a preliminary evaluation of environmental flow for the Qianhe River. There are still several key issues to be improved. The relationship curve between habitat suitability of targeted species and hydraulic indexes introduced from field studies of other places may not be precisely suitable for the studies river, and water temperature and overburden of the riverbed have not been taken into consideration yet. The combination of present methodologies, named as Holistic Methodologies [18], may bring significant improvement for environmental flow assessment. To make the environmental flow assessment more practical for the integrated ecological management of the Qianhe River, quantitative correspondence relationship between each component of instream
flow and ecological function is to be clarified, and discharge processes for different periods should be carried out.

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