利用流量延時曲線及集水區劃分技術探討最小在槽流量之研究

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摘要

台灣河川因季節之流況與流量差異甚大，常使水生生物面臨極大威脅，尤以人工水利設施，例如：水庫、防砂壩、攔河堰、取水工等，更是容易形成生死存亡之挑戰。旱季中的低流量，亦常導致野生生物利用河川廊道時最嚴重的困境；更甚者，低流量將致使水質進一步惡化。本研究利用頭前溪爲研究區位，利用數種常用的在槽流量評估方法，以數年前完工的隆恩堰爲重點，並以毛蟹爲指標生物及其上溯季節爲評估對象。在本研究中，最小在槽流量可由流量延時曲線、生物資料及隆恩堰操作規則等共同評估，並以現有水文站竹林橋之水文資料進行分析。同時採用美國陸軍工程師團水文工程中心所發展之地理資訊系統中集水區自動劃分軟體HEC-GeoHMS，作爲集水區萃取之計算。在獲得任一斷面中，經水利、水文、生物等評準建立之生態基流量後，可以進一步利用地理資訊系統推導至相同集水區上、下游任一非水文站之斷面。數值高程模型在本計算中提供有效便捷之集水區自動劃分依據，最小在槽流量之空間分佈並可藉此取得及建立。

（**關鍵字**：最小在槽流量、集水區劃分、數值高程模型、流量延時曲線、指標生物）

Using Flow Duration Curve and Watershed Delineation for Determining Minimum Instream Flow Requirement

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ABSTRACT

With the unique flow pattern and discharge variation during different seasons, the aquatic biological communities in Taiwan are struggled under nature and anthropogenic stresses. Especially, man-made hydraulic structures such as reservoirs, check dams, diversion works, and water intakes may result in big surviving challenge. The low flow rate in draught season can be the most critical reason for wildlife using river channel as the passage corridor. Furthermore, the instream water quality may be suffered and deteriorated by low discharge. This paper evaluated some popular

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instream flow methods on the Tou-Chen River watershed as a case study. In the Long-En-Yan water diversion filed investigation couple years ago, the *Eriocheir japonica* had been found and used as a bioindicator. In this study, the seasonal instream flow was determined by flow duration curves of the Chu-Lin gauge station, biological data, and diversion weir operation rules. In the meantime, the geographic information system software, HEC-GeoHMS developed by USACE, was employed to calculate the watershed delineation and other geological data. After the minimum instream flow suggestion made be hydraulic, hydrological or biological criteria at a certain river section, the requirement for downstream or upstream ungauged section can be established by geographic information system calculations. Digital elevation model was used to obtain the watershed delineation automatically in the computer program. The spatial distribution on instream flow requirement is easily derived in geographic information system.

(**Keywords** : minimum instream flow requirement, watershed delineation, digital elevation model, flow duration curve)

Introduction

Under the different conditions of instream discharge, the wildlife may struggle or face a seasonal environmental stress. How to maintain sufficient flow rate and habitat quality is a critical and vital challenge in so called bio-engineering methods. Minimum instream flow requirement in river channel is trying to protect the aquatic environment. Jowett (1997) indicated that organizations responsible for water resources management are becoming increasingly aware of their duties for environmental protection, creating an increasing interest in methods of assessing flow requirements for different instream uses. After the very important Proceedings of the Symposium and Specialty Conference on Instream Flows hold by American Fisheries Society (1976), the engineering fields and biological fields are still arguing this controversial topic. Although the debates of the instream flow requirement are much behind the international society, Taiwan also had a milestone conference supported by Water Resources Agency (2002a) intensively discussed on the minimum flow evaluation and regulations. However, the stream habitat is deeply influenced by hydrologic, geomorphologic, and biological activities. From any specific viewpoint may loss a complete perspective.

From the historical studies on the instream flow topics, these methodologies may be categorized into three major algorithms as (1) hydrologic evaluation (e.g. historical flow regime such as Tennant Method, 1976), (2) hydraulic evaluation (e.g. wetted perimeter breakpoint method such as Gippel and Stewardson, 1998) (3) habitat evaluation (e.g. integrated computer model such as Bovee, 1982). Above methods are explained in details as follows:

1. Hydrologic evaluation

For the easy application reasons, the

hydrologic evaluation methods are the most frequently applied algorithms. The typical calculation is called Montana Method/Tennant Method (Tennant, 1976). It was concluded on 11 streams in 3 states between 1964 and 1974. According to physical, chemical, and biological conditions, Tennant indicated that ten percent of the average flow is a minimum instantaneous flow recommended to sustain short-term survival habitat for most aquatic life forms. Thirty percent is recommended as a base flow to sustain good survival conditions. The criteria can be stated in Table 1.

Table 1. Instream flow requirement recommended by Tennant (after Tennant, 1976)

Description	Flow regimes (to average flow)	
	Draught season	Flood season
Flushing	200%	
Optimum	60~100%	
Outstanding	40%	60%
Excellent	30%	50%
Good	20%	40%
Fair or degrading	10%	30%
Poor or minimum	10%	10%
Severe degradation	<10%	

Tennant considered the average flow of a stream can be reacted as a composite manifestation of the watershed size, geomorphology, climate, vegetation, and land use. These phenomena were evidenced by biologists and hydrologists. From this viewpoint, the Tennant Method would be a good and quick method to determine instream flow requirement.

2. Hydraulic evaluation

Hydraulic evaluation is based on various parameters such as channel substrate, flow velocity, water stage, wetted perimeter, Froude number, sinuosity, and so on. Because these multiple factors may correlate to each other, they are more difficult to apply than hydrologic methods. The most concerned habitat patterns by the environmentalists are riffles because the shallow riffle reaches are the most responsive to reduced flow conditions (Reinfelds *et al.*, 2004). That is why Gordon *et al.* (1992) indicated that maintenance of suitable flow conditions across riffles will keep pool quality and running habitats. The most typical hydraulic evaluation method is looking for the breakpoint of relationship curve between discharge and wetted perimeter. Reiser *et al.* (1989) indicated that the wetted perimeter is the third commonly used method in North America.

Australian researchers (Reinfelds *et al.*, 2004) studied the perimeter breakpoint for minimum environmental flows using HEC-GeoRAS to deal the channel geometry calculations and HEC-RAS to simulate the hydraulic conditions. The solved wetted area-discharge curves were assessed using tangential breakpoint determination procedures described by Gippel and Stewardson (1998). The wetted area-discharge curves were found to be three-parameter power functions by the following equation:

$$y = c + aX^{b} \qquad (1)$$

The first derivatives of these functions were determined as follows:

$$dy/dx = baX^{b-1} \qquad (2)$$

Tangential breakpoints where proportionally equal reductions in discharge are accompanied by equal reductions in wetted area occur where $dy/dx = 1$.

3. Habitat evaluation

Jowett (1997) indicated that habitat methods are a natural extension of hydraulic methods. The difference between these tow evaluations are using biological references such as biological reactions or biological requirements rather than hydraulic parameters themselves only. There are many integrated habitat evaluation methods that can be found. The most frequently used method in North America is Instream Flow Incremental Methodology (IFIM) (Bovee *et al.*, 1998). The IFIM is grounded on ecological principles using the concepts proposed by Karr and associates (Karr *et al.*, 1986). Based on the index of biological integrity suggestions, the human-induced impacts to river systems may be concluded five major categories: flow regime, habitat structure, water quality, food source, and biotic interactions. The IFIM is integrated by these five models especially including the Physical Habitat Simulation System (PHABSIM) (Milhous *et al.*, 1989) to quantify hydraulic conditions and the micro-habitat simulations. The schematic diagram of the components and model linkage of IFIM is shown in Figure 1.

There are many integrated river habitat evaluation methods can be used other than IFIM. The UK environmental protection authorities designating River Habitat Survey (RHS) (Raven *et al.*, 1997) and Ohio State Environment Agency using Quantitative Habitat Evaluation Index (QHEI) (Ohio EPA, 1989) are typical examples. RHS is a standard method for capturing data on the physical habitat of rivers.

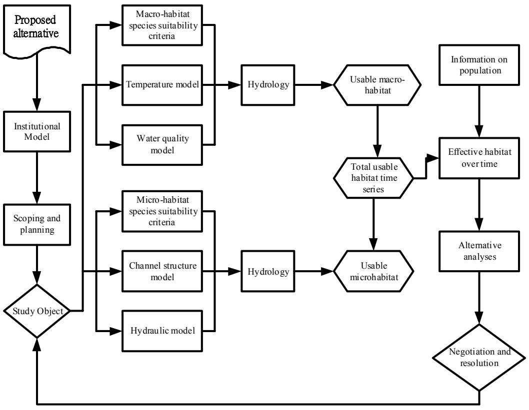


Figure 1. The conceptual flowchart of IFIM (after Bovee et al., 1998)

It has been applied in the United Kingdom and elsewhere. It is accepted as a standard method for assessing “hydromorphology” to support the European Water Framework Directive. Habitat Quality Assessment (HQA) (Raven *et al.*, 1998) is derived from RHS data and can be used to compare habitat quality on the River sites. The lower HQA scores of the river sites can be concluded that the habitats of these sites are in need of improvement.

Methods and Material

1. Study area

The study area, Chu-Lin gauge station

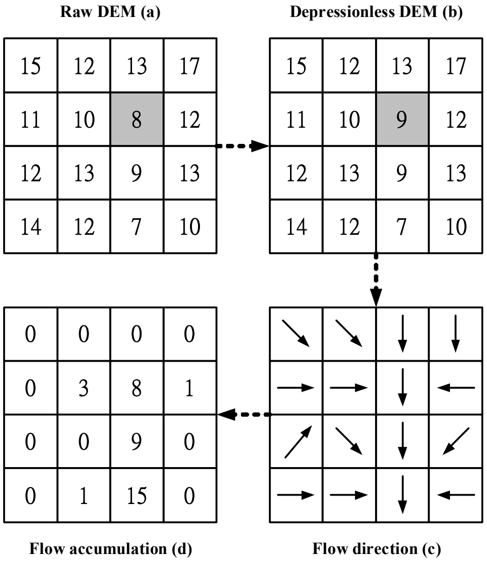
on the Touchen River watershed, is located at the downstream of the junction from two main tributaries Yu-Lo Stream and Sun-Pin Stream. This location is upstream to the Long-En-Yan diversion, the most important water intake for municipal water treatment facilities with a designed water supply rate for 6m^3/s. Field investigation from Taiwan's Water Resources Agency (2000) indicated that the Touchen River watershed can be divided into two flow regimes; one is natural environment with abundance original landscapes and forest lands, the other is disturbed by human intrusion and landuse. The Long-En-Yan diversion can be a breakpoint for the anthropogenic or natural domains separation. From the biological data, the most important discoveries on the records are: (1) *Zacco pachycephalus* was found unable to go upstream for the diversion work in June, (2) *Macrobrachium asperulum* was found as the major species among the migration aquatic life in July, and (3) *Eriocheir japonica* was found large quantities going upstream from August to September. With the shortest distance from the Long-En-Yan diversion, the Chu-Lin hydrologic station was used to simulate the flow. The coordinate for this station in UTM TWD67 is (258636, 2738037) with sub-watershed area 441.38 km^2, and it is located at the Chu-Lin Bridge. The discharge records can be checked from the hydrologic year books from 1980 to current stage.

2. Watershed delineation

Digital Elevation Models (DEMs) are the basic materials used for automated watershed delineation. The DEMs are arrays of elevation values. For its natural geographic properties, DEMs are normally presented in grid or raster format. A variety of methods have been developed to process raster DEMs automatically in order to delineate and measure the properties of drainage networks and river basins (Martz and Garbrecht, 1998). The geographic information system software, HEC-GeoHMS developed by USACE (2000), is employed to calculate the watershed delineation and other geological properties. It is based on the raster terrain analysis techniques. In the software developed by Olivera (2001), Jensen and Domingue's (1988) algorithms are used to calculate drainage networks using a map showing flow direction.

The typical processes can be illustrated as a 4x4 moving window shown in Figure 2. The original DEMs (Figure 2(a)) contain elevation value in each grid. Some DEMs have lowest points inside the matrix instead of border lines. In this situation, so-called depression will be a problem to arrange flow direction. The most frequently used techniques are depression filling shown in Figure 2(b). The flow direction map (Figure 2(c)) shows the direction in which a cell drains according to the steepest downhill slope from the cell. The models using the same techniques are termed single-direction or D-8 methods. After flow direction determined by connecting to its downstream cell, the flow contribution map can be derived using the flow accumulation for each cell shown in Figure 2(d). Flow accumulation map determines the number of upstream cells draining to a given cell. Upstream drainage area at a given grid can be calculated by multiplying the flow accumulation value with the cell area. Using flow accumulation numbers or upstream drainage areas, the stream definition can be obtained by user-defined threshold as cells belonging to the stream network.

By specifying the outlet point such as hydrological station or any point along the stream definition, the extracted terrain, flow direction, stream segments, and watershed for the study area will be created.



Raw DEM (a)

15	12	13	17
11	10	8	12
12	13	9	13
14	12	7	10

Depressionless DEM (b)

15	12	13	17
11	10	9	12
12	13	9	13
14	12	7	10

Flow direction (c)

↘	↘	↓	↓
→	→	↓	←
↗	↘	↓	↙
→	→	↓	←

Flow accumulation (d)

0	0	0	0
0	3	8	1
0	0	9	0
0	1	15	0

Figure 2. A typical 4x4 moving windows show DEM data and processes

3. Flow duration curve

The flow duration curve is a plot of discharge against the percent of time that the flow is equal to or exceeded. Some hydrologists also call it as discharge-frequency curve. In this study, the Weibull formula was employed to plot position. The probability P of an event equal to or exceeded is given by:

$$P = (\frac{m}{N+1})$$

(3)

where m is the order of magnitude, and N is the number of records. During the calculation, the discharge data are rearranged in a descending order. The percentage probability of the flow magnitude being equal to or exceeded is P_p, the equation can be written as:

$$P_p = (\frac{m}{N+1}) \times 100\%$$

(4)

The plot of the discharge Q against P_p is the flow duration. The ordinate Q_p at any percentage probability represents the flow magnitude that can be expected to be equaled or exceeded P_p% of time.

Ward and Robinson (2000) indicated that the flow duration curves with steep slope denote highly variable flows with a large quick flow component. Oppositely, mild sloping curves may relate to a large base flow portions. Especially, the lower end of the flow duration curves represents the perennial storage in the drainage basin. If a watershed with a flat or smooth lower end indicates abundant groundwater storage. Because the slope of the flow duration curve is useful measure of stream flow variability, the slope ratio can be further used to discuss watershed characteristics. Huang and Yang (2000) indicated that the flow duration curve is also used for flood control, hydropower potential, sediment transport, and drainage character studies of a basin. For the water quality protection purposes, the discharge for Q_{75} or Q_{90} in the flow duration curves can be defined as basic instream flow requirement. From the pollution viewpoint, the higher instream discharge provides better dilution and purification functions to pollutants. However, maintaining the instream flow rate still need consider the water resources allocation in the whole watershed especially with an urban downstream.

4. Bioindicator

Jowett (1997) explained the habitat is an encompassing term used to describe the physical surroundings of botany and fauna. The habitat evaluation methods consider the flow requirement based on specific biological requirements rather than the hydraulic parameters themselves. The most important thing is how to establish the habitat suitability criteria. Habitat suitability can be specified as seasonal requirements for the different biological species and their life stages. Scatena (2004) also pointed out that instream flow requirement should be using species specific needs and including ecology or habitat requirement of aquatic species in their instream flow determinations. In his investigation results, respondents indicated that fish, coastal or estuarine organisms, other organisms, freshwater shrimps, manatee, and crabs need the most consideration when determining instream flows. Based on the instream flow studies, the selected biological species and its life stage is the most critical factor in flow requirement considerations. This elected species for consideration is named bioindicator or target species.

In the study area, Water Resources Agency (2000b) used *Eriocheir japonica* to discuss the flow requirement. In the study report, *Eriocheir japonica* was observed with a going upstream season from July to September mostly concentrated in August. From the investigation results, *Eriocheir japonica* going upstream behavior is strongly related to flow rate shown in Figure3. Based on the field investigation, there will be no more *Eriocheir japonica* going upstream when the discharge is below 6.9 m^3/s. The suggested minimum flow rate is 7.4 m^3/s for *Eriocheir japonica* going upstream requirement in August.

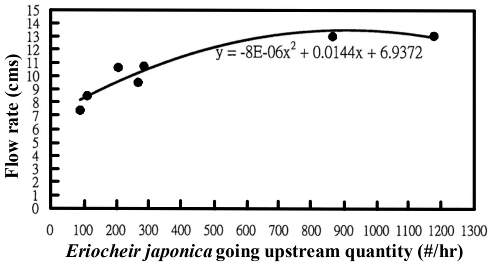


Figure 3. The relationship between Eriocheir japonica and flow rate (after Water Resources Agency (2000b))

However, the water resources engineers still have to face the conflict between industrial needs and biological requirements. In order to maintain a better aquatic life, a fish passage was built later in year 2003. An improved in-channel device was carried out to connect the passage gap caused by the Long-En-Yan diversion structure. Because

Eriocheir japonica is the target species, both sides of the fish way were built crawling slabs for going upstream auxiliary facilities shown in Figure 4.

Figure 4. The fish passage for aquatic life at the Long-En-Yan diversion (courtesy Water Resources Agency)

Results and Discussion

1. Watershed delineation

From the automated watershed delineation results, the given coordinates in UTM system were listed in Table 2. When the outlets along the stream networks were specified in the ArcView window, the upstream watershed can be automatically delineated by flow accumulation calculations (Figure 5). Obviously, the lower outlet obtains larger watershed area. The area ratio for watershed of Long-En-Yan water diversion over Chu-Lin Station is 1.092. Based on the watershed area contribution concepts, the calculated instream flow requirement at the Chu-Lin Station should multiply the ratio of 1.092 (calculated from Table 2) to obtain the real instream flow requirement of Long-En-Yan diversion. The obtained values can be further used as diversion operation suggestion.

Summary of watershed delineation specified by different outlets

Location	X (TWD67)	Y (TWD67)	Watershed area (ha)
Chu-Lin Station	258636	2738037	43829.9
Long-En-Yan Diversion	253119	2743216	47863.8
Nan-Liao Harbor	242794	2749682	53761.3

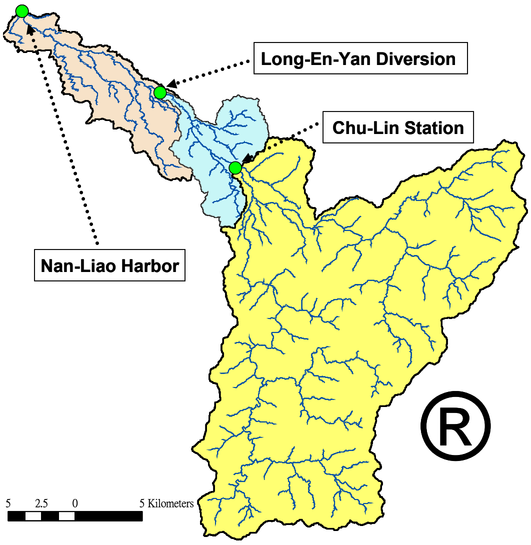


Figure 5. Watershed delineation results using HEC-GeoHMS

2. Flow duration curve

According to the flow duration analysis data from the Water Resources Management Research Laboratory website designed by Huang and Yang (2000), the average daily flow rate at the Chu-Lin Station is 22.54 m3/s from year 1980 to 2002. From duration curve analysis data, the discharge (Q_p, m^3/s) against the percentage probability of the flow magnitude being equal to or exceeded

Table 3. Summary of the daily flow rate being equal to or exceeded the percentage probability at the Chu-Lin Station (average Q=22.54 m3/s)

P_p=55	P_p=60	P_p=65	P_p=70	P_p=75
Q_p=8.57	Q_p=6.96	Q_p=5.55	Q_p=4.26	Q_p=3.46
P_p=80	P_p=85	P_p=90	P_p=95	P_p=100
Q_p=2.86	Q_p=2.18	Q_p=1.68	Q_p=0.88	Q_p=0.11

Table 4. Summary of the first ten-days in August flow rate being equal to or exceeded the percentage probability at the Chu-Lin Station (average Q =37.75 m3/s)

P_p=55	P_p=60	P_p=65	P_p=70	P_p=75
Q_p=24.34	Q_p=22.87	Q_p=21.06	Q_p=19.47	Q_p=*16.46*
P_p=80	P_p=85	P_p=90	P_p=95	P_p=100
Q_p=14.32	Q_p=9.55	Q_p=6.81	Q_p=2.54	Q_p=1.57

Table 5. Summary of the second ten-days in August flow rate being equal to or exceeded the percentage probability at the Chu-Lin Station (average Q =41.24 m3/s)

P_p=55	P_p=60	P_p=65	P_p=70	P_p=75
Q_p=25.72	Q_p=23.54	Q_p=20.30	Q_p=18.15	Q_p=17.57
P_p=80	P_p=85	P_p=90	P_p=95	P_p=100
Q_p=16.51	Q_p=14.93	Q_p=8.84	Q_p=3.72	Q_p=3.29

Table 6. Summary of the third ten-days in August flow rate being equal to or exceeded the percentage probability at the Chu-Lin Station (average Q =63.53 m3/s)

P_p=55	P_p=60	P_p=65	P_p=70	P_p=75
Q_p=33.22	Q_p=27.90	Q_p=24.66	Q_p=21.77	Q_p=*17.04*
P_p=80	P_p=85	P_p=90	P_p=95	P_p=100
Q_p=16.19	Q_p=14.37	Q_p=10.59	Q_p=7.61	Q_p=7.27

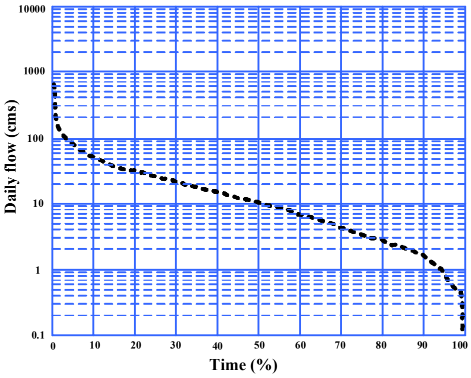


Figure 6. Daily flow duration curve at the Chu-Lin Station

(P_p, %) can be summarized in Table 3 and illustrated in Figure 6. The examples of the first ten-days, the second ten-days, and the third ten-days in August flow duration analysis results are also displayed in Table 4 to 6.

3. Discussion

Based on the above section results, the Chu-Lin hydrological station suggested minimum instream flow requirement can be determined by the Tennant's method (degrading level), flow duration curve (P_p=90%) and Water Resources Agency's (2000b) report. Flow duration curve P_p=90% is elected because it is nearest the values from Water Resources Agency's (2000b) report. The *Eriocheir japonica* in the report of Water Resources Agency (2002b) was selected as a bioindicator and the most critical time for going upstream is in August. In the study area, August is the flood seasons; the 30% average discharge should be used for the Tennant's method. The minimum instream flow requirement suggested at the Chu-Lin Station will be 22.54*0.3=6.76 (m^3/s) for the Tennant's method. Each ten-days P_{90} flow rate for the Chu-Lin Station flow duration curve will be 6.81, 8.84, and 10.59 (m^3/s) respectively.

Assuming this watershed area containing the constant contribution rate for the watershed discharge, the ratio of 1.092 should be used for the Long-En-Yan water diversion watershed. The suggested instream minimum flow rates for each ten-days in August by different methods are listed in the Table 7. The water diversion weir operation rules are obtained from Water Resources Agency (2000b).

Table 7. Instream flow requirement suggested by different methods for each ten-days in August at the Long-En-Yan diversion

Method Time	Tennant's	Flow duration	Operation rules	Bioindicator data
The first ten-days in August	7.38 (m^3/s)	7.44 (m^3/s)	3.90 (m^3/s)	7.40 (m^3/s)
The second ten-days in August	7.38 (m^3/s)	9.65 (m^3/s)	7.01 (m^3/s)	7.40 (m^3/s)
The third ten-days in August	7.38 (m^3/s)	11.56 (m^3/s)	6.41 (m^3/s)	7.40 (m^3/s)

Conclusions

In order to improve the water quality and quantity for the aquatic communities, it is better to reconsider the minimum instream flow requirement for different seasons and reset a proper flow rate according to biological activities. From the calculated results, the suggested minimum instream flow requirements determined by flow duration curve (P_p=90%) are higher than that by the Tennant's method. However, the current Long-En-Yan water diversion weir operation rules are not enough to maintain a degrading level of river environment. No matter from any viewpoint of each method used in this study, the operation rules need be further revised especially in August for the *Eriocheir japonica* going upstream season.

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