

# **ECOHYDRAULIC MODELING OF INSTREAM PHYSICAL HABITAT BY MODIFIED PHABSIM**

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## **ABSTRACT**

The Physical Habitat Simulation System (PHABSIM) is modified herein to investigate the variation of substrate composition and instream habitat with flowrate. The revised PHABSIM includes a sub-program performing substrate analysis under five schemes. *Sinogastromyzon puliensis* in Chou-Shui Creek of Taiwan is selected for the case study. The results indicate that the weighted usable area (WUA) corresponding to the specified substrate attribute is the highest, whereas the WUA based on the original substrate is the lowest. The WUA values corresponding to the above-critical bed material and the armor are similar. The maximum bedload size scheme is based on the selective transport condition representing a more realistic ecohydraulic modeling of the instream physical habitat.

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The Physical Habitat Simulation System (PHABSIM) is modified herein to investigate the variation of substrate composition and instream habitat with flowrate. The revised PHABSIM includes a sub-program performing substrate analysis under five schemes. *Sinogastromyzon puliensis* in Chou-Shui Creek of Taiwan is selected for the case study. The results indicate that the weighted usable area (WUA) corresponding to the specified substrate attribute is the highest, whereas the WUA based on the original substrate is the lowest. The WUA values corresponding to the above-critical bed material and the armor are similar. The maximum bedload size scheme is based on the selective transport condition representing a more realistic ecohydraulic modeling of the instream physical habitat.

## 1. INTRODUCTION

The Physical Habitat Simulation System (PHABSIM) was developed as a water resources management tool to assist in the establishment of instream flow requirements for supporting water control and allocation activities [1]. The NERC of U.S. Fish and Wildlife Service developed the IFIM conceptual framework and released in 1978 the first version of PHABSIM used for modeling instream habitat. This system was further expanded to perform hydraulic simulation and habitat analyses [2]. Despite certain limitations in PHABSIM [1], it has been widely recognized and become one of the most commonly used methods in North America. It has been also gaining acceptance in Europe [3].

The PHABSIM consists of two sub-systems, namely, hydraulic and habitat models. The former simulates the water surface levels and velocity distributions of the stream cross sections for each discharge of concern. These results are then incorporated with the habitat suitability curves specified for a particular species to estimate the usable habitat area corresponding to that flowrate. The habitat suitability curves concerned in PHABSIM include the preferences of the target species on flow velocity, depth, and channel properties. The criteria for flow velocity and depth reflect the assumption that lotic biota have their distribution and certain phases of their life cycles controlled by the hydraulic conditions within the water column [4]. Meanwhile, the physical properties of the channel, such as the substrate composition, cover, and vegetation also play important roles affecting the habitat of aquatic animal. A cross section is divided into a number of sub-areas (cells) for which the PHABSIM users assign the attributes of substrate, cover, and/or vegetation based on the field explorations, measurements, and auxiliary materials. The weighted usable area (WUA) in a stream reach is then evaluated by the following formula:

$$WUA = \sum_i [f(V_i, D_i, C_i) \cdot A_i] \quad (1)$$

where  $A_i$  is the stream area of the  $i$ th cell;  $f(V_i, D_i, C_i)$  is the combined suitability factor (CSF) for  $A_i$ , usually a product of the corresponding suitability weights for flow velocity, depth, and channel property is used [2].

In Eq. (1), the flow velocity and depth are the output results of the hydraulic model and both varying with discharge. The suitability weights corresponding to these results are accordingly adjusted with the flowrate. However, the physical properties of the channel remain unchanged once the attribute is specified. In other words, the variation of channel properties with flowrate is not realistically concerned in PHABSIM. For example, the bed shear stress induced by various flows can transport bedload particles of different sizes. Consequently, the dominant particle size of the stable substrate serving as potential habitat will be altered. The substrate suitability should be dynamically adjusted to reflect the change in particle size. It has been pointed out [1] that the variation of substrate status with flowrate should be considered for improving the physical habitat simulation. The aim of this study is to investigate the variation of substrate particle size with flowrate and evaluate its impact on instream physical habitat. To this end, PHABSIM is modified to include a sub-program that can perform substrate analysis under five different schemes.

## 2. METHODS

To investigate the variation of substrate with flowrate, one needs to evaluate the threshold particle size for incipient motion. It is hypothesized herein that particles with greater sizes than the threshold

cannot be mobilized by the given flow. Three types of threshold, namely, (1) critical particle size, (2) size of armor-layer particles, and (3) maximum size of bedload particles are adopted presently. They are described in the following.

## 2.1 Critical Particle Size

Iwagaki [5] developed a theory for sediment incipient motion and expressed the critical condition in an empirical form. His result, compatible with the widely used Shields' criterion, is expressed as

$$\left\{ \begin{array}{l} \tau^* = 0.05 \text{ for } R^* \geq 671 \\ \tau^* = 0.00849(R^*)^{3/11} \text{ for } 162.7 \leq R^* \leq 671 \\ \tau^* = 0.034 \text{ for } 54.2 \leq R^* \leq 162.7 \\ \tau^* = 0.195(R^*)^{-7/16} \text{ for } 2.14 \leq R^* \leq 54.2 \\ \tau^* = 0.14 \text{ for } R^* \leq 2.14 \end{array} \right. \quad (2)$$

where  $\tau^* = \tau_c / (\gamma_s - \gamma)d$ ,  $\tau_c$  = critical shear stress,  $\gamma$  and  $\gamma_s$  = specific weight of fluid and sediment, respectively,  $d$  = particle size;  $R^* = \sqrt{(\gamma_s / \gamma - 1)gd^3} / \nu$ ,  $g$  = gravitational acceleration,  $\nu$  = kinematic viscosity of fluid. Here  $\tau_c$  is replaced by the bed shear stress  $\tau_0$  ( $= \gamma DS$ ) to evaluate the corresponding critical size  $d_c$ , where  $D$  = flow depth,  $S$  = water surface slope.

## 2.2 Size Distribution of Armor-Layer Particles

Gessler [6] found that the probability for a sediment particle to stay is related to the ratio  $\tau_c / \tau_0$ . Given a particle size  $k$ , the corresponding critical shear stress  $\tau_c$  can be immediately determined by Eq. (2). The probability to stay can be expressed as the cumulative probability of the Gaussian distribution:

$$p(\xi) = \int_{-\infty}^{\xi} \frac{1}{\sqrt{2\pi}} \exp(-x^2 / 2) dx \quad (3)$$

where  $\xi = 1.754(\tau_c / \tau_0 - 1)$  is a function of  $k$ , hence  $p(\xi)$  can be alternatively written as  $p(k)$ . The size distribution of the armor-layer particles can be evaluated by

$$F_a(d) = \frac{\int_{d_{\min}}^d p(k) \cdot f_o(k) dk}{\int_{d_{\min}}^{d_{\max}} p(k) \cdot f_o(k) dk} \quad (4)$$

where  $F_a(d)$  = cumulative size distribution of the armor material;  $f_o(k)$  = size-distribution probability density function (pdf) of the original bed material;  $d_{\min}$  and  $d_{\max}$  are the minimum and maximum sizes of the bed material, respectively.

### 2.3 Maximum Size of Bedload Particles

Milhous [7] proposed a semi-empirical equation for the maximum size of the bedload particles:

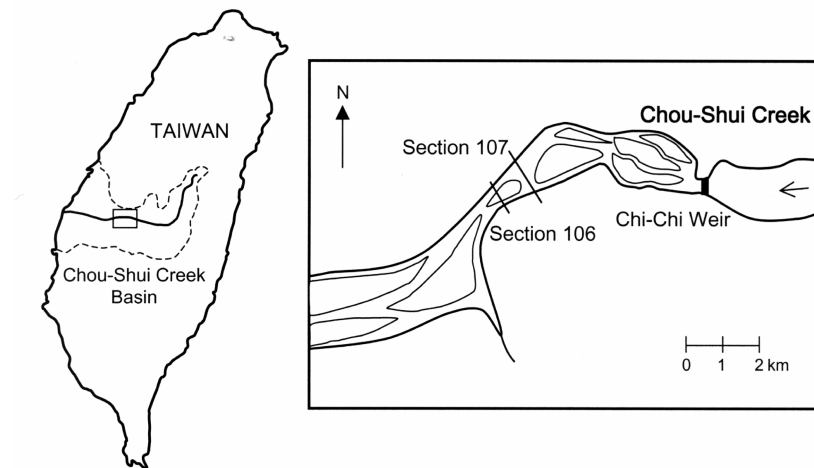
$$(d_{\max})_{bl} = (d_{50})_a \left[ \frac{RS}{0.018(\gamma_s / \gamma - 1)(d_{50})_a} \right]^{2.85} \quad (5)$$

where  $(d_{50})_a$  = median size of the armor material, which is determined by Eq. (4);  $R$  = hydraulic radius. He suggested Eq. (5) be used only when the median size of the armor is greater than the median size of the bedload, i.e., when the bedload particles move through the stable armor. Eq. (5) is thus appropriate for partial transport but not full transport of the bed material at higher flows.

## 3. CASE STUDY

### 3.1 Study Site

The study site is located in the midstream reach of Chou-Shui Creek, middle Taiwan (shown in Figure 1). Chou-Shui Creek, the largest river in Taiwan, drains a basin area of 3,155 km<sup>2</sup>. The study reach, between Sections 106 and 107, is 897 m in length with an average slope of 5/1000. The mid-channel gravel bars reveal the braided pattern of the study reach. Monthly mean flows derived from the 1941-1994 records of the Chi-Chi gauging station (5.4 km upstream of Section 107) indicate that the natural stream flows range from 40 to 270 m<sup>3</sup>/sec with a mean of 130 m<sup>3</sup>/sec. However, the majority of daily flows are within 40 and 100 m<sup>3</sup>/sec, hence the discharges between 30 and 150 m<sup>3</sup>/sec are used in the physical habitat simulations, for which the roughness coefficients of the cross sections are calibrated to best fit the reported flow stages.



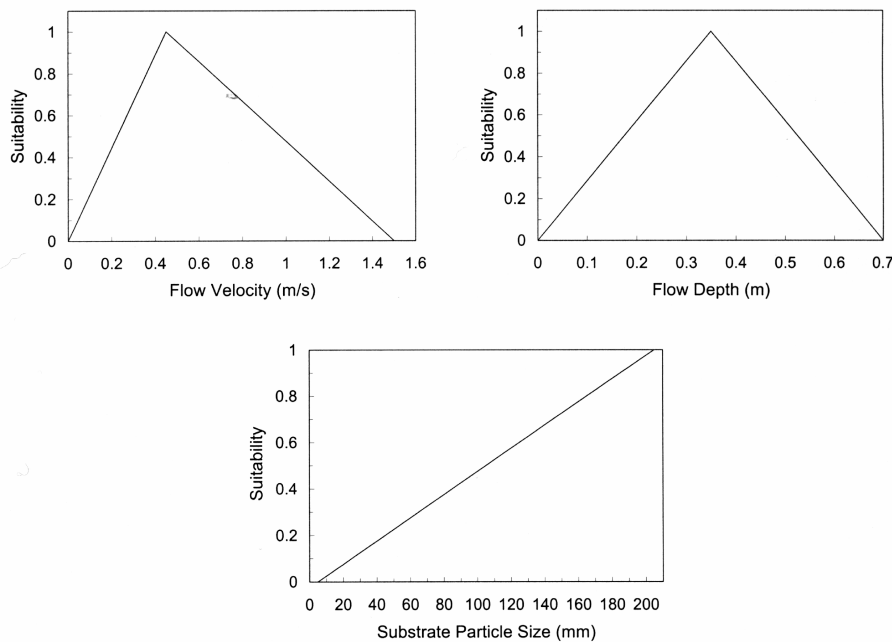
**Figure 1. Location Map of Chou-Shui Creek Basin and Study Reach**

It was proposed in 1984 that building a diversion weir to meet the expanded demand of water resources for multi-objective uses in the Chou-Shui Creek basin and its vicinity. The construction of the Chi-Chi diversion weir was initiated in 1993 and is to be completed in 2001. Fish passage facilities were also included in the hydraulic structure allowing the migration of local species. Flow diversion alters the downstream flow regime and thus the physical habitat of the instream biota. Assessment of the instream flow requirement in the downstream reach of Chi-Chi diversion weir is an essential task of ecological importance. The present study is concerned with the variation of

substrate status corresponding to different instream flow releases. Because the diversion weir reduces the sediment supplied to downstream, the flow strength and the composition of the existing bed material determine the grain sizes of the coarse surface layer developed in the downstream reach [8]. The original size distribution of the substrate prior to the construction of Chi-Chi weir can be approximated by a lognormal fit (with mean and standard deviation 38 and 89 mm, respectively) to the representative sizes of the bed material sampled at Section 106 in 1993 [9]. The pdf of the original size distribution,  $f_o(k)$ , is simply the differentiation of the lognormal distribution curve.

### 3.2 Target Species

Herein *Sinogastromyzon puliensis* is selected as the target species for habitat simulation because it is categorized as a Taiwanese endemic species claimed legislatively as one of the protected fish and wildlife. *Sinogastromyzon puliensis* has a flat-shaped body; it moves along the stones (gravel, cobble, boulder, or bedrock) and feeds on the stone-adherent algae and invertebrate. This species has been found in the downstream reach of Chi-Chi gauge station and its habitat criteria have been surveyed previously [10]. The suitability curves for flow velocity, depth, and substrate particle size are shown in Figure 2, which indicate that the favorable flow velocity and depth to this species are around 0.45 m/s and 0.35 m, respectively. The substrate suitability is represented by a curve that increases linearly in the range between 10 mm and 200 mm.



**Figure 2. Habitat Suitability Curves for Flow Velocity, Depth, and Substrate**

### 3.3 Schemes for Evaluating Substrate Suitability

Five different schemes are adopted herein to evaluate the values of substrate suitability corresponding to various classes of dominant grain size on the bed surface. These schemes either use a conventional method to specify substrate attribute or employ the threshold particle size to determine the nominal size of the stable substrate. They are described in the following.

#### 3.3.1 Scheme 1: Specified Substrate Attribute

This scheme specifies the substrate attribute based on the water surface level of the annual mean flow (130 m<sup>3</sup>/sec). The substrate attribute of each cell is specified as one of the following: (1) main channel; (2) stream bank; (3) mid-channel bar; and (4) floodplain. The values of suitability corresponding to these attributes are summarized in Table 1.

**Table 1. Suitability of Various Substrate Attributes**

| Substrate attribute | Suitability |
|---------------------|-------------|
| Main channel        | 1.0         |
| Stream bank         | 0.5         |
| Mid-channel bar     | 0.2         |
| Floodplain          | 0.1         |

### 3.3.2 Scheme 2: Nominal Size of Original Bed Material

This scheme uses the nominal particle size of the original bed material to evaluate the substrate suitability. The nominal size of the original bed material,  $d_o$ , can be calculated by

$$d_o = \int_{d_{\min}}^{d_{\max}} k \cdot f_o(k) dk \quad (6)$$

Definitions of the notations used herein can be found in Eq. (4).

### 3.3.3 Scheme 3: Nominal Size of Above-Critical Bed Material

Because the critical size  $d_c$  can be viewed as a threshold for incipient motion, the particles greater than  $d_c$  are assumed not to be mobilized by the given flow. These static particles form a stable surface layer that provides potential habitat for instream biota. Thus, the nominal size of the above-critical bed material is used to evaluate the corresponding substrate suitability. In doing so, the lower portion (for  $k \leq d_c$ ) of the original bed-material size distribution is discarded to seek the pdf of the above-critical bed material,  $f_{ac}(k)$ . Then the nominal size of these above-critical particles can be determined by replacing  $f_o(k)$  with  $f_{ac}(k)$  in Eq. (6) and integrating it from  $d_c$  to  $d_{\max}$ .

### 3.3.4 Scheme 4: Nominal Size of Armor Material

Armoring is typical in the downstream reach of a weir because of the reduced sediment supply [11]. The coarsened surface layer represents a different class of substrate for the instream habitat. Using the armor-layer size distribution determined from Eq. (4), it is possible for one to evaluate the nominal size of the armor material and the corresponding substrate suitability.

### 3.3.5 Scheme 5: Nominal Size of Non-transported Armor Material

When an armor layer is formed on the bed surface, the composition of the subsequent bedload can be finer grained than the existing armor material [12]. Given a flow and the size distribution of the armor associated with this flow, Eq. (5) can be used to estimate the maximum size of the bedload moving through the armor. It is assumed again that those armor particles coarser than  $(d_{\max})_{bl}$  are not to be transported by the given flow. The non-transported armor material provides a key element for the stable instream habitat. Similar to scheme 3, the lower portion (for  $k \leq (d_{\max})_{bl}$ ) of the armor-layer size distribution is removed to obtain the pdf of the immobile armor material,  $f_{sa}(k)$ . The nominal size of these non-transported armor particles can be determined by replacing  $f_o(k)$  with  $f_{sa}(k)$  in Eq. (6) and integrating it from  $(d_{\max})_{bl}$  to  $d_{\max}$ . Then, the nominal size of the stable armor material can be used to evaluate the corresponding substrate suitability.

## 4. RESULTS AND DISCUSSION

### 4.1 Variation of Substrate Particle Size with Flow

For schemes 1 and 2, the substrate status does not respond to the variation of flow because of the specified attribute and the fixed composition used. The nominal substrate grain size of scheme 2 is constantly 86 mm. However, for schemes 3-5, the nominal size of the stable substrate varies with the flowrate. As an illustration, the nominal particle sizes for the 12th cell of Section 106 are listed in the following Table.

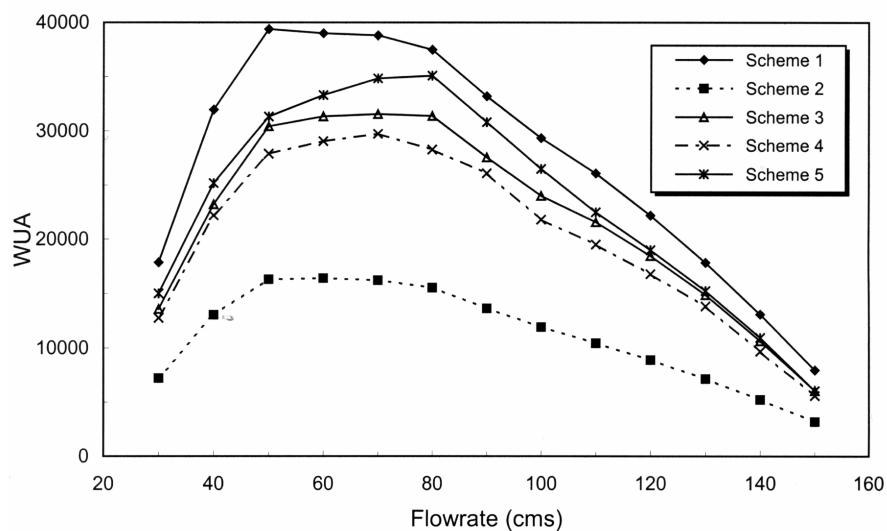
**Table 2. Nominal Grain Sizes (in mm) under Various Flows (for Cell 12 of Section 106)**

| Flow (m <sup>3</sup> /sec) | 30  | 50  | 70  | 90  | 110 | 130 | 150 |
|----------------------------|-----|-----|-----|-----|-----|-----|-----|
| Scheme 3                   | 217 | 233 | 244 | 253 | 260 | 267 | 272 |
| Scheme 4                   | 190 | 201 | 208 | 213 | 218 | 222 | 225 |
| Scheme 5                   | 335 | 394 | 438 | 475 | 509 | 538 | 564 |

The results shown in Table 2 reveal that the nominal grain size of the stable substrate consistently increases with flowrate. The variation for scheme 5 is the steepest, while the variation for scheme 4 is the mildest. Moreover, under the same flow, the nominal sizes for schemes 5 and 4 are also the largest and smallest, respectively. Both facts are probably due to the thresholds used to cut out the lower portions of the gradation curves in schemes 3 and 5. The results have indicated that the maximum bedload size is generally greater than the critical grain size under identical flow condition, except for the flows providing very small shear stresses. For such weak flows, the validity of Eq. (5) becomes questionable because of the limited data from which the formula was derived.

### 4.2 Variation of Instream Physical Habitat with Flow

Figure 3 gives the simulated results showing the variations of WUA with flowrate for various substrate evaluation schemes. To each flow simulated, the corresponding WUA values for schemes 1 and 2 are respectively the greatest and the smallest. For any given flowrate, the magnitude of WUA increases consistently following the order of scheme as 2, 4, 3, 5, and 1. This agrees with the results shown in Table 2 and is also a consequence arising from the differences in modeling stable substrate. The results appear to indicate that the substrate suitability values corresponding to the specified attributes tend to be on the optimistic side, whereas the nominal size of the original bed material tends to undervalue the substrate suitability.



**Figure 3. Variations of WUA with Flowrate for Various Substrate Evaluation Schemes**

The variations of the WUA curves for schemes 1 and 2 are independent of the substrate status. However, the WUA curves for schemes 3, 4, and 5 are the outcomes resulting from the combined effect of flow velocity, depth, and substrate suitability. For flows less than 50 m<sup>3</sup>/sec, the suitability curves for flow velocity and depth are both on the rising limbs. The suitability of flow velocity reaches its maximum at 50 m<sup>3</sup>/sec and starts to fall, while the suitability of flow depth continues to rise and reaches the maximum at 80 m<sup>3</sup>/sec. When the flowrates are greater than 80 m<sup>3</sup>/sec, both suitability curves are on the falling limbs. For various substrate schemes, the consistently steep slopes of the WUA curves in the ranges of flow < 50 m<sup>3</sup>/sec and > 80 m<sup>3</sup>/sec are attributed to the dominant effect of flow velocity and depth. In the range between 50 and 80 m<sup>3</sup>/sec, the variations of WUA values are sensitive to the suitability of stable substrate. For scheme 3, the WUA increases initially but then starts to decrease at 70 m<sup>3</sup>/sec, yet the WUA appears to be relatively constant within this range. The trend of variation for scheme 4 is similar to that of scheme 3, but the slopes are steeper for scheme 4. The WUA for scheme 5 increases monotonously in this range, indicating that the suitability of stable substrate is the dominating factor. Although both schemes 3 and 5 use threshold grain size to distinct the stable and unstable portions of the substrate, the Shields' critical size is represented by the median size of the mobilized population and thus tends to underestimate the threshold size for incipient motion. The maximum bedload size used in scheme 5 is based on the selective transport condition that probably allows a more realistic ecohydraulic modeling of the instream physical habitat.

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