The uncertainty analysis of the wetted perimeter method via axis scaling for setting minimum ecological in-stream flow requirements

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Abstract The minimum ecological in-stream flow requirement (MEIFR) is the in-stream flow requirement necessary to guarantee the basic ecological function of a river. This paper discusses the uncertainty involved in one of the MEIFR evaluation techniques, the Wetted Perimeter (WP) method, due to axis scaling based on an analytical solution of MEIFR, under the assumption of simple triangular cross-section. It is clearly shown that the solution of MEIFR based on original variables is stable and independent of the data series. That based on scaled variables, however, is highly related to the data series, time period, and scaling factor. The maximum difference of MEIFR based on the scaled variables via Maximum, Z-score and Summation scaling schemes relative to that based on original variables reaches 36%. These results suggest that in order to decrease the uncertainty of the WP method, axis scaling should be used with caution.

Key words minimum ecological in-stream flow requirements; wetted perimeter method; analytical solution; axis scaling; water resources management

INTRODUCTION

The minimum ecological in-stream flow requirement (MEIFR) is the in-stream flow requirement (IFR, King & Louw, 1998; Rowntree & Wadeson, 1998; Hughes, 2001; Houghes & Hannart, 2003; Levite *et al.*, 2003; Symphorian *et al.*, 2003) necessary to guarantee the basic ecological functions of a river. Estimates of MEIFR are becoming an important index of water resources management in China and all over the world. Local governments, state and federal water resources management agencies and consultants are all interested in determining the MEIFR. Similarly, stakeholders have a need to acknowledge the impacts of estimates of MEIFR on decision-making. To date, an impediment to an accurate estimation of MEIFR is the uncertainty involved in MEIFR evaluation techniques. The lack of observed MEIFR for validation makes determination of the reliability of estimation methods impossible.

The wetted perimeter (WP) method (Annear & Conder, 1984; Gordon *et al.*, 2004), as a hydraulic method, is one of several popular methods to estimate MEIFR (Thoms & Sheldon, 2002). It uses the critical point on the relationship curve between wetted perimeter and discharge to determine MEIFR. If the discharge is less than the critical minimum discharge corresponding to the critical point, the wetted perimeter declines rapidly. With decreasing flow, assuming the aquatic habitat is given by the wetted perimeter, a small decrease in flow will result in a significant decrease in the available aquatic habitat, increasing the living pressure of the biome. Above the critical minimum discharge, the wetted perimeter declines slowly, and a large decrease in discharge will produce only a small decrease in wetted perimeter. By defining the wetted perimeter as an index sensitive to habitat quality, the critical minimum discharge corresponding to the critical point is defined as MEIFR in the meaning that if a river keeps the discharge at the level of MEIFR, the optimal ecological function of the river, including aspects of physical, chemical and biological components and their interactions (Acreman, 2005), can be guaranteed.

Unlike the Tennant method (Tennant, 1976), which uses a subjective percentage of historic annual discharge to determine MEIFR, the WP approach has a relatively clear mathematical definition of MEIFR. Unlike habitat, holistic and hybrid methods, which need large amounts of detailed ecological data (see the review in Liu *et al.*, 2006), the WP method just needs the data of streamflow and channel geometry. These features perhaps make WP the least uncertain MEIFR evaluation technique among others. However, the WP method has considerable uncertainty in the determination of the critical point. In the WP method, the critical point was originally determined subjectively by eye from a graph (Collings, 1974; Cochnauer, 1976; Nelson, 1980). Gippel & Stewardson (1998) pointed out that it is not possible to select the breakpoint on wetted perimeter–discharge curves reliably by eye, since the appearance of the slope of the curve is strongly dependent on the relative scaling of the axes. They therefore proposed that axes must be scaled before estimating MEIFR by defining the critical point where the slope equals 1 (slope technique), or where the curvature is maximized (curvature technique). Typically, a logarithmic or power law function is fitted to the observed relationship between flow and wetted perimeter.

Scaling the axes, or standardizing the variables is a common technique (e.g. Liu *et al.*, 2001; Ouarda *et al.*, 2001; Mo & Beven, 2004; Riad *et al.*, 2004). There are several approaches to scale axes. One is to linearly rescale the data to lie in the interval between 0 and 1 by subtracting the minimum, and then dividing by the range; or dividing the data by the maximum value; or by dividing by the summation (Mo & Beven, 2004) of all coordinates. Another approach is to scale individual variables to standard normal, by subtracting the mean and dividing by the standard deviation (Liu. *et al.*, 2001). There are many other options. Application of such transformations prior to the analysis attempts to remove the influence of scaling effects from the analysis, with the aim of obtaining a simpler expression (Ouarda *et al.*, 2001). Furthermore, when plotting the results for a large number of catchments, variables with the largest means tend to dominate the display. As discussed by Friendly & Kwan (2003), scaling axes can effectively result in an incoherent display in which no systematic trends or relations can be seen.

This paper discusses the uncertainty in the WP method for estimating the MEIFR due to axis scaling. Based on the MEFIR deduced in Liu *et al.* (2006) for original variables, analytical solutions of MEIFR based on scaled variables by three scaling schemes are first deduced. Then the dependency of MEIFR on the data series, scaling scheme and climate factor is discussed. Finally conclusions are given.

An analytical solution of MEIFR based on original and SCALED VARIABLES

Liu *et al.* (2006) deduced an analytical solution of MEIFR, as shown in the second row of Table 1, based on original variables by the slope technique and curvature technique for a hypothetical triangular cross-section with water depth, D, channel width over water surface W and the angle between banks 2θ. Similarly, MEIFR based on scaled variables via three scaling schemes is deduced in this paper. The first scheme is to define a relative wetted perimeter, p, and relative discharge, q, by dividing discharge Q and wetted perimeter P by a quantity to make Q and P dimensionless. The quantity can be the maximum value of the data series (hence called Maximum Scheme), or median or mean. For the Maximum Scheme, this gives (Table 1):

Table 1 MEIFR based on original and scaled variables via curvature and slope technique.

Variables	Curvature (C)	Slope (S)
Original (o)	$MEIFR_{Co} = a^{\frac{1}{1-b}} b^{\frac{b}{1-b}} (\frac{2-b}{1-2b})^{\frac{b}{2b-2}}$	$MEIFR_{So} = a^{\frac{1}{1-b}} b^{\frac{b}{1-b}}$
Maximum (m)	$MEIFR_{Cm} = (\frac{P_{\max}}{Q_{\max}})^{\frac{b}{1-b}} a^{\frac{1}{1-b}} b^{\frac{b}{1-b}} (\frac{2-b}{1-2b})^{\frac{b}{2b-2}}$	$MEIFR_{Sm} = (\frac{P_{\max}}{Q_{\max}})^{\frac{b}{1-b}} a^{\frac{1}{1-b}} b^{\frac{b}{1-b}}$
Z-score (z)	$MEIFR_{Cz} = (\frac{\sigma_P}{\sigma_Q})^{\frac{b}{1-b}} a^{\frac{1}{1-b}} b^{\frac{b}{1-b}} (\frac{2-b}{1-2b})^{\frac{b}{2b-2}}$	$MEIFR_{Sz} = (\frac{\sigma_P}{\sigma_Q})^{\frac{b}{1-b}} a^{\frac{1}{1-b}} b^{\frac{b}{1-b}}$
Summation (s)	$MEIFR_{Cs} = (\frac{S_P}{S_Q})^{\frac{b}{1-b}} a^{\frac{1}{1-b}} b^{\frac{b}{1-b}} (\frac{2-b}{1-2b})^{\frac{b}{2b-2}}$	$MEIFR_{Ss} = (\frac{S_P}{S_Q})^{\frac{b}{1-b}} a^{\frac{1}{1-b}} b^{\frac{b}{1-b}}$

Note: $a = (\sqrt{S}/32/n)(\sin 2\theta)^{5/3}$, b = 8/3, n is Manning roughness coefficient with the unit of $m^{-1/3}$ s, S is the energy grade slope (non-dimensional), 2θ is the angle between the riverbanks (see Liu *et al.*, 2006).

$$q = Q/Q_{max}, \qquad p = P/P_{max} \tag{1}$$

where Q_{max} and P_{max} are the maximum values of discharge and wetted perimeter, respectively.

Similarly, by defining:

$$q = (Q - \overline{Q})/\sigma_Q, \qquad p = (P - \overline{P})/\sigma_P \tag{2}$$

where σ_Q and σ_P are the standard deviations of Q and P, $\overline{Q}$ and $\overline{P}$ are the averages of Q and P, we get the Z-score scheme. By defining:

$$q = Q/S_Q, \qquad p = P/S_P \tag{3}$$

where S_Q and S_P are the summations of data series of Q and P, we get Summation scheme. Results of MEIFR deduced based on the three scaling schemes are shown in Table 1.

DISCUSSIONS

Via different values of data series

From Table 1, it is obvious that the solution of MEIFR based on original variables is independent of the data series (maximum wetted perimeter and discharge). However, the solution of MEIFR based on scaled variables is highly related to the data series. Taking the Maximum scheme as an example, assuming θ = 60°, n = 0.044 and S = 0.0032, the results of MEIFR based on the hypothetic data set with different values of the maximum wetted perimeter and discharge are compared in Fig. 1. It is shown that both the slope and curvature methods of estimating the MEIFR based on original variable are stable; that is, not sensitive to variations in the value of the maximum wetted perimeter and discharge. However, MEIFR estimates based on scaled variables are sensitive to this scaling factor for both techniques. Because the maximum values are highly dependent on the time period, the results will depend on the selected period, introducing more uncertainty in the MEIFR estimates than found without scaling.

With different schemes of axis scaling

The role of axis scaling is further assessed by testing different scaling schemes. If the MEIFR results based on the different scaling schemes vary, the additional axis scaling methods will also

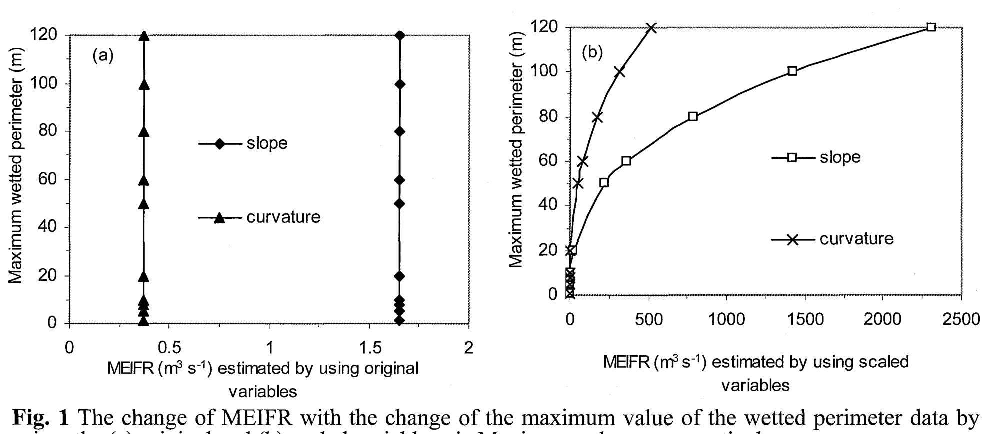

Fig. 1 The change of MEIFR with the change of the maximum value of the wetted perimeter data by using, the (a) original and (b) scaled variables via Maximum scheme, respectively.

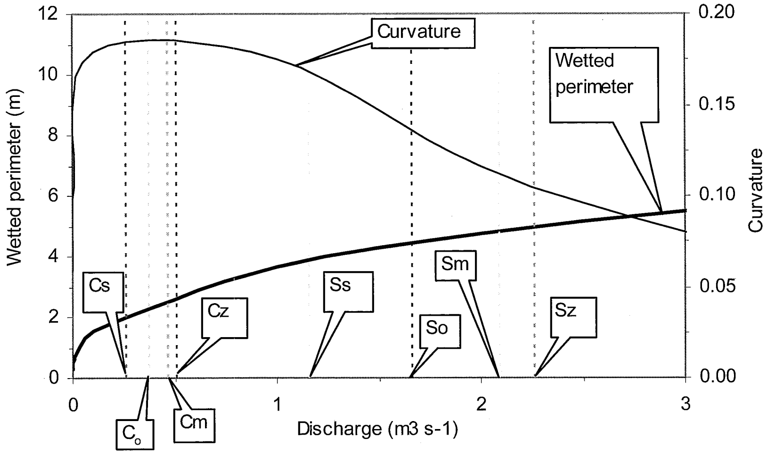

Fig 2 The MEIFR estimated by different schemes (pointed by arrows, the explanation of Cs, Co, Cm, Cz, Ss, So, Sz, see Table 1).

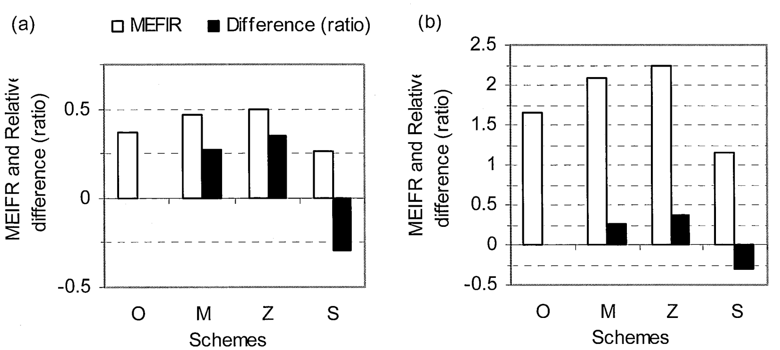

Fig. 3 The specific values of MEIFR estimated via: (a) curvature and (b) slope techniques based on original (noted as o in x-axis) and scaled variables by using three scaling schemes (noted as M, Z and S, respectively) for a hypothetical river.

result in increased uncertainty. As in the above section, assuming $\theta = 60°$, $n = 0.044$ and $S = 0.0032$, based on the hypothetical data set with the value of the maximum wetted perimeter and discharge being 8.66 m and 10 $m^3 s^{-1}$, respectively, the original and scale variables with the three scaling schemes can be calculated based on Table 1. The results are shown and explained in Fig. 2.

Generally speaking, the results via Maximum scheme and Z-score scheme are not obviously different; all are larger than the results with original variables. The summation scheme brings a smaller result than the results with original variables. The maximum difference of MEIFR based on the scaled variables relative to that based on original variables reaches 36%, as shown in Fig. 3. Therefore, in order to get a reasonable estimation of MEIFR, axis scaling should be used with caution.

Should MEIFR be independent of the climate?

While it is obvious that scaled variables may bring more uncertainties than the original variables as shown above, we also have to admit that even using original variables, WP still displays uncertainty. The fact that the left-hand-side of the MEIFR equations in the second row of Table 1 are not the same tells us that determination of which technique (slope or curvature) is more accurate needs further study. Furthermore, it shows that MEIFR based on original variables is only related to channel geometries, independent of the climate. Surely from both a hydrological and ecological view, rivers in different climate zones will have different MEIFR values, even based on the same channel structure. Further, how the scaling of the axes affects other channel profiles needs to be determined. More research will be necessary on the principles of the WP method itself, with more general study on various cross-section channels.

CONCLUSIONS

This paper analyses the uncertainty of the WP method due to axis scaling. Based on wetted perimeter method under the assumption of a triangular cross-section, an analytical solution to the estimation of MEIFR suggests that in order to decrease the uncertainty of WP, axis scaling should be used with caution. Whether the unscaled formulation is generally independent of the climate signal needs further study. While this study is focused on the estimation of MEIFR for channels with a triangular cross section, it does have applicability for actual catchments. This kind of channel is not unusual in headwater regions, where most of the rivers are ungauged (Liu *et al.*, 2006). This work is expected to be valuable for predicting MEIFR in headwater areas as one of the components of the Prediction in Ungauged Basins initiative of the International Association of Hydrological Sciences (Sivapalan *et al.*, 2003).

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