Flow resistance due to stream meandering: an evaluation of existing methods and implications for streamflow estimation

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Session VII

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Resistance to flow due to meandering of streams

Motivation and Objectives

Resistance to flow and energy losses

Resistance to flow: it is the process whereby downstream mean flow energy is dissipated (Venditti 2013).

Resistance to flow ⟷ **Energy losses**

Why deal with resistance to flow and energy losses?

- It influences the flow velocity, turbulence phenomena, hydraulic geometry, and shear stress along movable boundaries (Segura Serrano 2020).
- Resistance to flow is thus at the core of the stream’s water and sediment conveyance capacities, and as such ultimately determines also the distribution and extent of bed and bank erosion (Cheng 2022).
- It is a critical factor in flood management, stream restoration and re-naturalization, establishment of environmental flows to sustain aquatic ecosystems, and mitigation of climate change.

Methods for energy loss quantification due to stream meandering

Conventional methods for estimating the additional energy loss due to meandering are mainly of two types:

Empirical Methods:

- Soil Conservation Service (SCS) method (Cowan,1956; Fasken, 1963)
- Leopold et al. (1960) method
- Linearized Soil Conservation Service (LSCS) method (James and Wark, 1992)
- Shiono et al. (1999) method

Yield considerably different and unsatisfactory results (James 1994; Segura Serrano 2020).

Theoretical Methods:

- Rozovskii (1957)
- Chang (1988)

Theoretical formulations based on steady, subcritical and fully developed flows within circular bends, assuming rectangular and wide channels.

A different approach has been explored by Zhang et al. (2022), who used their own numerical solver of the 3D Reynolds Averaged Navier-Stokes (RANS) equations to determine bed shear stress in meandering streams and compared it to straight channels, evaluating energy loss based on the shear stress ratio.

Methods under consideration

Chang (1988) → **Theoretical formulation**

Zhang et al. (2022) → **Theoretical/numerical formulation**

Why are the methods by Chang (1988) and Zhang et al. (2022) of interest?

1. They both have a very strong theoretical foundation.
2. Yet, they have not been properly evaluated.

Is there any need to do further work on energy losses due to meandering of the stream or are any of these methods suitable enough already?





Specific objectives

1. To conduct an analysis of the methods by Chang (1988) and Zhang et al. (2022).
2. To evaluate the methods by Chang (1988) and Zhang et al. (2022) to quantify additional resistance to flow due to stream meandering against experimental data.

Review of methods under consideration

Chang (1988) and Zhang et al. (2022)

Review of methods under consideration

Method by Chang (1988)

Chang considered the rate of energy expenditure per unit channel length and expressed this as the sum of two components: that associated with longitudinal resistance, and that due to transverse circulation. The considerations are restricted to steady, subcritical, and fully developed flows in circular bends with wide and rectangular cross-sections. The resulting equation is as follows:

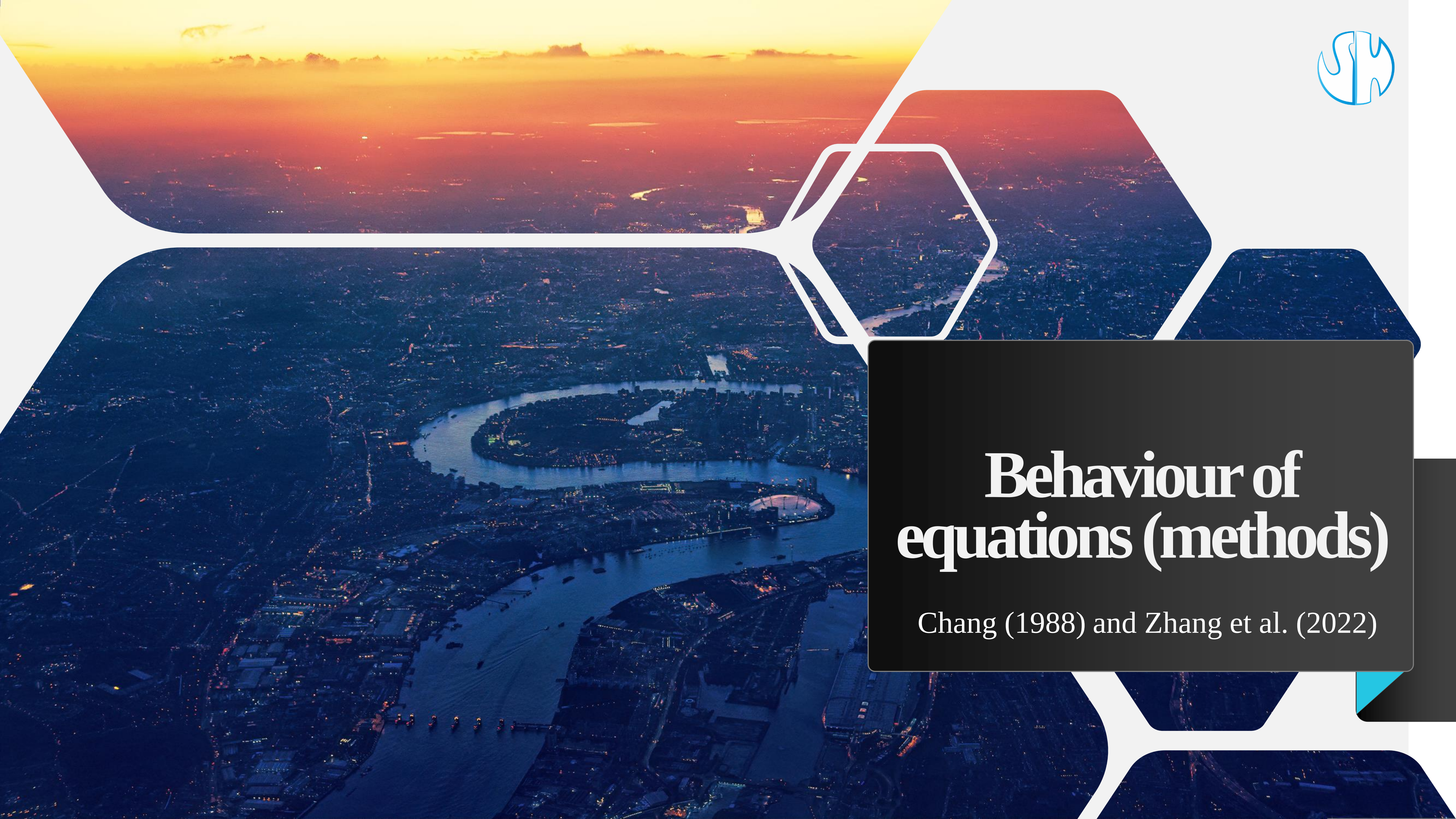
$$\frac{1}{c^2} = \frac{1}{c_s^2} + \left(\frac{13.22c^{-1} + 16.57c^{-2} - 41.37c^{-3}}{0.565 + 2.83c^{-1}} \right) \left(\frac{h_{av}}{r_c} \right)^2 . \quad (1)$$

Method by Zhang et al. (2022)

Zhang et al. modelled the planimetric shape of the channel centerline as a sine-generated curve, which “closely approximates the shape of real river meanders” (Langbein and Leopold 1966). Their study focused on scenarios characterized by large width-to-depth ratios ($B/h_{av} >\approx 10$) and small Froude numbers ($Fr <\approx 0.3$).

Using an entire meander loop as the computational domain, Zhang et al. derived the following expression:

$$c^2 = c_s^2 \cdot \left\{ 1 - \frac{13}{(B/h_{av})^{1.1}} \theta_0^{1.8} \left[\exp\left(-0.062\theta_0^{1.8}\right) - 0.05 \right] \right\} . \quad (2)$$



Behaviour of equations (methods)

Chang (1988) and Zhang et al. (2022)

Behaviour of Eqs. (1) and (2)

The behaviour of Eqs. (1) and (2) is analyzed under assumption of a flat streambed with the stream centerlines represented by sine-generated curves (see Fig. 1).

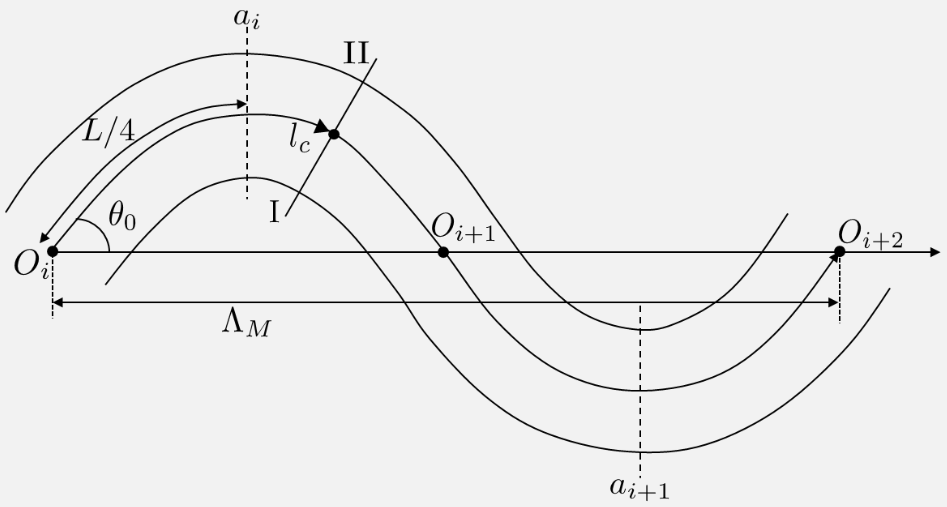


Fig. 1. Definition sketch of a sine-generated meandering stream (from da Silva and Ebrahimi 2017).

To evaluate the differences between Eqs. (1) and (2) the deviation from unit of the ratio of energy loss strictly attributed to the stream's meandering relative to the total energy loss c^2/c_s^2 is considered.

Behaviour of Eqs. (1) and (2)

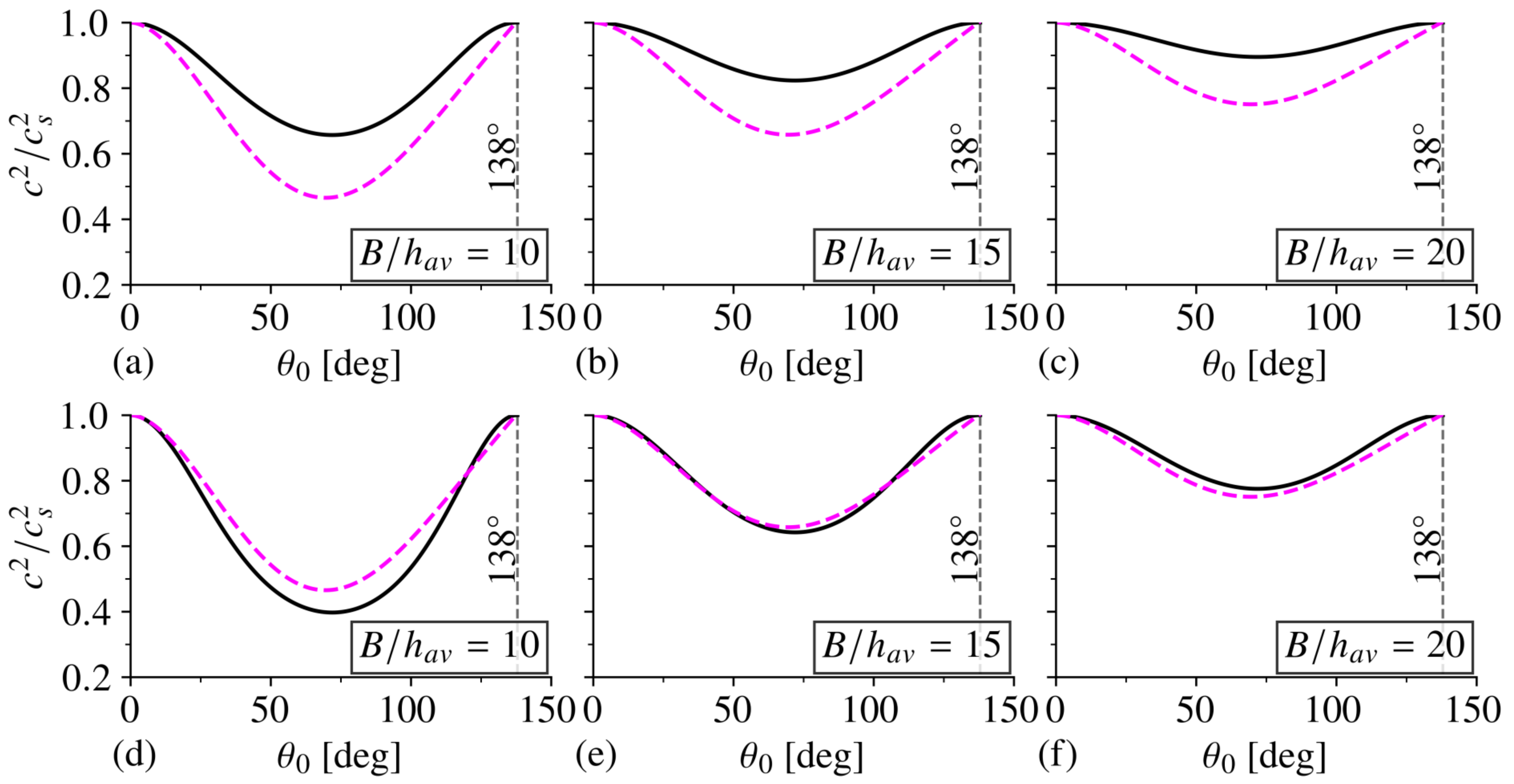


Fig. 2. Family of c^2/c_s^2-curves versus θ_0 for specified values of B/h_{av} and c_s: (a-c) $c_s = 10$; (d-f) $c_s = 20$.

Black line: Chang (1988).

Magenta line: Zhang et al. (2022).

Performance against data

Chang (1988) and Zhang et al. (2022)

Description of experimental data

This work comprises laboratory data from 15 literature sources produced between 1960 and 2016. In addition to data from published datasets, unpublished laboratory data (A.D. Binns, personal communication (PC) to the 2nd author, 2010) were included.

Table 1 Geometric and hydraulic parameters of the experimental data.

Source	N	θ_0 [deg]	Λ_M [m]	$Q\times10^3$ [m^3 s^{-1}]	$D_{50}\times10^3$ [m]	B [m]	$h_{av}\times10^2$ [m]	$R_h\times10^2$ [m]	$S\times10^3$
Leopold et al. (1960)	51	18-45	0.65-1.22	0.54-3.26	2.00	0.15;0.17	2.7;4.1	2.0;2.7	0.97-11.80
Hooke (1975)	4	55	10.33	10.00-50.50	0.30	1.00	5.2-12.8	4.7-10.2	2.07-2.23
Hasegawa (1983)	2	20;30	2.04;2.33	0.59;1.87	0.43	0.22;0.30	1.4;2.6	1.2;2.2	3.33;6.25
Ikeda and Nishimura (1986)	1	40	2.64	2.60	0.15	0.30	5.4	4.0	1.39
Whiting and Dietrich (1993a)	4	10;20	2.00	1.04-1.67	0.67	0.25	1.5-2.0	1.3-1.7	4.20-6.40
Whiting and Dietrich (1993b)	6	100;115	2.00	0.42-1.26	0.62	0.13;0.25;0.46	1.1-2.5	1.1-1.8	4.10-6.40
da Silva (1995)[1]	1	30	2.51	2.10	2.20	0.40	3.2	2.8	1.00
Tape (2001)[1]	1	70	2.51	1.84	2.20	0.40	3.1	2.7	1.00
El-Tahawy (2004)	1	70	5.03	3.00	0.65	0.80	3.1	2.9	2.00
da Silva and El-Tahawy (2008)	6	70	5.03	6.50-13.40	0.65	0.80	3.5-7.5	3.2-6.3	2.22-4.00
da Silva et al. (2008)	2	70	5.03	2.15;6.21	0.65	0.80	1.2;2.4	1.2;2.3	8.00
Binns and da Silva (2009)[2,3]	5	70	5.03	7.00-13.80	0.65	0.80	4.1-4.5	3.8-4.1	2.50-8.00
Binns (PC, 2010)	4	70	5.03	3.30-32.77	0.65	0.80	1.7-15.6	1.6-11.2	1.80;2.40;6.70
Termini (2011)	2	110	3.14	5.00;12.00	0.65	0.50	3.0;5.2	2.7;4.3	3.71
Binns (2012)[3]	12	20;45;95	1.88	1.60-3.00	0.65	0.30	2.0-3.2	1.8-2.7	4.00-7.69
Song et al. (2016)	7	30;45;60	2.00;2.20;2.50	0.75-1.35	0.58	0.10;0.15;0.20	2.4-4.6	1.8-2.8	3.72-4.66

Data is also available in: [1]da Silva et al. (2006), [2]Binns and da Silva (2011), and [3]Binns and da Silva (2015).

Performance against laboratory data

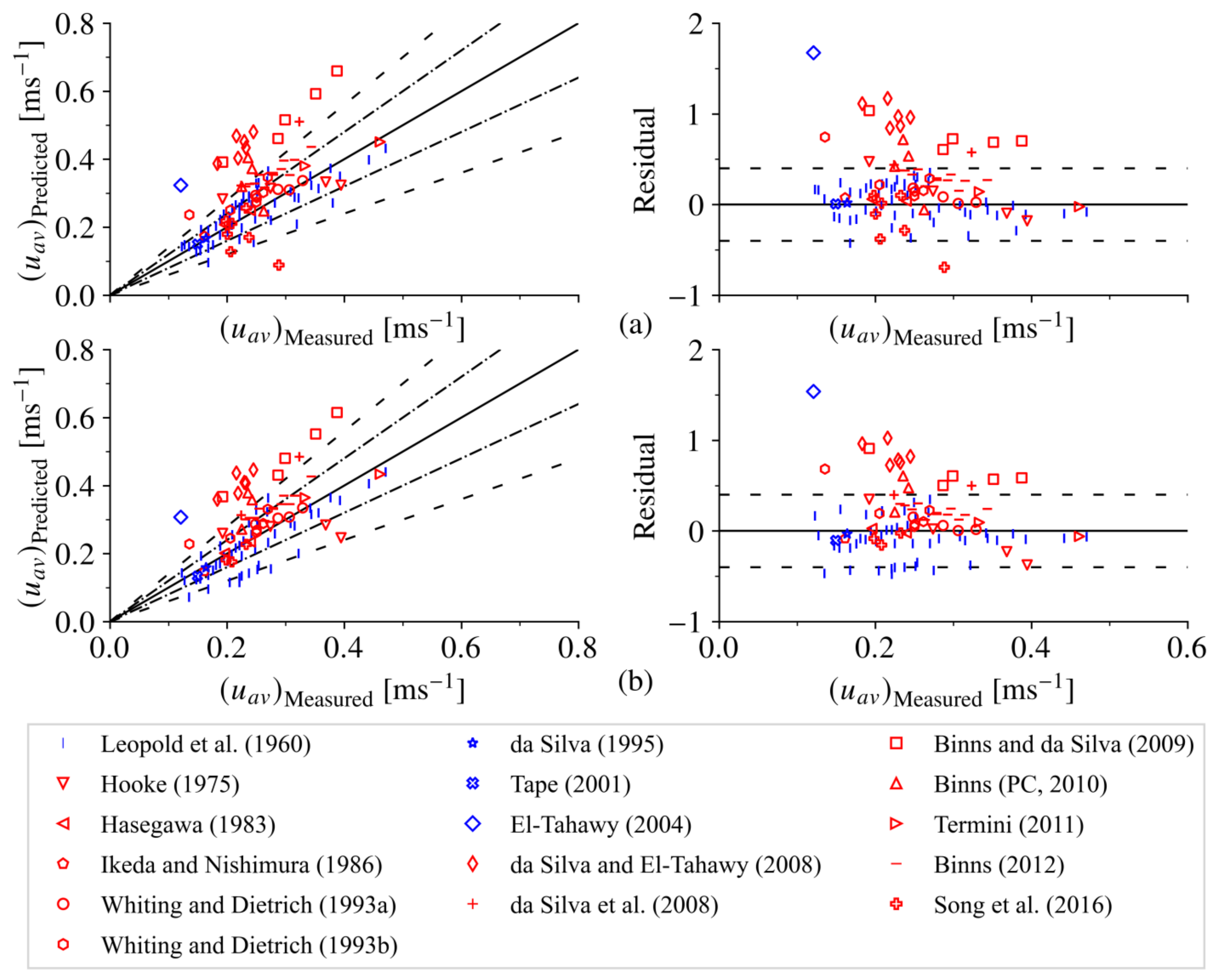


Fig. 3. Predicted versus measured u_{av} and corresponding residual plots for experimental data produced using (a) Chang (1988) and (b) Zhang et al. (2022). Dashed-dotted and dashed lines are the 20 and 40% error-range lines, respectively. Blue: flat bed data; red: deformed bed data.

Table 2. Percentage of predicted values of u_{av} within specified error ranges and percentage DAPAL for the methods under consideration.

Method	Error Ranges (%)			% DAPAL
	0–20	0–40	0–60	
Chang (1988)	51	81	86	69
Zhang et al. (2022)	55	77	89	57

Performance against laboratory data

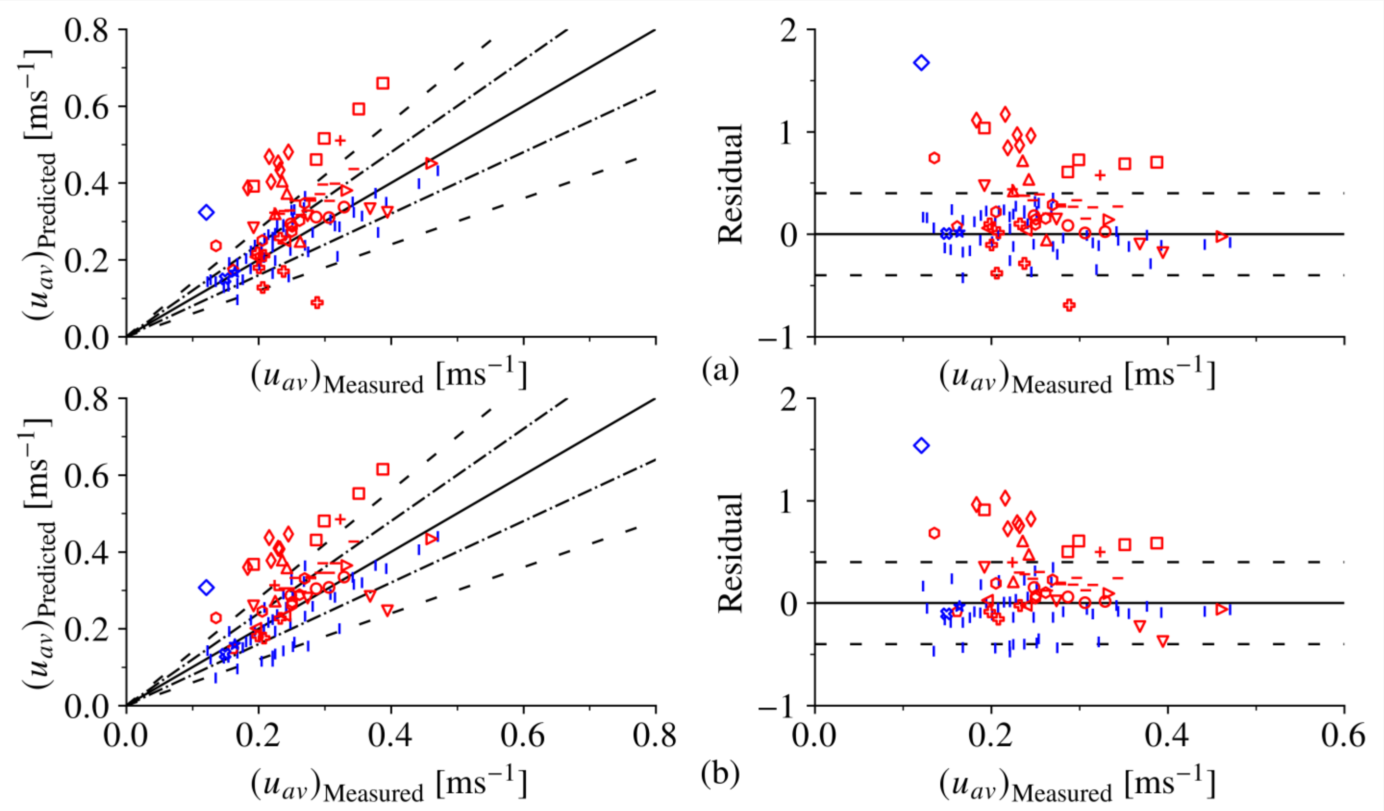


Table 3. Percentage of predicted values of u_{av} within specified error ranges and percentage DAPAL for the methods under consideration sorted by bed condition.

Method	**Flat bed condition**				**Deformed bed condition**			
	Error Ranges (%)				**Error Ranges (%)**			
	0–20	**0–40**	**0–60**	**% DAPAL**	**0–20**	**0–40**	**0–60**	**% DAPAL**
Chang (1988)	65	96	98	52	38	65	75	85
Zhang et al. (2022)	64	84	98	30	46	70	80	84

Performance assessment

The fact that estimations of u_{av} are worse for data with deformed streambeds over those with flat beds likely arise not from bed shape but from the limitations of the methods in capturing the influence of B/h_{av} on energy losses due to stream meandering (see Fig. 4).

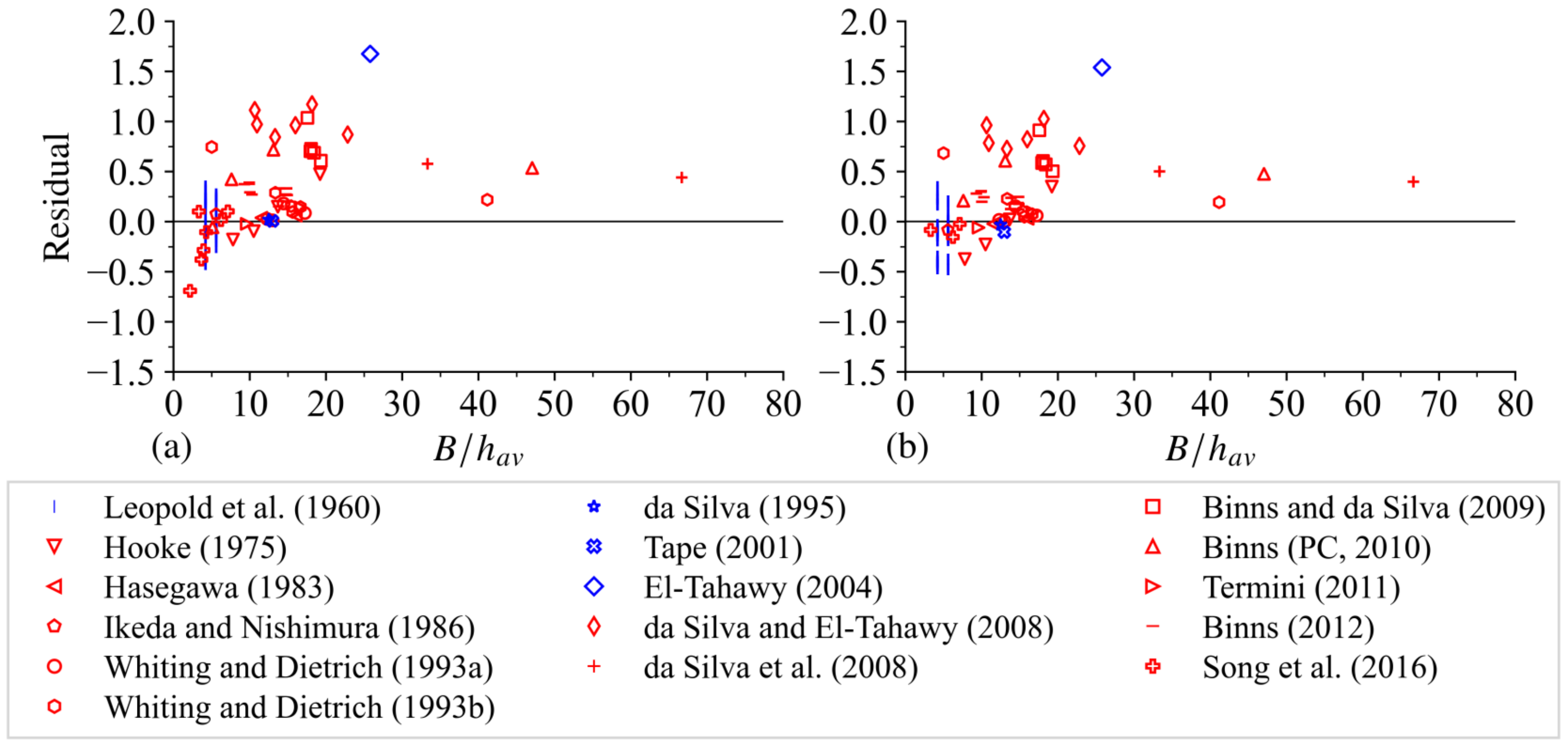


Fig. 4. Predicted versus measured u_{av} residual plots produced using (a) Chang (1988) and (b) Zhang et al. (2022) as a function of B/h_{av}. Colour of symbols as in Fig. 3.

Performance assessment

An effort was made to investigate the underestimation of flow resistance by both methods. Figure 5 illustrates this analysis, presenting a plot of c^{-2}-c_s^{-2} versus B/h_{av} for data having $60° \leq \theta_0 \leq 80°$, and includes both measured values of c^{-2}-c_s^{-2} as well as the graphs of Eqs. (1) and (2) corresponding to $c_s = 12.5$ (average value of c_s for the selected data).

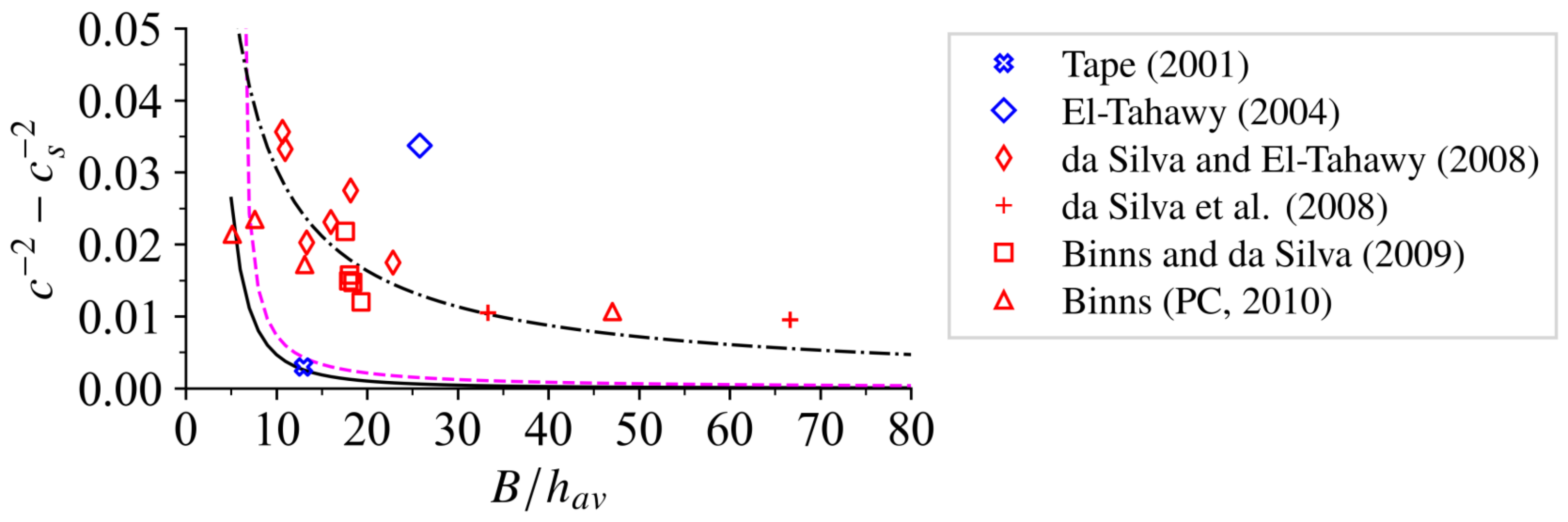


Fig. 5. Plot of c^{-2}–c_s^{-2} versus B/h_{av}. Eq. (1): black-solid line; Eq. (2): magenta-dashed line; general pattern of data: black-dashed-dotted line.

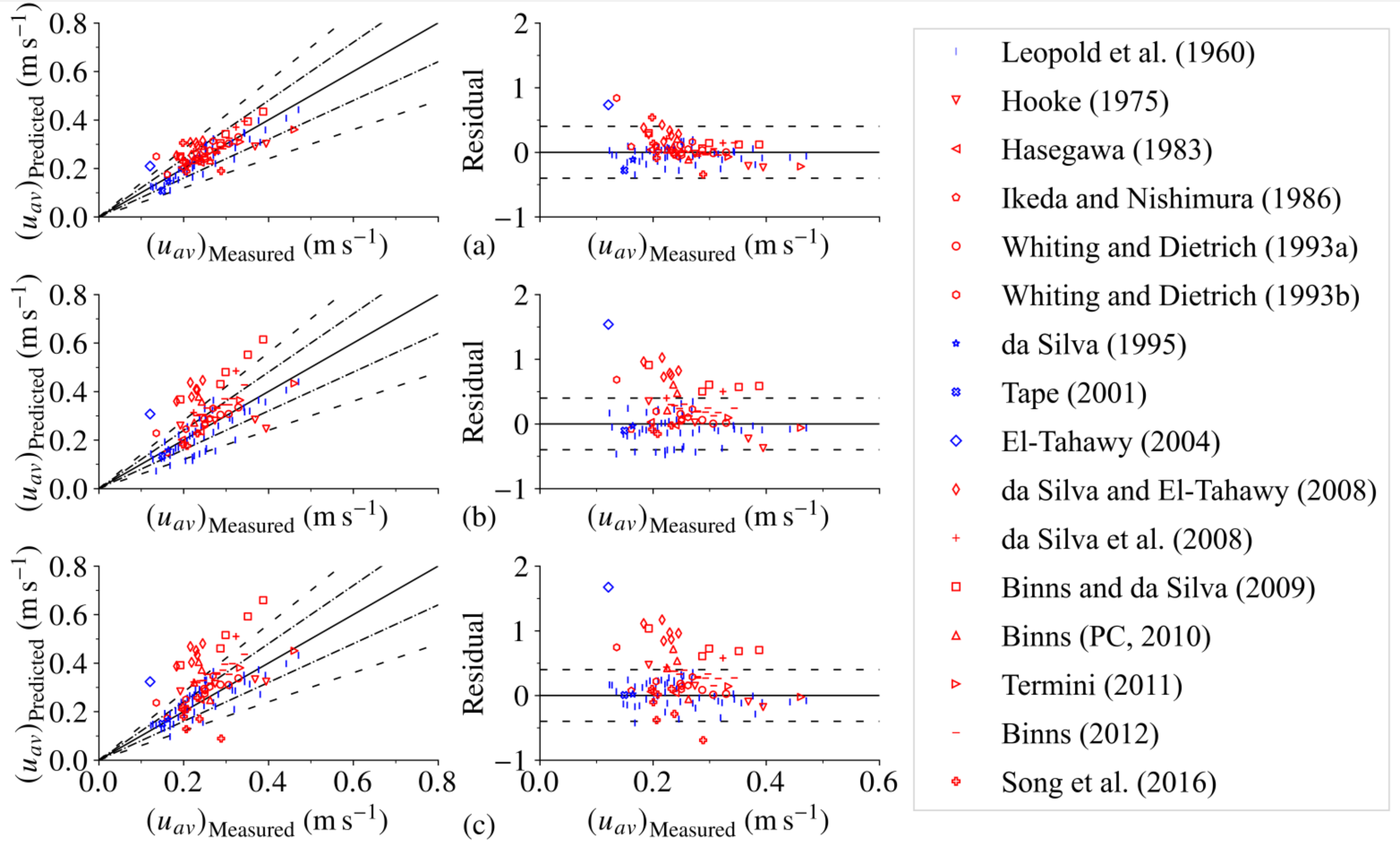
Conclusions

- Both equations under consideration (Chang 1988 and Zhang et al. 2022) yield inadequate predictions of flow resistance in meandering streams.
- They inaccurately represent the dependency on the B/h_{av} ratio, which results in a significant underestimation of flow resistance, leading to great overestimations of u_{av}, i.e., considerable overestimations of streamflow capacities.
- Given the critical role of flow resistance in hydraulic and environmental engineering, these results emphasize the importance to exercise great caution when applying these methods in practice.
- This work highlights the need to develop improved methods to predict the additional resistance to flow introduced by stream meandering, essential for the sustainable management of water systems in face of growing environmental challenges.

Future work / Recent progress

1. To develop a new method to quantify the additional resistance to flow due to stream meandering.
2. To evaluate the improvements of new method in quantifying the additional resistance to flow due to stream meandering, using laboratory and field data.

Performance against laboratory data



(a) New empirical equation.

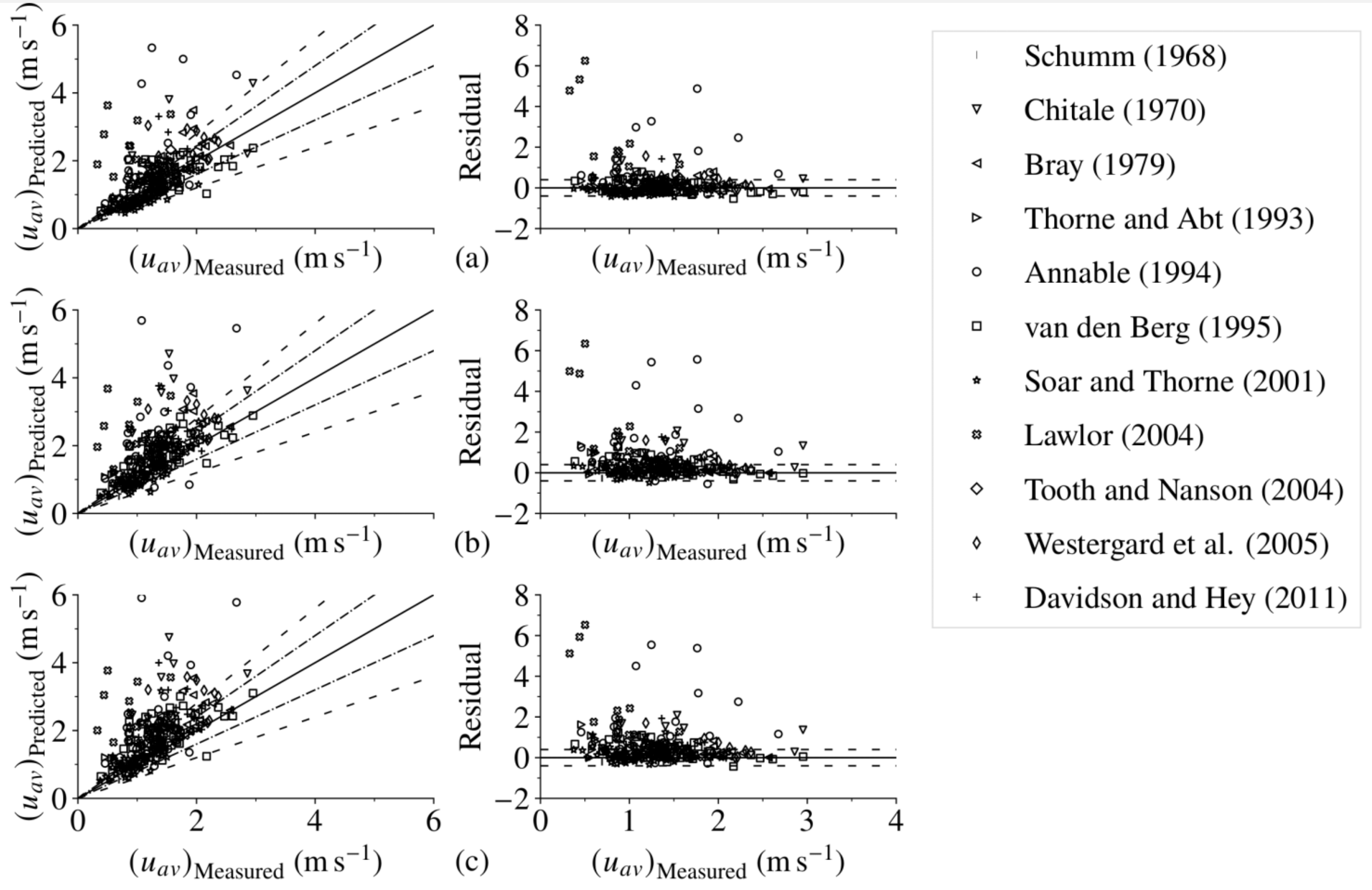
(b) Zhang et al. (2022).

(c) Chang (1988).

$$\frac{1}{c^2} = \frac{1}{c_s^2} + \frac{0.1}{(B/h_{av})^{0.8}}\left(5e^{-0.45\Lambda_M/B} + 0.45\right)(2.4086 - \theta_0)\,\theta_0 e^{-1.5(\theta_0 - 1.28)^2}$$

Method	Error Ranges (%)			
	0–20	0–40	0–60	% DAPAL
New	80	96	98	53
Zhang et al. (2022)	55	77	89	57
Chang (1988)	51	81	86	69

Performance against field data



(a) New empirical equation.

(b) Zhang et al. (2022).

(c) Chang (1988).

$$\frac{1}{c^2} = \frac{1}{c_s^2} + \frac{0.1}{(B/h_{av})^{0.8}} \left(5e^{-0.45\Lambda_M/B} + 0.45\right) \left(2.4086 - \theta_0\right) \theta_0 e^{-1.5(\theta_0 - 1.28)^2}$$

Method	Error Ranges (%)			
	0–20	0–40	0–60	% DAPAL
New	51	78	87	55
Zhang et al. (2022)	37	61	76	80
Chang (1988)	35	59	71	87

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