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An ANFIS-based approach for predicting the bed load for moderately sized rivers

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Abstract

A total of 346 sets of bed-load data obtained from the Kinta River, Pari River, Kerayong River and Langat River were analyzed using four common bed-load equations. These assessments, based on the median sediment size (d_{50}), show that the existing equations were unable to predict the measured bed load accurately. All existing equations over-predicted the measured values, and none of the existing bed-load equations gave satisfactory performance when tested on local river data. Therefore, the present study applies a new soft computing technique, i.e. an adaptive neuro-fuzzy inference system (ANFIS), to better predict measured bed-load data. Validation of the developed network (ANFIS) was performed using a new set of bed-load data collected at Kulim River. The results show that the recommended network can more accurately predict the measured bed-load data when compared to an equation based on a regression method.

Keywords: Sediment transport; Bed load; Loose-bed rivers; ANFIS, Malaysia

1. Introduction

A river is a dynamic system governed by hydraulic and sediment transport processes. Over time, the river responds to changes in channel cross section, increased or decreased sediment carrying capacity, and erosion and deposition along the channel, all of which affect bank stability and river morphology. In order to sustain cultural and economic developments along a river, it is essential to understand the principles of sediment transport for application to engineering and environmental problems associated with its natural state and human activities.

Currently, there are various sediment transport equations that have been developed based on different approaches to predict bed-load transport rates. The Einstein bed-load function is one of the equations developed and is based on a probability approach, which can be found in every major textbook on alluvial-river mechanics and sediment transport (Graf, 1971; Chang, 1988; Yang, 1996; Chien and Wan, 1999). A modified Einstein equation was established using the measured data at several rivers in Malaysia by using a regression method (Chang et al., 2007).

The adaptive neuro-fuzzy inference system (ANFIS) is a hybrid scheme that uses the learning capability of the artificial neural network or ANN to derive the fuzzy if-then rules with appropriate membership functions worked out from the training pairs, which in turn leads to the inference (Jang and Sun, 1995; Tay and Zhang, 1999). The difference between the common neural network and the ANFIS is that, while the former captures the underlying dependency in the form of the trained connection weights, the latter does so by establishing the fuzzy language rules. The treatment of data non-linearities in this way

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Notation

C_v	volumetric concentration
d_{50}	median sediment size (mm)
Dgr	dimensionless particle parameter
g	gravity acceleration (m/s^2)
n	Manning's roughness coefficient
Q	discharge (m^3/s)
Q_b	bed-load discharge (m^3/s)
R	hydraulic radius (m)
S_o	water-surface slope
S_s	specific gravity of sediment
T	water-surface width (m)
T_b	bed load (kg/s)
y_o	flow depth (m)
ρ_s	density of natural sediments (kg/m^3)
τ_o	bed shear stress (kg/m^3)
τ_c	critical shear stress (kg/m^3)
ν	kinematic viscosity
ϕ	transport parameter
ψ	flow parameter

has been recently found to be useful in fields like hydrology (Nayak et al., 2004; Kisi, 2005), fluvial hydraulics (Bateni et al., 2007), traffic engineering (Sayed et al., 2003) and soil analysis (Akbulbut et al., 2004). Kisi (2005) concluded that ANFIS model is more flexible than the ANN model considered in prediction of suspended sediment, so in the present study only ANFIS has been considered to predict measured bed-load data.

The present study summarizes the recent results obtained based on field data collected at four river catchments in Malaysia, i.e. the Kinta, Kerayong, Langat and Kulim rivers (Yahaya, 1999; Ab. Ghani et al., 2003; Ariffin, 2004; Chang et al., 2007). This study shows that the measured bed load can be predicted accurately for Malaysian rivers using a neural network technique – ANFIS.

2. Study sites

The data collection programme was implemented at four river catchments (Fig. 1) in Malaysia from 1998 until 2007. Initially, the study was carried out at Pari River at Taman Merdeka and Kerayong River at Kuala Lumpur from 1998 to 1999 (Yahaya, 1999). The second study was done at the Kinta River catchment, which consists of four rivers, namely the Kinta River, Raia River, Pari River and Kampar River (Ab. Ghani et al., 2003). The third study was carried out at the Langat River catchment, which consists of the Langat River, Lui River and Semenyih River from 2000 until 2002 (Ariffin, 2004). The fourth study was later completed at Kulim River in 2007 (Chang et al., 2008). A short description of the four rivers (Fig. 2) is given in Sections 2.1–2.4, including the present land use and catchment size (Table 1).

Fig. 1. Location of rivers for the present study.

2.1. Kerayong River

Kerayong River is the main tributary of Klang River in Kuala Lumpur. The catchment area is about 52 km^2 (Fig. 2a), and 80% of the study area has been developed. The topography of the catchment area consists of upstream of Kerayong River, which is hilly, to downstream, which is relatively flat. The measurements were made at four study sites: SK1, SK2, SK3 and SK4.

2.2. Kinta River

The Kinta River catchment (Fig. 2b), with an area of 2540 km^2, is located in the central-eastern section of Perak State. The topography of the catchment consists of steep forest-covered mountains and hills in the north and east, which slowly give way to the expansive Kinta Valley to the south of Ipoh, which lies between the 10 m and 50 m contours. Land use of the Kinta Valley consists of agriculture (e.g. rubber, oil palm and fruit trees), urban development and unproductive ex-mining land, including tailings and ponds. The major tributary of Kinta River from the northwest is the Pari River (245 km^2), which joins at Ipoh. Tributaries from the steeper eastern catchment include the Raia River (250 km^2) and Kampar River (430 km^2), which join the Kinta River at Tg Tualang.

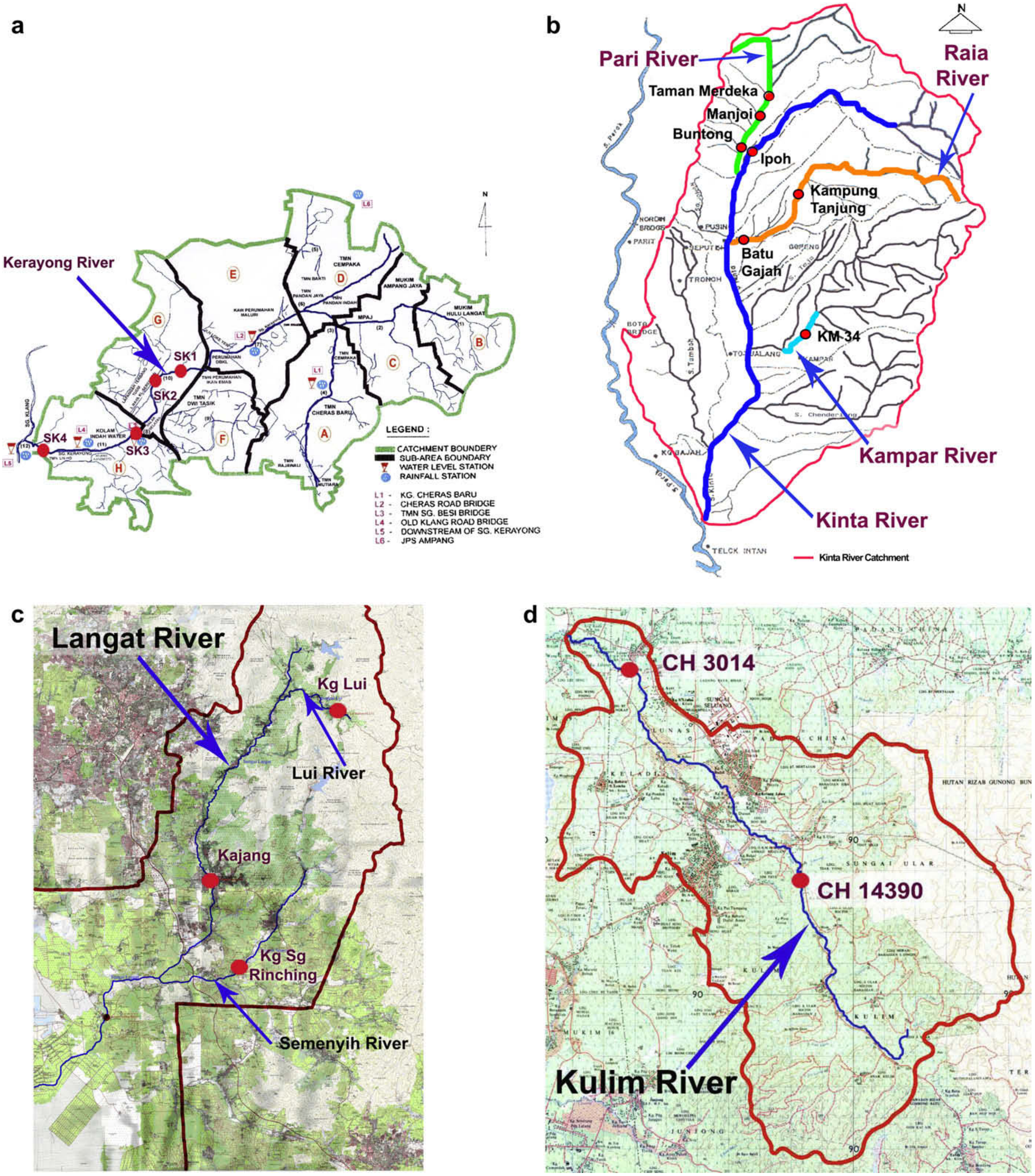

Fig. 2. Study sites: (a) Kerayong River catchment; (b) Kinta River catchment; (c) Langat River catchment; (d) Kulim River catchment.

Initially, measurements were made in 1998 at Taman Merdeka, which is located at the Pari River, by Yahaya (1999). The study was then continued at several study sites, which consist of four rivers: Kinta River, Raia River, Pari River and Kampar River. The studies were conducted at six sites based on the following criteria:

(a) Natural reach: undeveloped upper or middle reach (less than 30% catchment development) – Kampar River at KM 34.
(b) Natural reach: developed middle reach (more than 30% development) – Raia River at Kampung Tanjung and Batu Gajah.

Table 1
Range of field data for present study (Yahaya, 1999; Ab. Ghani et al., 2003; Ariffin, 2004; Chang et al., 2008).

Study site	Kinta River catchment							Kerayong River catchment	Langat River catchment			Kulim River catchment	
Total catchment area (km^2)	2540							48	2350			130	
Location	Kampar River at KM 34	Raia River at Kampung Tanjung	Raia River at Batu Gajah	Kinta River at Ipoh	Pari River at Manjoi	Pari River at Buntong	Pari River at Taman Merdeka	Kerayong River at Kuala Lumpur	Langat River at Kajang	Lui River at Kg Lui	Semenyih River at Kg Sg Rinching	Kulim River at CH 14390	Kulim River at CH 3014
No. of samples	21	20	21	20	20	20	16	24	20	92	50	10	12
Discharge, Q (m^3/s)	7.98–17.94	3.60–8.46	4.44–17.44	3.80–9.65	9.72–47.90	9.66–17.04	5.28–24.35	0.85–6.08	3.75–39.56	0.74–17.17	2.60–8.04	0.73–3.135	3.73–9.98
Water-surface width, T (m)	20.2–21.1	22.2–25.6	17.3–20.8	24.6–28.0	20.3	19.3–19.5	18.0	18.0	15.0–20.0	15.0–17.0	13.5–15.0	9.0–13.0	13.0–19.0
Flow depth, y_o (m)	0.55–1.28	0.24–0.49	0.41–1.76	0.35–0.57	0.69–1.87	0.68–0.89	0.54–1.30	0.22–0.59	0.45–1.39	0.23–0.99	0.36–0.82	0.20–0.54	0.36–0.58
Hydraulic radius, R (m)	0.52–1.14	0.23–0.47	0.39–1.51	0.31–0.55	0.65–1.77	0.63–0.81	0.51–1.13	0.21–0.55	0.42–1.22	0.22–0.89	0.34–0.73	0.23–0.57	0.40–0.63
Water-surface slope, S_o	0.0010	0.0036	0.0017	0.0011	0.0011	0.0012	0.0013	0.0013	0.004–0.005	0.0003–0.009	0.0023–0.015	0.001	0.001
Median sediment size, d_{50} (mm)	0.85–1.10	0.60–1.60	0.50–0.85	0.40–1.00	1.70–3.00	0.85–1.20	2.00–3.10	2.80–3.00	0.37–2.13	0.50–1.74	0.88–2.29	1.00–2.40	1.10–2.00
Aspect ratio, T/y_o	17–38	46–107	12–45	48–86	11–29	22–29	14–34	30.5–81.82	14.4–33.5	17.2–65.8	17.1–41.5	23.4–44.8	26.0–52.5
Shear stress, τ_o (kg/m^2)	5.08–11.19	8.15–16.43	6.59–25.11	3.38–5.94	6.99–19.05	7.47–9.57	6.22–13.90	2.60–6.76	17.97–60.24	3.83–48.82	7.93–94.68	2.22–5.55	3.95–6.16
Critical shear stress, τ_c (kg/m^2)	0.44–0.61	0.44–1.04	0.40–1.19	0.40–1.19	1.06–2.22	0.44–0.68	1.31–2.31	2.03–2.22	0.20–1.57	0.40–1.26	0.45–1.56	0.54–1.66	0.61–1.31
Bed load, T_b (kg/s)	0.40–1.25	0.20–1.82	0.25–1.37	0.02–1.21	0.40–0.80	0.35–0.79	0.31–0.75	0.09–0.23	0.02–1.29	0.04–1.55	0.65–3.16	0.06–0.33	0.11–0.36

Modified reach: developed middle reach (more than 30% development) – Kinta River, Pari River at Manjoi and Buntong.

2.3. Langat River

The Langat River (Fig. 2c) catchment lies within the Selangor state and Negeri Sembilan state. The tributaries, the Lui River and the Semenyih River, flow into the main Langat River. The river drains the northern and western part of the Hulu Langat district down to Dengkil, where it meets its major tributary, the Semenyih River. The catchment area of the Langat River is 1240 km^2 and flows out of the Klang Valley area to the Straits of Melaka. About 45% of the catchment is steep mountainous country, rising to heights of 1525 m, and the remaining area is hilly land with some swamps along the river at its lower reaches. In both the upper and lower regions along the Lui River and Semenyih River, there are scatters of rubber plantations and isolated villages. The Langat River around the Kajang area is densely populated, judging from the vast amount of traffic volume. In contrast, the lower region of the Langat River is yet to be fully developed. There are rubber and oil palm plantations within the region. The four study sites are located in Kajang and Dengkil along the Langat River, Kg Lui along the Lui River and Kg Sungai Rinching along the Semenyih River.

2.4. Kulim River

The study area is located at the southern part of Kedah in the northwestern corner of Peninsular Malaysia (Fig. 2d). It lies within the district of Kulim and upstream of Seberang Perai in Penang State. The Kulim River catchment consists of 15 sub-catchments, with a total catchment area of 130 km^2. At the headwaters, the Kulim River (Fig. 2d), catchment is hilly and densely forested and the Kulim River arises on the western slopes of the Gunung Bongsu Range. It then flows in a northwesterly direction and joins the Keladi River in the vicinity of Kulim. Downstream of Kulim, the sub-catchment is primarily rubber and oil palm estate. The river slopes are steep and the channel elevation drops from 500 m to 20 m above mean sea level over a distance of 9 km. The central area of the catchment is undulating with elevations ranging from 100 m down to 18 m above mean sea level. Bed-load measurements were made at two study sites, which are located at CH 14390 (upstream) and CH 3014 (downstream).

3. Sediment data collection

Field measurements were conducted at the selected cross sections of the study sites by using methods recommended in the Hydrological Procedure (DID, 1976, 1977) and recent manuals (Yuqian, 1989; USACE, 1995; Edwards and Glysson, 1999; FISRWG, 2001; Lagasse et al., 2001; Richardson et al., 2001). The data collection includes flow discharge, bed load, water-surface slope and bed material. Details of the analysis are given in Ab. Ghani et al. (2003) and Chang et al. (2007).

3.1. Flow discharge

A range of flow discharge (Q) measurements covering low and high regimes were carried out using a current meter. The measurement procedure was based on Hydrology Procedure No. 15: River Discharge Measurement by Current Meter (DID, 1976). Measurements taken include flow depth (y_o), velocity (V), and water-surface width (T). The water-surface slopes (S_o) of the study reaches were determined by taking measurements of water levels over a distance of 200 m at the cross section (FISRWG, 2001). For all study sites, the water-surface slopes were found to be mild with ranges between 0.001 and 0.005.

3.2. Bed load

Bed-load samples were collected at seven evenly spaced measuring points for each cross section (Chang et al., 2004). Bed-load transport in the layer 0–76 mm above the river bed was measured with a Helley-Smith sampler. The bed-load samples were trapped in a collecting bag that was 460 mm long with a mesh size of 0.25 mm. The spacing between measuring points differs from one cross section to the other, depending on the river width. At each cross section, bed-load samples were taken at each measuring point for 10 min. A single transverse of bed-load measurement was made for each cross section. The flows were found to be steady during all the measurements. The bed-load samples that were trapped in the collecting bag were emptied into labeled plastic bags. The bed-load transport rate (T_b) was computed based on these seven samples. The accuracy of the present bed-load transport measurements is in the order of 0.1–1.0 kg/s.

3.3. Bed material

River bed materials were collected using a Van Veen grab sampler. Seven samples were collected at points similar to those of the bed-load sampling. A median sediment size (d_{50}) was used for the present study analysis.

3.4. Summary

A total of 346 data sets were obtained at four river catchments. Table 1 shows a summary with ranges for discharge, water-surface width, flow depth, hydraulic radius (R), water-surface slope, median sediment size, aspect ratio (T/y_o), shear stress (τ_o), critical shear stress (τ_c) and bed load. The median sediment sizes for all sites show that the study reaches are made up of sand and gravel with d_{50} ranging from 0.40 to 3.00 mm. The aspect ratios for the study sites at four river catchments are between 11 and 107, indicating that they are moderately sized channels. The critical shear stress was calculated using Van Rijn's (1984) relationship, as shown in Table 2. It was found that bed shear stress is significantly

Table 2
Critical shear stress (Van Rijn, 1984).

$\tau_c/(\rho g(S_s-1)d_{50})$	$\mathrm{Dgr}=d_{50}[(S_s-1)g/v^2]^{1/3}$
$0.24\ \mathrm{Dgr}^{-1.0}$	$\mathrm{Dgr}<4$
$0.14\ \mathrm{Dgr}^{-0.64}$	$4<\mathrm{Dgr}<10$
$0.04\ \mathrm{Dgr}^{-0.1}$	$10<\mathrm{Dgr}<20$
$0.013\ \mathrm{Dgr}^{0.29}$	$20<\mathrm{Dgr}<150$
0.056	$\mathrm{Dgr}>150$

greater than the critical shear stress at all study sites, which indicates that bed-load transport occurs.

4. Study background

4.1. Sediment transport equations assessment

The evaluations for a total of 346 data sets based on median sediment size (d_{50}) have been performed using four commonly used bed-load equations: the Einstein (1942, 1950) bed-load function, Einstein–Brown equation (Brown, 1950), Meyer-Peter and Müller (1948) equation and Shields (1936) equation. The performances of the equations were measured using the discrepancy ratio (DR), which is the ratio of the predicted load to measured load (DR = predicted/measured). In this study, a discrepancy ratio of 0.5–2.0 (DR = 0.5–2.0) was used as a criterion in the evaluation of the selected equations. The evaluation of these equations shows that all the existing equations, in most cases, over-predicted the measured values, as shown in Table 3 (Chang et al., 2007). All four equations produced an average discrepancy ratio greater than 10. As mentioned before, the water-surface slopes for rivers in the present study were found to be mild that result in lower bed-load rates and hence overprediction of the measured values by the existing equations, which were developed from rivers in western countries with much steeper slopes. Therefore, it is concluded that none of the existing bed-load equations gave satisfactory performance when tested on Malaysian local river data.

4.2. Development of modified Einstein equation

Most of the bed-load equations, such as Einstein, Einstein-Brown, and Meyer-Peter-Müller, as well as total load equations, such as Engelund-Hansen (1967) and Graf (1971), employ the transport parameter (ϕ) and flow parameter (ψ). The general relationship between these two parameters is given below:

$$\phi=f(\psi) \tag{1}$$

Both parameters can be defined as:

$$\psi=\frac{(S_s-1)d_{50}}{RS_o} \tag{2a}$$

$$\phi=\frac{c_v VR}{\sqrt{g(S_s-1)d_{50}^3}} \tag{2b}$$

S_s is the specific gravity of sediment; C_v is the volumetric concentration; and g is the acceleration of gravity.

Einstein (1950) could not derive the exact form of the relationship between ϕ and ψ because the values of several variables were unknown (Ettema and Mutel, 2004). Hence, the corresponding value of ϕ is determined based on empirical data as:

$$A\phi=f(B\psi) \tag{3}$$

where A and B are constants depending on the particle shape and step length, as well as water velocity distribution. The derived equation using field and experimental data is given as:

$$\phi=40\left(\frac{1}{\psi}\right)^3 \tag{4}$$

for small values of $\Psi<10$.

Chang et al. (2007) modified Einstein's equation (3) by deriving the values of constants A and B using the 346 sets of Malaysian local bed-load data and obtained the following equation:

$$3.811\phi=\mathrm{e}^{-0.491\psi} \tag{5}$$

Eq. (5) has an accuracy of 65% in predicting bed-load transport for all the measured data within DR = 0.5–2.0. The average discrepancy ratio of Eq. (5) for all 346 river data is 1.68 (Chang et al., 2007).

In this study, attempts were made to improve the Einstein equation to yield a better prediction of bed-load transport and for application to the moderate-size and loose-bed rivers in Malaysia. As a result, the ANFIS technique was used in this study to predict bed-load transport in Malaysian rivers more accurately.

5. The networks

A neural network represents the interconnection of neurons, each of which basically carries out the task of combining multiple inputs, determining its strength by comparing the combination with a bias (or alternatively passing it through a non-linear transfer function) and firing out the result in proportion to such a strength as indicated below:

$$O=1/\left[1+\mathrm{e}^{-S}\right] \tag{6}$$

$$S=(x_1w_1+x_2w_2+x_3w_3+\cdots)+\theta \tag{7}$$

where O is the output from a neuron; x_1, x_2, … are the input values; w_1, w_2, … are the weights along the linkages connecting any two neurons and indicate the strengths of the connections; and θ is the bias value. Eq. (6) indicates a transfer function with a sigmoid nature, which is commonly used; although, there are other forms available, like sinusoidal, Gaussian, and hyperbolic tangent. Textbooks (Kosko, 1992; Wasserman, 1993) give theoretical details of the working of an ANN. The known input–output patterns are first used to train a network; the strengths of interconnections (or weights) and

Table 3
Summary of sediment transport assessment (Chang et al., 2007).

Study site	Location	Total of data	Discrepancy ratio for selected bed-load equations							
			Einstein (1942, 1950) bed-load function		Einstein–Brown equation (Brown, 1950)		Meyer-Peter and Müller (1948) equation		Shields (1936) equation	
			Total of data falls within 0.5–2.0	Average of discrepancy ratio	Total of data falls within 0.5–2.0	Average of discrepancy ratio	Total of data falls within 0.5–2.0	Average of discrepancy ratio	Total of data falls within 0.5–2.0	Average of discrepancy ratio
Kerayong River catchment (Yahaya, 1999)	Kerayong River at Kuala Lumpur	24	0	23.8	1	9.1	1	20.7	1	24.0
Kinta River catchment (Yahaya, 1999)	Pari River at Taman Merdeka	16	0	36.5	0	24.0	0	27.6	0	80.7
Kinta River catchment (Ab. Ghani et al., 2003)	Pari River at Manjoi	20	0	89.3	0	73.2	0	57.4	0	230.1
	Pari River at Buntong	20	0	57.0	0	77.0	0	38.8	0	231.6
	Raia River at Kampung Tanjung	20	0	76.9	0	265.8	0	65.4	0	387.5
	Raia River at Batu Gajah	21	0	33.3	0	411.8	0	48.7	0	396.2
	Kinta River at Ipoh	20	0	78.5	0	96.0	0	54.4	0	216.4
	Kampar River at KM 34	21	0	27.5	0	33.2	0	18.3	0	88.84
Langat River catchment (Ariffin, 2004)	Langat River at Kajang	20	0	55.2	0	19,112.1	0	1216.7	0	14,016.9
	Lui River at Kg Lui	92	0	64.3	0	1838.6	0	158.0	0	948.0
	Semenyih River at Kg Sungai Rinching	50	0	23.3	0	2261.1	0	92.0	1	923.0
Kulim River catchment (Chang et al., 2007)	Kulim River at CH 14390	12	0	15.5	0	6.3	0	11.28	0	18.2
	Kulim River at CH 3014	10	0	34.6	0	19.74	0	24.8	0	81.2

bias values are fixed accordingly. Thereafter, the network becomes ready for application to any unseen real-world example. A supervised type of training involves feeding input–output examples until the network develops its generalization capability, while an unsupervised training would involve classification of the input into clusters by some rule. In the supervised training, the network output is compared with the desired or actual one, and the resulting error, or the difference, is processed through a mathematical algorithm. Normally, such algorithms involve an iteration process to continuously change the connection weights and bias until the desired error tolerance is achieved. The traditional training method is standard back-propagation, although numerous training schemes are available to impart better training with the same set of data, as indicated by Londhe and Deo (2003) in their harbour tranquility studies.

Most of the previous works that address ANN applications to water resources have included the feed forward type of the architecture, where there are no backward connections, which are trained using the error back-propagation scheme or the FFBP configuration. Drawbacks of ANN include that it needs more training time and the difficulties in deciding hidden neurons in hidden layer for better predictions. Therefore, the present study applies a new soft computing technique, ANFIS. The input in ANFIS (Fig. 3) is first converted into fuzzy membership functions, which are combined together. After following an averaging process to obtain the output membership functions, the desired output is finally achieved. Mathematical expressions that describe ANFIS are given in Section 5.1.

5.1. The ANFIS networks

This network (Fig. 3) works as follows. Let x and y be the two typical input values fed at the two input nodes, which will then transform those values to the membership functions (say bell-shaped) and give the output as follows. (Note in general, w is the output from a node, μ is the membership function, and M_i and N_i are fuzzy sets associated with nodes x, y.)

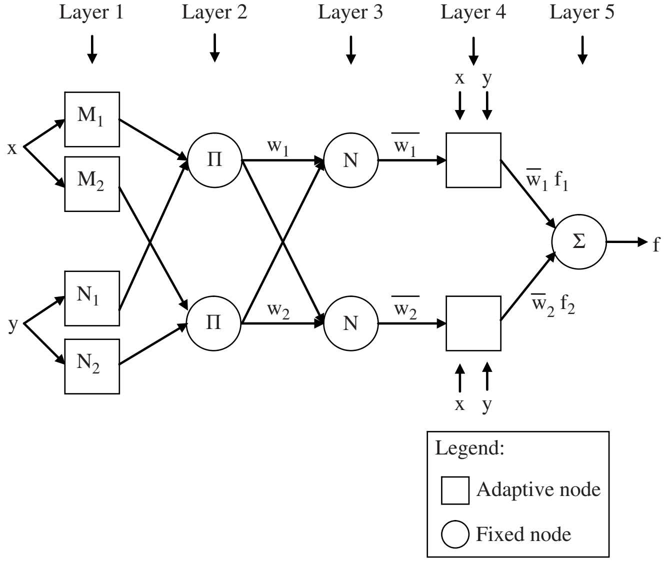

Fig. 3. ANFIS network architecture.

$$\mu_{M_i}(x) = \frac{1}{1 + |(x - c_1)/a_1|^{2N_1}} \tag{8}$$

where a_1, b_1, and c_1 are changeable premise parameters. Similar computations are carried out for the input of y to obtain $\mu_{N_i}(y)$. The membership functions are then multiplied in the second layer, e.g.

$$w_i = \mu_{M_i}(x)\mu_{N_i}(y) \quad (i = 1,2) \tag{9}$$

Such products or firing strengths are then averaged:

$$\overline{w_i} = w_i / \sum w_i \quad (i = 1,2) \tag{10}$$

Nodes of the fourth layer use the above ratio as a weighting factor. Furthermore, using fuzzy if-then rules produces the following output: (an example of an if-then rule is: if x is M_1 and y is N_1, then $f_1 = p_1x + q_1y + r_1$)

$$\overline{w_i}f_i = \overline{w_i}(p_ix + q_iy + r_i) \tag{11}$$

where p, q, and r are changeable consequent parameters. The final network output f was produced by the node of the fifth layer as a summation of all incoming signals, which is exemplified in Eq. (11).

A two-step process is used for faster training and to adjust the network parameters to the above network. In the first step, the premise parameters are kept fixed, and the information is propagated forward in the network to layer 4. In layer 4, a least-squares estimator identifies the important parameters. In the second step, the backward pass, the chosen parameters are held fixed while the error is propagated. The premise parameters are then modified using gradient descent. Apart from the training patterns, the only user-specified information required is the number of membership functions for each input. The description of the learning algorithm is given in Jang and Sun (1995).

The following scenarios are considered in building the ANFIS model (Fig. 4) with the inputs and output shown in the network. From the collected data sets used in this study, around 80% of these patterns were used for training (chosen randomly until the best training performance was obtained), while the remaining patterns (20%) were used for testing, or

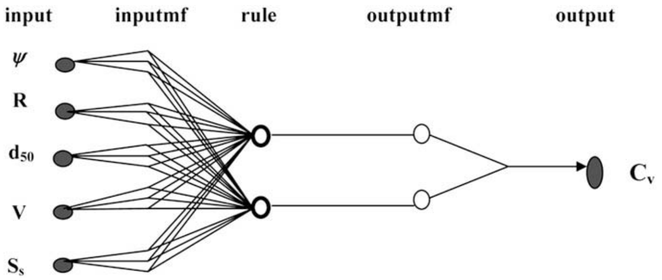

Fig. 4. The ANFIS model for sediment.

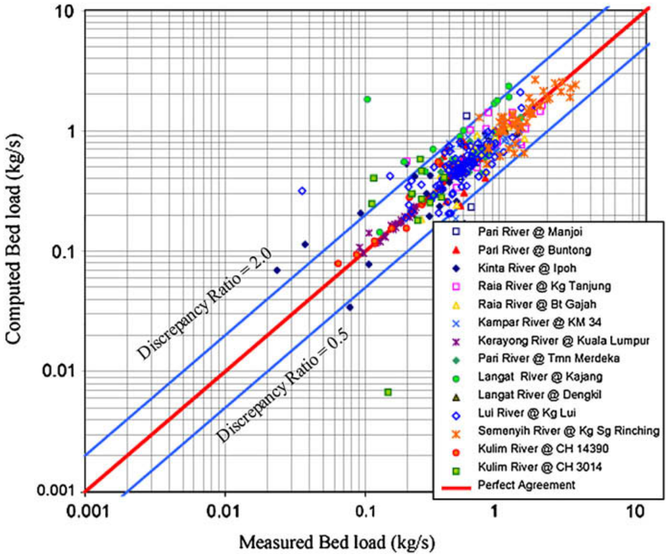

Fig. 5. Predicted bed load against measured bed load using ANFIS.

validating, the ANFIS model. Software was developed to perform the analysis, and can be obtained from the first author.

Utilizing the values of C_v from the ANFIS model, the predicted bed-load rate, T_b, is computed as follows:

$$C_v = \frac{Q_b}{Q} \tag{12}$$

and

$$T_b = Q_b \times \rho_s \tag{13}$$

Q_b is the bed-load discharge, and ρ_s is the density of natural sediments, which is approximately equal to 2650 kg/m^3.

From the analysis, the proposed ANFIS model yielded an accuracy of 90.4% in predicting bed-load transport for all the measured data within DR = 0.5−2.0 (Fig. 5). The average discrepancy ratio for the ANFIS model is 1.18.

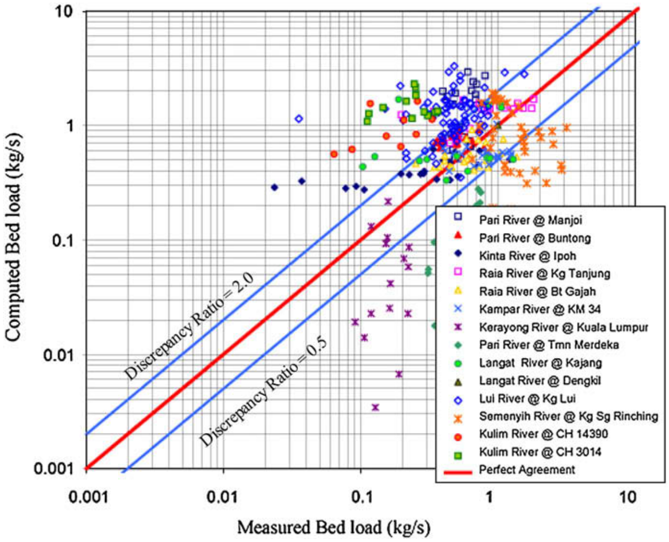

Fig. 6. Predicted bed load against measured bed load using Eq. (5) (Chang et al., 2007).

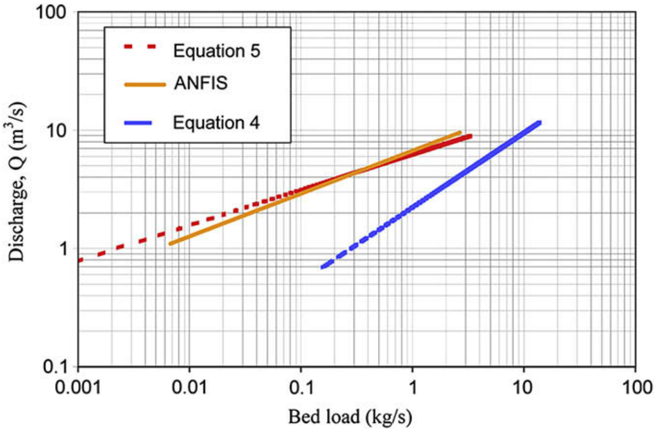

Fig. 7. Comparison of bed-load rating curves.

For comparison, Fig. 6 shows the accuracy of 65% for bed-load prediction using a regression method (Eq. (5)). It can be concluded that the trained ANFIS model performs well when compared to the modified Einstein's equation (5).

Fig. 7 shows the bed-load rating curves for the regression and ANFIS methods. The results show that the predictions by Eq. (5) and ANFIS method tend to merge at higher bed-load rates. However, the original equation by Einstein (Eq. (4)) tends to predict a much higher bed-load rate for a similar flow discharge. Therefore, it is recommended that either Eq. (5) or the ANFIS method to be used for rivers in Malaysia with similar characteristics to those moderately sized rivers in the present study.

6. Conclusions

The study investigates the use of ANFIS technique as an alternative to more conventional bed-load predicting equations, based on measured field data of several Malaysian rivers. ANFIS is less time consuming and more flexible than ANN, by employing fuzzy rules and membership functions incorporating with real-world systems. Existing bed-load transport equations over-predicted the measured bed-load values from several moderately sized rivers, confirming that none of the existing bed-load equations gave satisfactory performance. Using the recommended ANFIS network, the computed bed-load transport rates were in much closer agreement with the measured values when applied to the moderate-size and loose-bed rivers in Malaysia. Based on 346 data sets collected from the Kerayong, Kinta, Langat and Kulim river catchments, the present study indicates that employing local sediment transport data yielded a network that can predict measured bed-load transport in moderately sized rivers more accurately.

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