Synthesis of Analytical and Field Data on Sediment Transport over an Active Bay Shoal

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Abstract
This paper reports field measurements of bed and suspended load transport of marine sand measured *in-situ* on a bay shoal over several spring tides and relates these to analytical assessments of van Rijn. The synthesis of the field and analytical data aims to calibrate the analytical models, providing additional insight on bed-load transport thicknesses, bed load and suspended sediment concentrations. The field study site comprised a sand shoal featuring large sand waves attesting to high sediment transport rates under strong tidal flows. Bed load transport data comprised velocities using a combination of ADCP acoustic and GPS technologies. Bed sediments were sampled and tested for grain size distribution and fall velocities. Suspended transport data comprised ADCP backscatter information with suspended sediment sampling. Some 20,000 data points comprising depth-averaged and bed load velocities and backscatter data have been processed with fall velocity and sieved grain size data. The results inform the goodness of fit of the analytical approaches and the scale of the natural random scatter in field measurements.

Keywords: bed load; suspended sediment transport; ADCP; GPS; van Rijn.

1. Introduction
This paper reports field measurements of bed and suspended load transport of marine sand measured *in-situ* on a bay shoal over several spring tides and relates these to analytical assessments of van Rijn [4] [5] [6] [7] [8] [9]. The synthesis of the field and analytical data aims to calibrate the analytical models, providing additional data on bed-load transport thicknesses, bed load and suspended sediment concentrations.

2. Field Data and Testing
The field study site comprised an extensive sand shoal near the ocean entrance to Port Phillip Bay, Victoria (Figure 1). The shoal experiences tidal currents with speeds exceeding 1.5 m/s on spring tides. The depth over the shoal crest is around 10 m and the seabed features large sand waves of several metres amplitude with wave lengths in the order of 100 m (Figure 1), attesting to large sediment transport rates under strong tidal flows. Seabed level variations of around three metres are common over a period of two years as a result of the migration of sand waves (Figure 1).

Field data on bed load and suspended load transport were collected by UNSW Water Research Laboratory [11]. Bed load transport data comprised the measurement of bed-load transport velocities using a combination of acoustic and GPS techniques [10]. An RDI 1200kHz ADCP determined current velocities in 0.25 m bins and bed load velocities using an &R20 pulse length (~2 m). Boat movements were determined using RTK-GPS. Bed sediments were sampled and tested for grain size distribution and fall velocities.

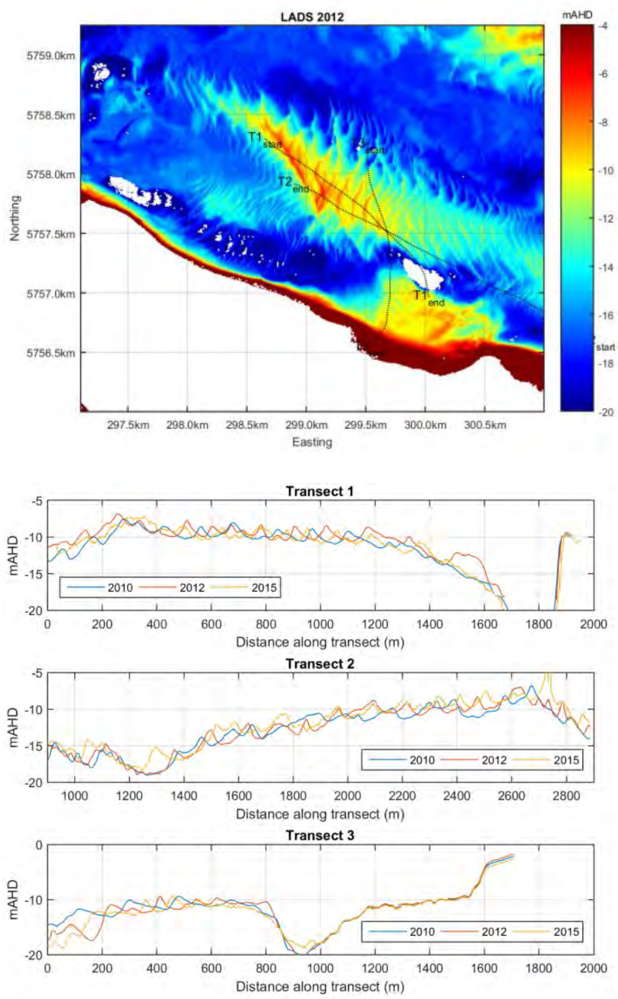

Figure 1 Bathymetry of study area showing the tidal shoals and locations of transects indicating sand wave features and their temporal variability [2].

Suspended sediments were sampled using a pump attached to a turbidity sensor [11]. A level logger measuring depth at five second intervals was attached at the pump intake location. Samples were pumped to the surface and stored in 500 mL bottles for analysis. A range of backscatter readings (and depths) were targeted to capture the full range of backscatter observed during the field investigation.

The field data were obtained over a period of three days. The data presented herein comprised current metering and suspended sediment sampling at three stationary locations (A, B and C in Figure 2) on successive days (22nd & 23rd April 2015).

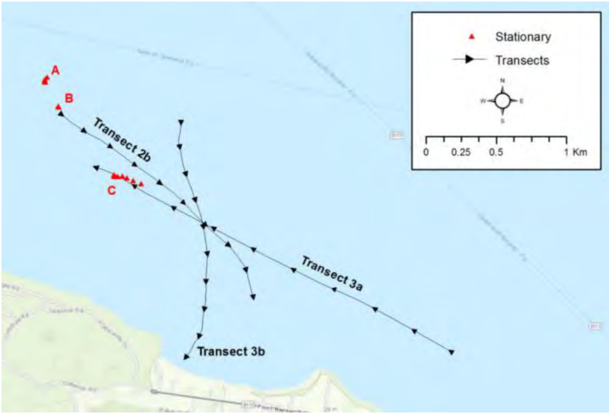

Figure 2 Locations of stationary and transect sites for bed tracking, backscatter and current velocity measurements and suspended sediment sampling [11].

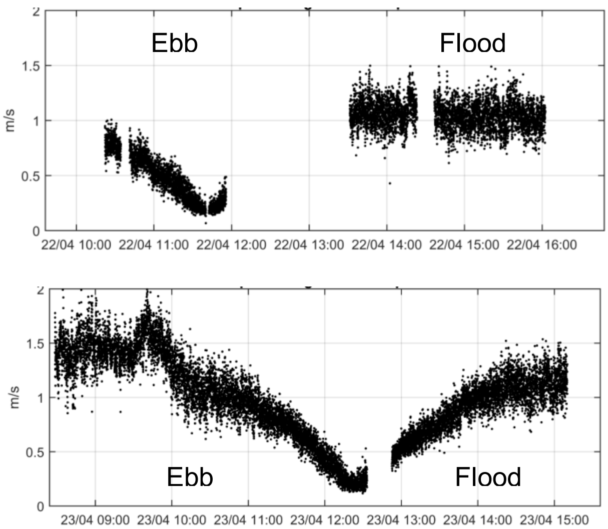

Figure 3 Depth averaged current speeds obtained on 22/04/2015 at Stations A and B (top) and 23/04/2015 at Station C (bottom) [2]

Velocity data were recorded at a frequency of around 0.5 Hz, giving some 20,000 data points. Each velocity data point was replaced with a 1 minute running average to minimise scatter.

Bottom tracking speeds, on average, were a factor of 0.13 smaller than the depth-averaged currents at Site A, 0.24 at Site B and 0.11 at Site C. However, the spread of data was large, with R^2 values being -0.92, -0.12 and 0.19 respectively.

Sediment fall diameters ranged from D_{50} = 0.32 mm to 0.45 mm and D_{90} = 0.40 mm to 0.65 mm (Table 1).

Table 1 Bed sediment grain sizes

Site	Sample	Fall Velocity (cm/s)		Fall Diameter (mm)		Sieve Diameter (mm)	
		W_{50}	W_{90}	D_{50}	D_{90}	D_{50}	D_{90}
A	2A	5.50	6.60	0.39	0.47	0.37	0.48
	2B	5.40	6.48	0.38	0.46		
B	3A	4.43	5.82	0.32	0.41	0.36	0.49
	3B	4.54	5.59	0.33	0.40		
C	6	6.36	8.61	0.45	0.65	0.30	0.63

The fall diameter, D, was computed from the measured fall velocity, w_s, using the following relationship [6]:

$$w_s = 10\,\vartheta\,D^{-1}[(1+0.01(s-1)\,g\,D^3\,\vartheta^{-2})^{0.5}-1] \qquad (1)$$

where the kinematic viscosity, ϑ, for seawater at 16°C is 1.16×10^{-6} m²/s.

3. Analytical Formulations

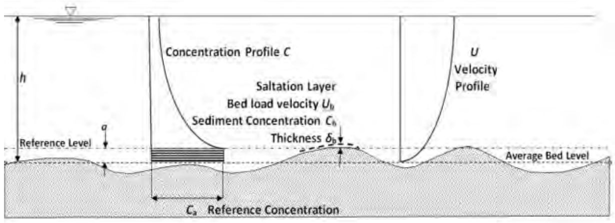

Figure 4 Definition schema [6]

3.1 Bed Sediment Transport

Van Rijn has published comprehensive research of analytical, laboratory and field studies of bed load transport under currents and waves that is applied widely [4], [6], [7], [8], [9]. Van Rijn [8] proposed a simplified formula for bed-load transport under current only conditions as:

$$q_b = 0.015\,\rho_s\,U\,h\,(D_{50}/h)^{1.2}\,M_e^{1.5} \qquad (2)$$

where q_b = bed-load transport rate (kg/s.m); $M_e = (U-U_{cr})/[(s-1)gD_{50}]^{0.5}$ (-); U = depth-averaged velocity (m/s); U_{cr} = critical depth-averaged velocity for initiation of motion (m/s); D_{50} = median particle size (m); h = water depth (m); ρ_s = sediment density (kg/m³); $s = \rho_s/\rho_w$ specific density (-).

All computed values are said to be within a factor two from the measured bed load transport rates for velocities larger than 0.6 m/s [8]. The measured values are under-predicted (factor two to three) for velocities close to initiation of motion [8].

3.2 Suspended Sediment Transport

Van Rijn [6] defined the suspended sediment concentration C at a level z above the bed, for $z/h < 0.5$ as:

$$C = C_a\,[a\,(h\text{-}z)\,/\,z\,(h\text{-}a)]^{Z'} \qquad (3)$$

where C_a is the reference concentration at a level a above the bed (Figure 4); a is ½ the bedform height, $3D_{90}$ or $0.01h$ (minimum); z is the height above the bed; $Z' = w_s/(\beta k\, u_{*,c})$ = suspension number; w_s = fall velocity, $\beta = 1+2(w_s/u_{*,c})^2$ = diffusion factor; k = von Karmon constant (0.4), $u_{*,c}$ = current-related bed shear velocity.

The simplified formula for suspended load transport, q_s (kg/s.m), under steady flow proposed by van Rijn [9] reads as:

$$q_s = 0.03\,\rho_s\,U\,D_{50}\,M_e^2\,D_*^{-0.6} \qquad (4)$$

where $D_* = D_{50}[(s\text{-}1)g/\vartheta^2]^{1/3}$ dimensionless particle size (-); $M_e = (U\text{-}U_{cr,sus})/[(s\text{-}1)\,g\,D_{50}]^{0.5}$(-); $U_{cr,sus} = 2.8\,(h/D_{50})^{0.1}\,[(s\text{-}1)\,g\,D_{50}]^{0.5}$ (m/s).

The suspended transport is somewhat under-estimated for fine sediments (< 0.1 mm) and for velocities close to the critical velocity for suspension [8], [9], which is around 0.6 m/s for the data herein.

4. Synthesis of Analytical and Field Data

4.1 Bed Load Transport

The bed load transport from the field data is given by:

$$q_b = U_b\,C_b\,\rho_s\,\delta_b \qquad (5)$$

where U_b = bed tracking velocity (m/s); C_b = bed load sediment concentration (- ; 0.65 max); δ_b = thickness of bed load transport layer (m).

Both the bed load sediment concentration and the layer thickness will depend on the transport parameter T and the dimensionless grain size D_* thus [4], [6]:

$$T = (\tau_b - \tau_{b,cr})/\tau_{b,cr} \qquad (6)$$

Where $\tau_b = \rho g(U/C')^2$; $C' = 18 \log(12h/3D_{90})$ grain-related Chezy coefficient; $\tau_{b,cr} = \theta_{cr}(s\text{-}1)\rho g D_{50}$ critical Shield's parameter.

The bed load sediment concentration C_b is [6]:

$$C_b = 0.18\,C_o\,T/D_* \qquad (7)$$

Where $C_o = 0.65$ (- ; maximum bed sediment concentration).

The bed load thickness, δ_b, has been assumed to be a function of grain diameter, D, dimensionless grain diameter D_* and transport parameter, T, as shown in Figure 5.

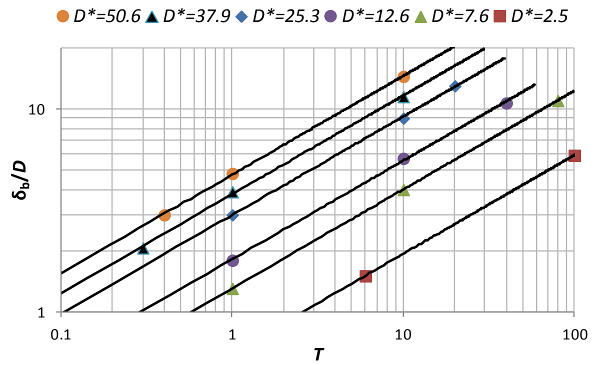

Figure 5 Relative bed load thickness as a function of the transport stage parameter, T, and the dimensionless particle size D_* [4], [6]

For seawater at 16°C, the relationship in Figure 5 can be expressed as follows:

$$\delta_b = 340\,D_{50}^{1.7}\,T^{0.5} \qquad (8)$$

Bed load transport rates were calculated from the bed tracking data with bed load sediment concentrations using Equation 7, thicknesses using Equation 8 and compared with the van Rijn formulations using grain size parameters determined from fall velocity measurements (fall diameters) and sieving (Figure 6).

Time histories of the bed tracking transport rate data synthesised with the van Rijn formulations using fall and sieved diameters are in Figure 7, which shows natural variations in rates of around half an order of magnitude.

Calculated bed load sediment concentrations varied around an average of 0.07 (200 kg/m^3) with a maximum of 0.20 (500 kg/m^3). Bed load thicknesses varied around an average of 1.5 mm ($3D_{90}$) with a maximum of 2.9 mm ($6D_{90}$), which was in the order of that assumed originally as $2D$ by Einstein [1] and as observed as $8D_{90}$ later in flume studies by Ramooz & Rennie [3].

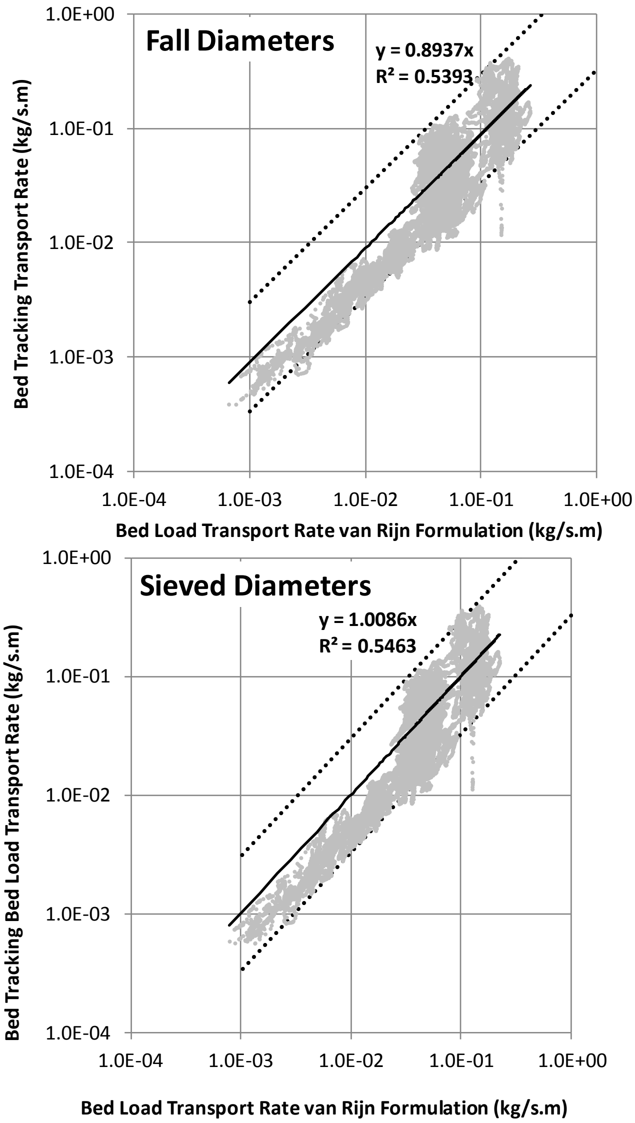

Figure 6 Synthesis of the bed tracking transport rate data with the van Rijn formulations using fall diameters (top) and sieved diameters (bottom). Dashed lines denote factors 0.33 to 3.0

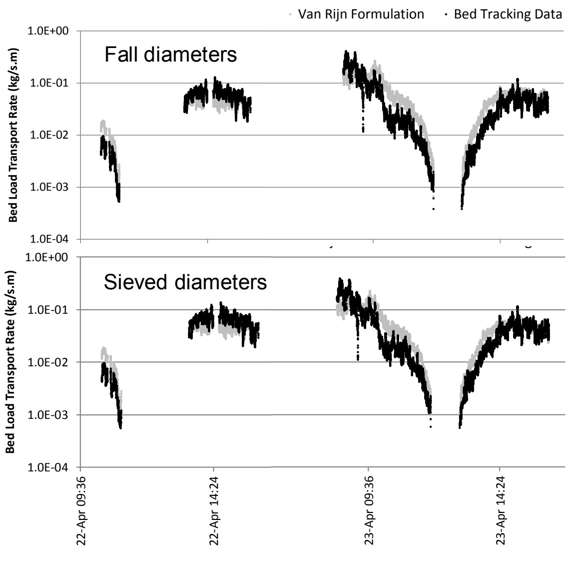

Figure 7 Time history of the bed tracking transport rate data synthesised with the van Rijn formulations using fall diameters (top) and sieved diameters (bottom).

4.2 Suspended Load Transport

The field data on measured suspended sediment concentrations are plotted against modelled data in Figure 8 using fall diameters and assuming $a = 3D_{90}$, which indicated that Equation 3 over-estimated the field data by a factor of 4.

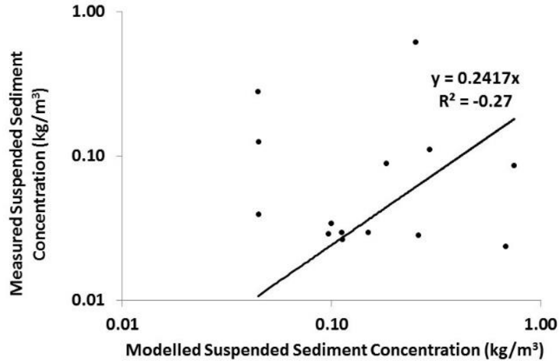

Figure 8 Relationship between measured and modelled suspended sediment concentrations using calculated values for β varying from 2.9 to 4.8

For the modelled data in Figure 8 the calculated values for β varied from 2.9 to 4.8 with an average of 4.1. Given the limited knowledge of physical processes involved, it is not advisable to use a β-factor greater than 2.0 [6]. Nevertheless, a β-factor of 3.33 applied to all the data returned a better relationship between the measured and modelled suspended sediment concentrations (Figure 9). The calculated values were very sensitive to the value adopted for the β-factor.

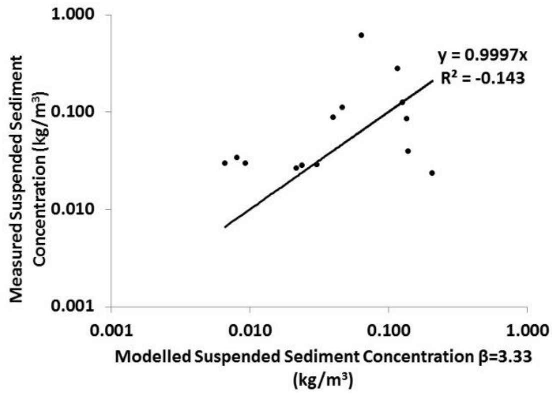

Figure 9 Relationship between measured and modelled suspended sediment concentrations using β = 3.33

The relationship between measured suspended sediment concentrations and ADCP backscatter data used in the computations herein is shown in Figure 10. While the data were not well-conditioned and the relationship shown was not a good fit, the relationship was used to calculate suspended sediment transport rates from the backscatter data, which were compared with the van Rijn formulation using grain size parameters determined from fall velocity measurements and those from sieving, presented in Figure 11, with time history comparisons presented in Figure 12.

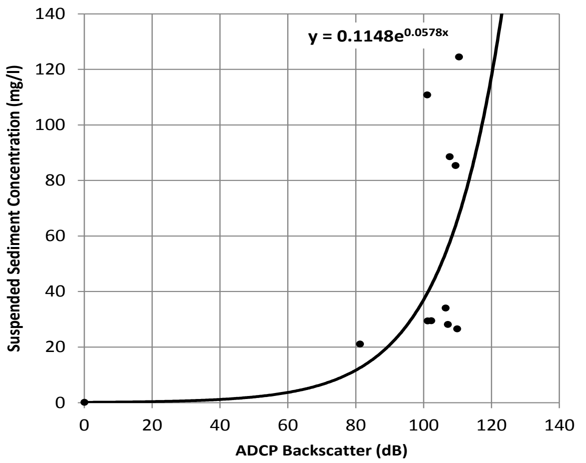

Figure 10 Adopted relationship between measured suspended sediment concentrations and ADCP backscatter data used in the computations herein.

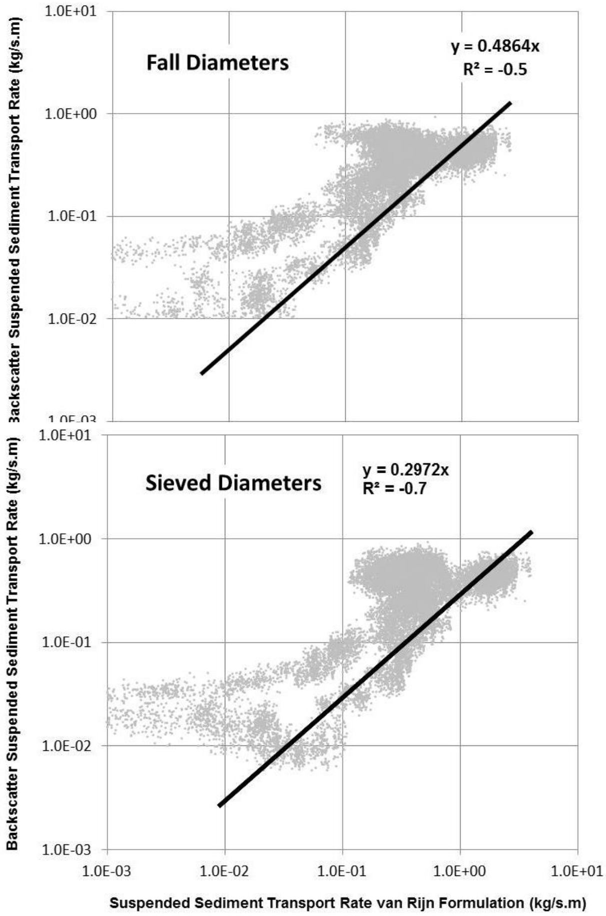

Figure 11 Comparison of the back scatter suspended transport rate data with the van Rijn formulation using fall diameters (top) and sieved diameters (bottom).

5. Discussion

5.1 Bed Load Transport

The data synthesised herein with the analytical formulations of van Rijn [8] for bed load transport indicated a natural scatter of a factor of 3 (0.33 to 3.0), as was indicated also by the extensive flume data to which the formulae were calibrated [4], [6].

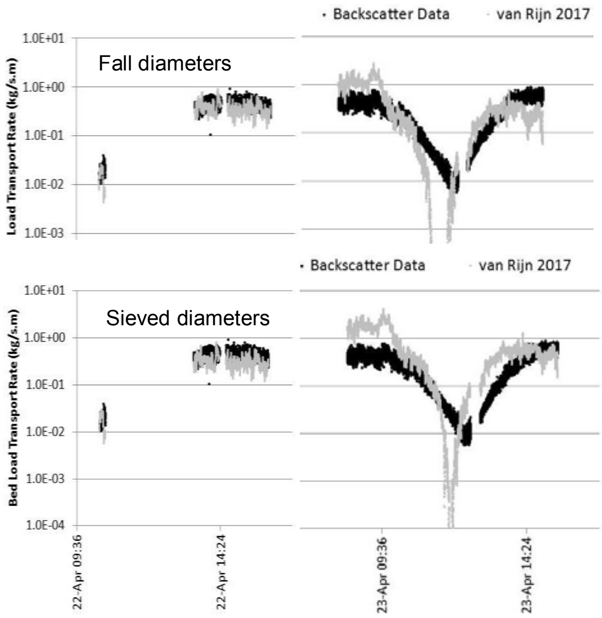

Figure 12 Time history comparisons of the back scatter suspended transport rate data with the van Rijn formulation using fall diameters (top) and sieved diameters (bottom).

The sieved diameters gave a better goodness of fit, although the difference was small.

Van Rijn [6] computes the bed load velocity as:

$$U_b = 1.5\ T^{0.6}[(s\text{-}1)gD]^{0.5} \qquad (9)$$

Comparisons of calculated bed load velocities, using D_{50}, with the field bottom tracking data indicated that Equation 9 over-estimated consistently the measured values by a factor of around 3 (Figure 13). This implied that either the sediment concentrations or the bed load thicknesses, or both, may be under-estimated by the formulae or that the bed tracking data may be under-estimating the velocities.

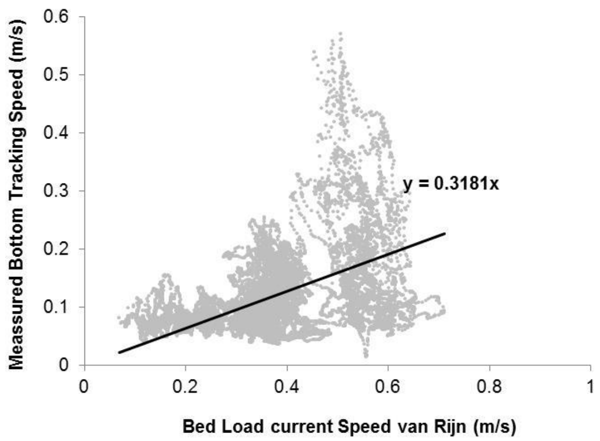

Figure 13 Comparison of the bed tracking measured current speed data with the van Rijn formulation using sieved diameters.

5.2 Suspended Load Transport

The rate of the total suspended load transport was higher than that of the bed load, as is predicted analytically [8]. However, field estimates of the rate are difficult to calibrate. The relationship between backscatter readings and measured suspended sediment concentrations is difficult to determine accurately. For the data herein, all but one of the higher values of suspended sediment concentrations measured were sampled on flood tides, which may have brought sediments to the site in suspension from the entrance area where the wave energy was much higher; that is, the suspended sediments sampled may not have been generated solely by the current speeds at the sampling site. All but one of the ebb tide samples had much lower concentrations, the flow originating from quiescent conditions.

While the relationship between the measured and modelled suspended sediment concentrations was not good, the formula for calculating the rate provided a better fit for the trend when fall diameters were used. However, either diameter could be made to fit the data well by adjusting the empirical coefficient. The field data generated scatter of an order of magnitude.

The backscatter data produced suspended sediment transport rates of around 0.01 to 0.1 kg/m^3 when the van Rijn formula gave rates that were orders of magnitude smaller. It is likely that this has resulted from reflecting particles in the water column that were not bed sediments but, possibly, were organics of neutral buoyancy or other extraneous materials.

The field data (backscatter readings calibrated to suspended sediment sampling, depth-dependent flow speeds) were calculated entirely independently from the analytical data (sediment grain size, average flow speed, water depth). Notwithstanding the large scatter as expected from such random field data, that the trend lines for the modelled versus measured data had surprisingly good fits with slopes ranging from 0.5 for fall diameters and to 0.3 for sieved diameters. Better fits can be obtained by using the field data to calibrate the analytical data by adjusting the empirical coefficient.

6. Conclusions

Improved assessments of bed load and suspended load transport over a bay shoal under strong tidal flows can be made when formulae are synthesised and calibrated with site-specific field data.

For estimates of bed load transport, the sediment concentrations, the bed load thicknesses or both may be under-estimated by the van Rijn formulae or the bed tracking data may be under-estimating the bed load velocities. Sieved diameters gave a slightly better result for bed load transport whereas a far better calibration for suspended sediment transport was achieved using fall diameters.

The field data herein demonstrated the random nature of natural processes with bed load transport estimates having a precision of no better than a factor of three (0.3 to 3.0) whereas the precision of suspended sediment transport estimates was no better than a factor of around five (0.2 to 5.0).

7. Acknowledgement

Field data were collected by the Water Research Lab. UNSW for the Department of Environment, Land, Water & Planning, Victoria. David Williams (AIMS) provided advice on bed tracking.

8. References

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