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From: Matt Pinkerton, NIWA
Date: 4 September 2015
Re: Contribution to source terms report for TTR

1 Source rates for the hydrodynamic model

1.1 Objective

The proposed mining of iron-sand in the South Taranaki Bight will release sediment into the water column. The hydrodynamic model (Hadfield, 2015) is designed to simulate the movement of this material in the environment. The source rates (i.e. mass flow rates) of sediment discharged from the mining process are needed to drive this modelling. Sediment will be discharged from two sources: (1) "overflow", from the hydrocyclone; and (2) "underflow" from the de-ored sand being returned to the seabed. See TTR (2015) for details of the proposed mining operation. Mass flow rates for both sources are required.

In revisions to the modelling since 2013, it was decided to model the sediment according to its sinking rate rather than its nominal particle size (Hadfield, 2015). Using sink rate rather than particle size in the modelling allows for the effect of flocculation[1] to be taken into account. The revised hydrodynamic modelling (Hadfield, 2015) is hence based on four categories of sinking rate:

Nominal sinking speed = 10 mm/s (sinking speeds >3.2 mm/s)

- Nominal sinking speed = 1 mm/s (sinking speeds 0.32 – 3.2 mm/s)
- Nominal sinking speed = 0.1 mm/s (sinking speeds 0.032 – 0.32 mm/s)
- Nominal sinking speed = 0.01 mm/s (sinking speeds <0.032 mm/s)

The objective of this part of the work was to use laboratory measurements by Hydraulics Research Wallingford (HRW) to estimate the appropriate source rates in each of these sinking speed classes for the hydrodynamic model.

1.2 Laboratory measurements by HRW

Samples of the sediment likely to be discharged by the mining process were provided to HRW by TTR. Four experiments on sinking speed were carried out on this material by HRW in 2014 and 2015, and are briefly summarised below. The experiments are described in detail in: HRW (2014), HRW (2015), Dearnaley (2014), Dearnaley (2015), and Dearnaley & Spearman (2015).

1.2.1 Beaker experiment

Sediment was resuspended by stirring into a beaker of water (either fresh water or salt water). At periods of 10 minutes, 1 hour and 5 hours after stirring stopped, samples of water were withdrawn from three different depths in the beaker and the concentration of the withdrawn sample measured gravimetrically. The proportion of the initial concentration remaining in suspension at a given time after stirring stopped gives information on the proportion of mass in the sample with a sinking speed less than a certain value.

[1] Flocculation is the process by which small particles can bind together and create larger, loosely-bound groups of particles (called "flocs") that sink faster than the individual particles.

1.2.2 Bucket experiment

The beaker experiment was repeated in a larger container. This provided additional information on the proportion of mass with certain sinking speeds.

1.2.3 Bucket turbidity measurements

An infra-red turbidity sensor was used to measure changes in turbidity with time in the bucket. These data provide a check on whether the combination of estimated sink rates and optical properties of the sediment (Pinkerton & Gall, 2015) are plausible.

1.2.4 Camera measurements of flocs

HRW (2014) used a camera system (called LabSFLOC-2) to measure the frequency, size and sinking speed of flocs in freshwater and saltwater.

1.3 Proportions of mass with different sink rates

The data from the HRW beaker test and bucket tests were combined and used to derive the relationship between sinking speed (v, mm/s) and the proportion of mass of the sample with a sinking speed less than v (m, %). It is important to note that this analysis works in terms of the cumulative distribution of sinking speed, and does not group sediment into sinking rate categories. By analysing the data in terms of the continuous distribution of sinking speed we avoid having to assume any arbitrary grouping of sink speeds. The continuous distribution can then be used to estimate the proportion of mass in any sink rate categories required by the modelling.

The analysis approach is to use the proportion of sediment remaining in suspension at a given depth below the water surface (x) after a given settling time (t) as an indication of the proportion of the mass that has a lower settling speed than x/t. The concentration c(x,t) divided by the initial concentration at that depth x will approximately be equal the proportion of the mass with a sinking speed less than x/t. This analysis assumes that advective sinking (rather than diffusion) is the key process determining the mass remaining in suspension at a given time.

A regression line was fitted to the cumulative sink rate data given in Table 1-1 (beaker test) and Table 1-2 (bucket test) as shown in Figure 1-1. The form of this relationship shown in Equation 5-1 was chosen because it has the properties of m tending to 100% as v tends to infinity, and m tending to 0% as v tends to zero. Fitting a different shape of curve for the data, using a quadratic rather than a linear regression in log-log space, was tried. For the salt-water case, the quadratic fit slightly improved the proportion of deviance explained (from R^2=0.932 to R^2=0.950). There was no improvement in fit for the freshwater case. Given the marginal improvement, the simpler curve shape was used.

Salt-water: $$ln\left(\frac{m}{100}\right) = -0.4809v^{-0.3895}$$ [Equation 5-1a, salt water]

Fresh-water: $$ln\left(\frac{m}{100}\right) = -0.3680v^{-0.4800}$$ [Equation 5-1b, fresh water]

Table 1-1: Beaker test: summary data used to derive the relationship between sinking speed and cumulative mass. Data based on HRW (2014), table 3.3. The total depth of water in the beaker is 12.6 cm. “Critical sinking speed” is the speed that sediment would need to sink at to reach the depth at which the measurement of concentration was made in the time since stirring stopped.

Test	**Type**	**Approx. temperature of test (°C)**	**Depth as proportion of total depth** (%)	**Time** (mins)	**Mass in 50ml** (mg)	**Depth below surface** (mm)	**Critical sinking speed at temperature of test** (mm/s)	**Critical sinking speed at 17°C** (mm/s)	**Conc**. (g/l)	**Conc/initial** (%)
Beaker	Salt	17	25	10	14.5	31.5	0.0525	0.0525	0.29	29
Beaker	Salt	17	50	10	15.2	63	0.105	0.105	0.304	30.4
Beaker	Salt	17	75	10	19.9	94.5	0.1575	0.1575	0.398	39.8
Beaker	Fresh	17	25	10	15.1	31.5	0.0525	0.0525	0.302	30.2
Beaker	Fresh	17	50	10	17.1	63	0.105	0.105	0.342	34.2
Beaker	Fresh	17	75	10	18.8	94.5	0.1575	0.1575	0.376	37.6
Beaker	Salt	17	25	60	4.1	31.5	0.00875	0.00875	0.082	8.2
Beaker	Salt	17	50	60	3.2	63	0.0175	0.0175	0.064	6.4
Beaker	Salt	17	75	60	7	94.5	0.02625	0.02625	0.14	14
Beaker	Fresh	17	25	60	2.3	31.5	0.00875	0.00875	0.046	4.6
Beaker	Fresh	17	50	60	4.8	63	0.0175	0.0175	0.096	9.6
Beaker	Fresh	17	75	60	5.7	94.5	0.02625	0.02625	0.114	11.4
Beaker	Salt	17	25	300	0.5	31.5	0.00175	0.00175	0.01	1
Beaker	Salt	17	50	300	0.6	63	0.0035	0.0035	0.012	1.2
Beaker	Salt	17	75	300	1.3	94.5	0.00525	0.00525	0.026	2.6
Beaker	Fresh	17	25	300	0.1	31.5	0.00175	0.00175	0.002	0.2
Beaker	Fresh	17	50	300	0.1	63	0.0035	0.0035	0.002	0.2
Beaker	Fresh	17	75	300	0.2	94.5	0.00525	0.00525	0.004	0.4

Table 1-2: Bucket test: summary data used to derive the relationship between sinking speed and cumulative mass. Data based on Dearnaley & Spearman (2015) table 2 ("bucket" test). The total depth of water in the bucket is 21 cm. "Critical sinking speed" is the speed that sediment would need to sink at to reach the depth at which the measurement of concentration was made in the time since stirring stopped. An adjustment of 11% was made to sinking speeds in the bucket test to allow for the lower temperature and higher dynamic viscosity during this test. The results will be applicable to water of an approximate temperature of 17°C.

Test	**Type**	**Approx. temperature of test (°C)**	**Depth as proportion of total depth** (%)	**Time** (mins)	**Mass in 50ml** (mg)	**Depth below surface** (mm)	**Critical sinking speed at temperature of test** (mm/s)	**Critical sinking speed at 17°C** (mm/s)	**Conc**. (g/l)	**Conc/initial** (%)
Bucket	Salt	12	50	10		105	0.175	0.1943	0.437	43.7
Bucket	Salt	12	50	60		105	0.029167	0.0324	0.094	9.4
Bucket	Salt	12	50	180		105	0.009722	0.0108	0.031	3.1
Bucket	Salt	12	50	300		105	0.005833	0.0065	0.021	2.1
Bucket	Fresh	12	50	10		105	0.175	0.1943	0.475	47.5
Bucket	Fresh	12	50	60		105	0.029167	0.0324	0.091	9.1
Bucket	Fresh	12	50	180		105	0.009722	0.0108	0.025	2.5
Bucket	Fresh	12	50	300		105	0.005833	0.0065	0.015	1.5

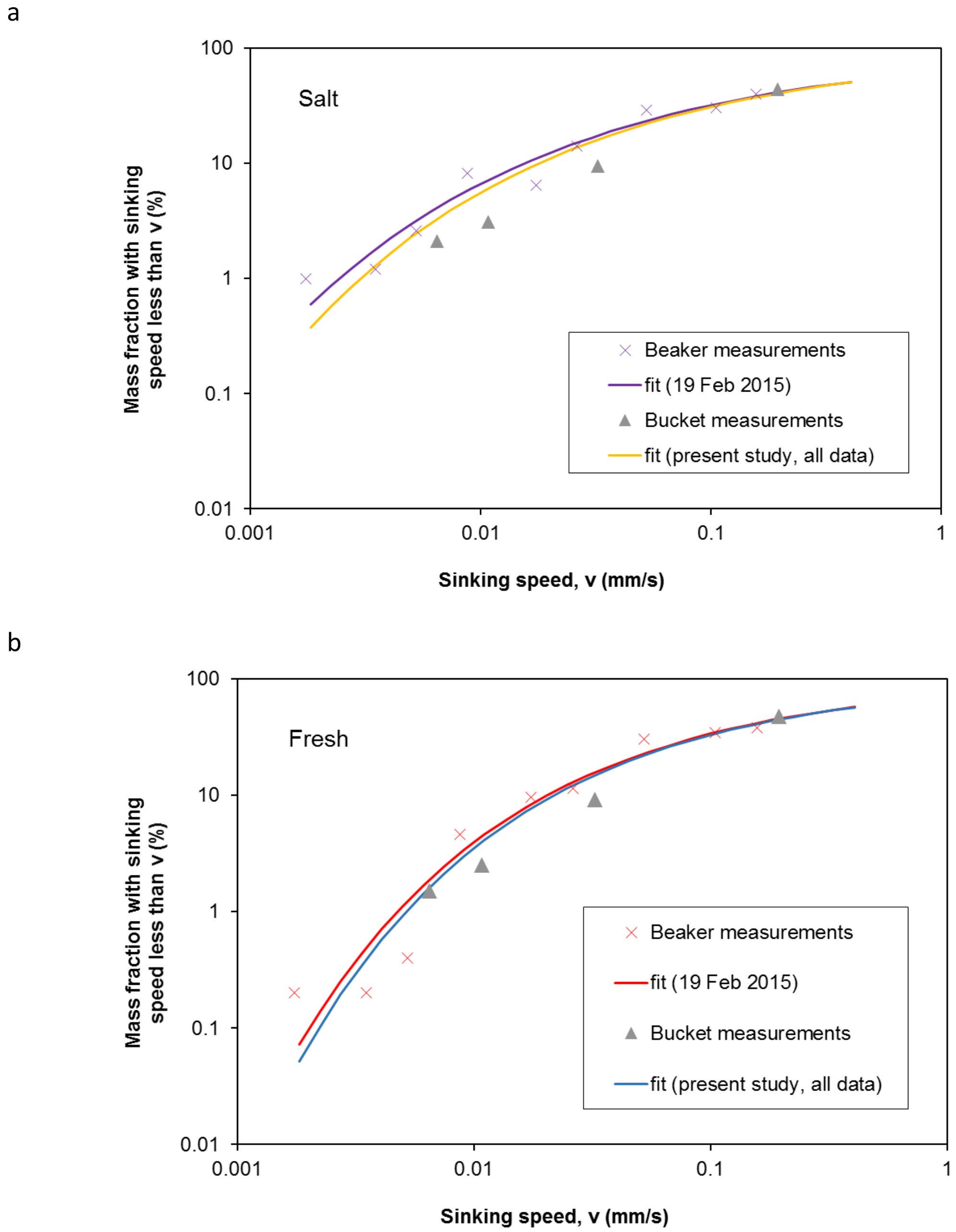

Figure 1-1: Analysis of sink-rate measurements using beaker and bucket tests. Data are shown in Table 1-1 and Table 1-2.

1.4 Higher sinking speeds

The beaker and bucket settling experiments described in Section 1.3 provide information on the proportions of the mass with settling rates between 0.0018 and 0.19 mm/s but provide no information on settling rates greater than this. Information on higher sinking rates are needed to estimate source rates in the 1 mm/s and 10 mm/s classes.

To provide a lower bound of sinking rates, estimates based on the cumulative mass distribution given by HRW (2014) can be used to estimate the sinking rate distribution in the absence of flocculation using Stokes Law settling (Equation 5-2; blue, green and red lines in Figure 1-2). Here, v is the particle's terminal settling velocity (m/s), g is the gravitational acceleration (m/s^2), ρ_p is the mass density of the particles (kg/m^3), ρ_f is the mass density of the fluid (kg/m^3), μ is the dynamic viscosity (kg/ms) and R is the radius of the particle (m, assumed spherical). The analysis used a specific gravity of 2.82 (Table 3.1, HRW 2014) and water density and dynamic viscosity for seawater with salinity of 35 and temperature of 12°C. If flocculation occurs, the sinking speeds will be lower than given by Stokes Law, but it is not clear by how much

Stokes Law settling: $$v = \frac{2}{9}\frac{(\rho_p - \rho_f)}{\mu} g R^2$$ [Equation 5-2]

A two-part function as shown in Equation 5-3 is suggested for sinking rates across the whole range of sinking rates (0.001 – 30 mm/s). The sink rates distribution from this equation is consistent with the presence of large flocs with sinking rates 0.3–3 mm/s (as measured by the LabSFLOC-2 measurements), and leads to estimates of turbidity that are consistent with measurements of bucket turbidity (Figure 1-3).

Salt-water: $$ln\left(\frac{m}{100}\right) = \max[-0.4809v^{-0.3895}, -0.2725v^{-0.8856}]$$ [Equation 5-3a]

Fresh-water: $$ln\left(\frac{m}{100}\right) = \max[-0.3680v^{-0.4800}, -0.2170v^{-0.8856}]$$ [Equation 5-3b]

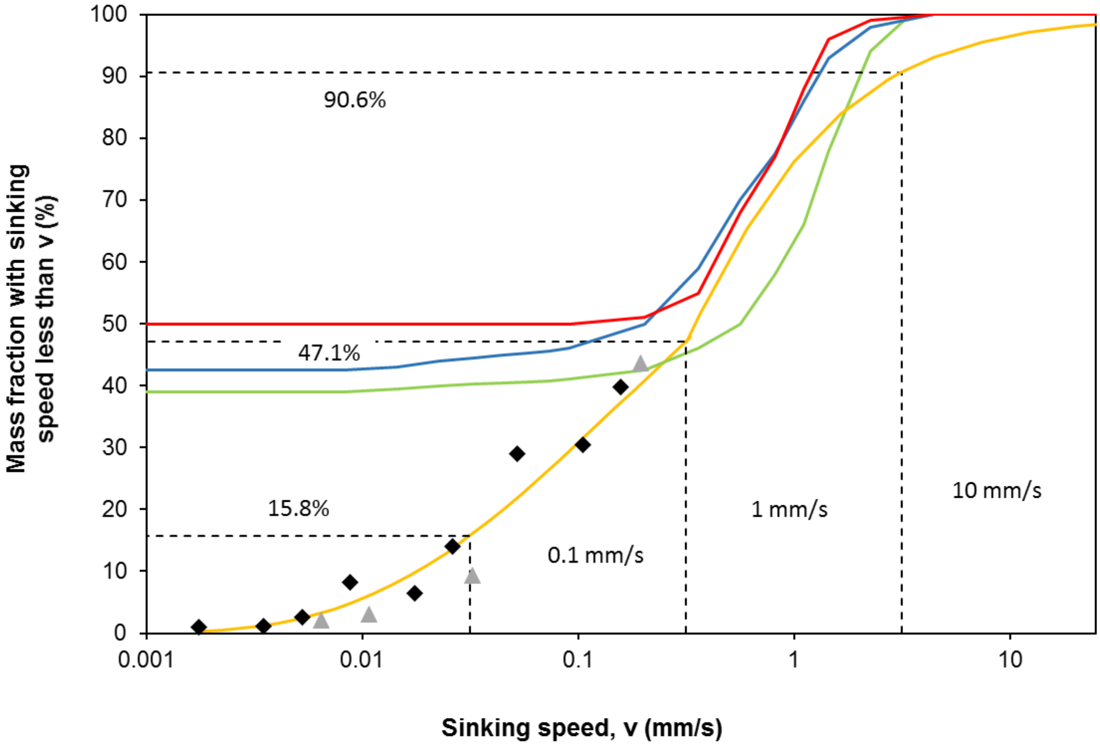

Figure 1-2: Proposed sinking rates of sediment in salt water. Black diamonds are “beaker test” values measured by HRW (2014). Grey triangles are “bucket test” data (Dearnaley & Spearman, 2015). Orange line: proposed sinking rate distribution. The lower portion of the orange line (v<0.32 mm/s) is fitted as described in the text (Equation 5-1a). The upper portion is given by Equation 5-3a in order to fit the “bucket” turbidity test measurements (HRW, 2014). The thin dashed lines indicate suggested boundaries for sinking rate categories for the revised modelling. Blue, green, red lines show Stoke’s Law settling speeds based on blue/green/red particle size distributions shown in HRW (2014, Figure 3.3) and indicate that sinking speeds are always greater than Stokes Law – as expected if flocculation occurs.

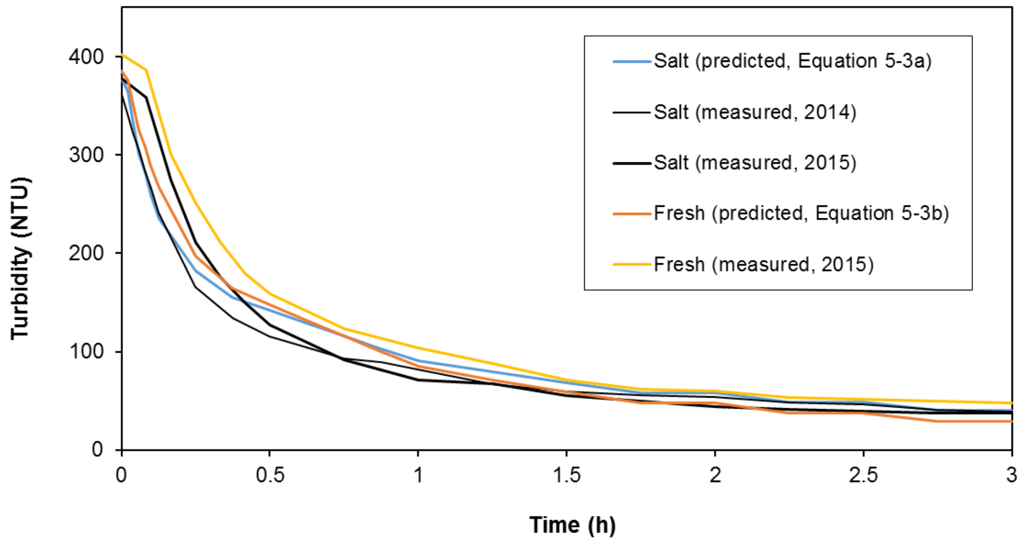

Figure 1-3: Comparison of modelled and measured turbidity. Estimates of turbidity (backscatter at 865 nm scaled to measured Normalised Turbidity Units (NTU) of salt water at t=1 second) based on Equation 5-3a and using measurements of the mass-specific backscatter of particles (Pinkerton & Gall, 2015) and effective floc densities in salt-water and fresh-water from HRW (2014).

1.5 Recommended source rates

Here, we propose using the Equation 5-3a for estimating source rates in the revised hydrodynamic modelling, which leads to source rates shown in Table 1-3.

1.6 Source rate analysis by HRW

1.6.1 Slow sinking sediment (0.01 and 0.1 mm/s classes)

The experiments on sinking speed carried out by HRW in 2014 and 2015, were analysed as described in HRW (2014), HRW (2015), Dearnaley (2014), Dearnaley (2015), and Dearnaley & Spearman (2015). The analysis by HRW used a model of 1-dimensional settling ("1DV"), based on sediment in three size classes and including diffusion.

The HRW 1DV model estimates that the slow-settling sediment has a higher sinking speed than Equation 5-3a. This leads to smaller source rates in the 0.01 mm/s sinking classes than Table 1-3, but similar source rates to that in Table 1-3 for the 0.01 mm/s and 0.1 mm/s classes combined. The difference between the analysis of HRW and that described here seems to be mainly due to whether diffusion or simply low sinking rate is primarily responsible for the tail of slow settling sediment observed in the HRW beaker and bucker experiments. These differences are not very large and it is reasonable to use an average of the two methods to drive the sediment transport model of Hadfield, (2015).

1.6.2 Faster sinking sediment (1 and 10 mm/s classes)

HRW use data from the LabSFLOC2 camera system to estimate the proportion of mass with sinking rates above about 0.3 mm/s. The LabSFLOC2 camera system measured sinking rates in samples from a recirculating system, and this system is likely to lead to different amounts of flocculation than the beaker and bucket tests. Hence, the LabSFLOC2 data cannot be used directly to infer the relative amounts of mass in the 1 and 10 mm/s categories from the beaker and bucket tests. It is not known whether the beaker/bucket test or recirculating system is likely to more closely resemble flocculation and sinking rates in the natural environment.

1.6.3 Comparison of sediment profiles

The shapes of the predicted profiles of suspended sediment using Equation 5-3a (Figure 1-4) are somewhat different to those in Dearnaley & Spearman (2015; Figure 1 for the beaker test; figure 5 for the bucket test). Overall, these predictions appear to be no better and no worse than those using the HRW 1DV model (Dearnaley & Spearman, 2015).

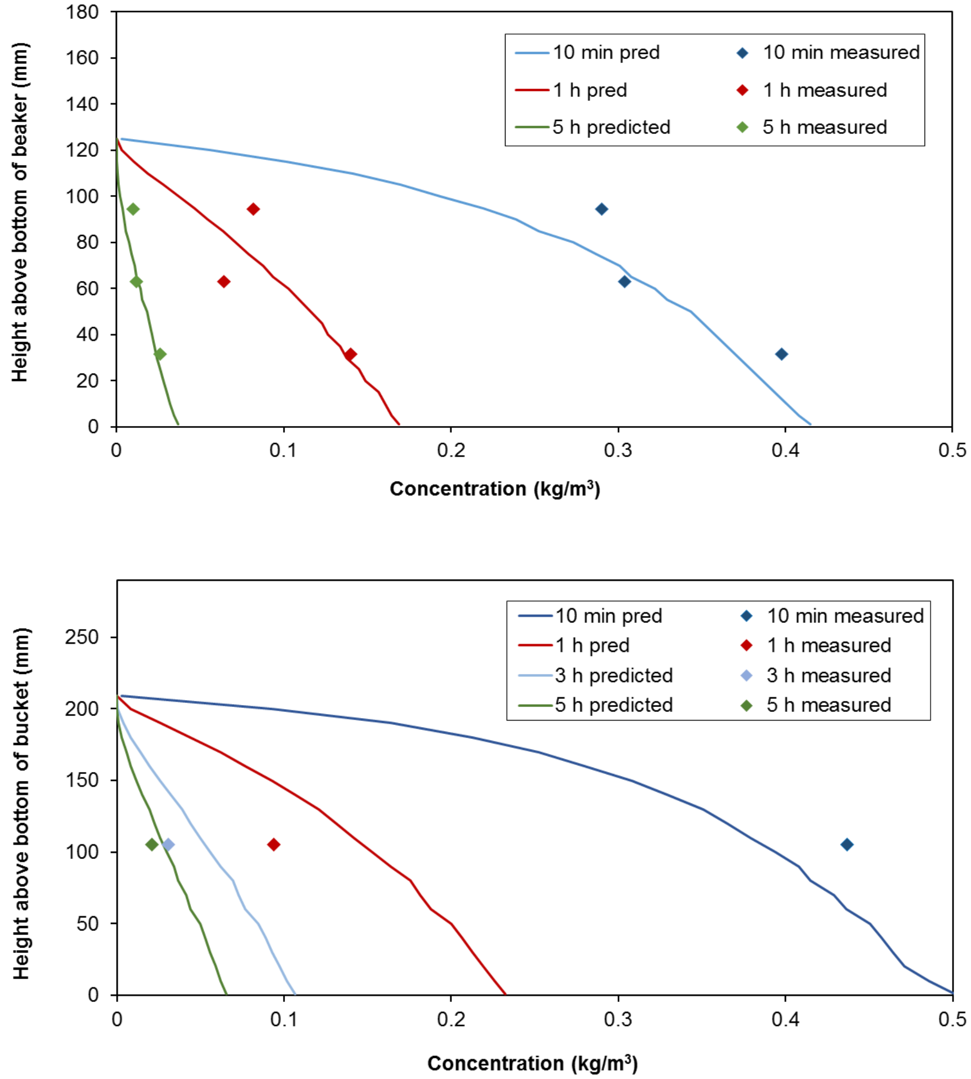

Figure 1-4: Predicted and measured profiles of sediment concentration. Predicted profiles of sediment concentration at different times after ceasing stirring for **a**: beaker test (compare to Dearnaley & Spearman (2015) Figure 1); and **b**: bucket test (compare with Dearnaley & Spearman (2015), figure 5).

1.6.4 Source rates used in Hadfield (2015)

The source rates used in Hadfield (2015) hydrodynamic modelling were the average of those in Table 1-3 and those recommended using the HRW 1DV model (Dearnaley & Spearman, 2015). This is reasonable; there are two estimates of source rates and in the absence of being able to show one or the other is more appropriate, a middle value is used as the “best estimate”.

Table 1-3: Revised source rates for the hydrodynamic modelling.

	Model sediment categories			Proportion by mass (%)				Source rate (kg/s)				
				HRW (2014)		Present study						
Source	D (µm)	Settling speed (mm/s)		>38 µm	<38 µm	>38 µm	<38 µm	Hadfield (2014)	HRW (2014)	Present study	% trapped[1]	Source rate[2]
Overflow (hydro-cyclone)	39-90	10	>3.2	100	67	100	9.4	16.1	54.8	21.5	100	0
	16-38	1	0.32-3.2			0	43.5	31.4		25.2	70-90	2.5 - 7.6
	16	0.1	0.032-0.32	0	28	0	31.3	13.1	16.2	18.1	25-50	9.0 - 13.6
	<8	0.01	<0.032	0	5	0	15.8	13.3	2.9	9.1	5	8.7
Underflow (de-ored sand)	39-90	10	>3.2	100	67	100	9.4	15	20.4	15.8	100	0
	16-38	1	0.32-3.2			0	43.5	5.3		3.5	70-90	0.4 - 1.1
	16	0.1	0.032-0.32	0	28	0	31.3	1.4	2.3	2.5	25-50	1.3 - 1.9
	<8	0.01	<0.032	0	5	0	15.8	1.4	0.4	1.3	5	1.2

[1] Source: HRW (2015) who state that values depend on width of mining strip.

[2] Source rate for far-field modelling. Where ranges are given, lower values assume a 900 m wide mining strip, and higher values a 300 m mining strip.

2 Acknowledgements

We thank Alison MacDiarmid, John Zeldis and Julie Hall (all NIWA) for review and comments.

3 References

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