

THE ELUSIVENESS OF SEDIMENT TRANSPORT PREDICTIONS

Jesper S. Damgaard¹ and Richard L. Soulsby²

There are inherent uncertainties in both the measurement and the prediction of sediment transport rates and morphological simulations. This paper discusses the various types and sources of uncertainty. In the first part, a framework and a terminology are established, and a number of well-controlled laboratory experiments of suspended sediment concentrations are analysed to dissect the variability observed in sediment concentration measurements. We introduce a scatter parameter and categorise variability into predictable, unpredictable but explainable and unexplainable. The second part introduces the concept of robustness in sediment transport and morphodynamic modelling, and discusses practical implications.

Keywords: sediment transport; sediment modelling; morphodynamic modelling

INTRODUCTION

Marine sediment transport and morphodynamic predictions are important for a number of practical engineering applications. The challenge we face as coastal engineers is that the inherent uncertainties are much larger than are found in other civil engineering disciplines. These uncertainties originate both in the non-linear physics governing sediment transport and in the difficulties in measuring sediment transport rates - in the field and even in the laboratory. As a result, sediment transport models can exhibit enormous variability. Consequently, clients commissioning studies for such practical applications require not only best-practice predictions from models or other methods, but also a measure of the reliability of these predictions.

Practical coastal modelling applications include harbour infill, shoreline erosion, sediment ingress in cooling water systems, channel infill and scour around structures. Regardless of the application, the road to a prediction involves a determination of suspended sediment concentrations and/or the total load sediment transport rate. Sediment transport predictors range from simple formulae to complex numerical models based on some sort of turbulence resolution engine. Often the morphodynamic response of a system is sought. The generic modelling progression is to first solve the hydrodynamic equations to derive the hydrodynamic forcing field (distributions of velocity vectors, water surface levels and wave fields). Armed with these parameters and information about the sediment and the water viscosity, the bed-load transport, the suspended sediment concentration and, hence, the total sediment flux can be calculated. The response of the seabed can then be determined by calculating the divergence in the sediment flux. By introducing time steps and repeating the whole process, the time-dependent evolution of the seabed, i.e., the morphodynamic response, can be simulated.

Thus, correct prediction or modelling of the sediment transport is a prerequisite for producing overall quality predictions of the given coastal application.

The assessment of errors and sensitivities was addressed by Soulsby (1997), including typical uncertainties in the input parameters, and also in derived parameters. In the present paper we update this, discussing further aspects of the elusiveness of sediment transport predictions. Field and laboratory measurements of sediment transport rates and morphological changes are a prerequisite for the development of predictive formulae and/or models, since all the predictive tools need some degree of calibration and validation. But if we cannot fully trust the precision of the measured data, what implications does that have for the development and use of our models? We will look at three sets of laboratory measurements and investigate the repeatability of these sets. A 'scatter parameter' will be introduced to quantify the level of variability in measured data.

The repeatability of measured data influences the amount of information we can extract from them when comparing against our predictive tools. It is, for instance, not possible to develop a model that can predict the majority of simulated sediment transport rates with a precision better than $\pm 20\%$ if the data against which it is calibrated are only accurate to within a factor of two. We will discuss the implications of repeatability of data sets for the development and use of our models. In the course of that discussion, we will introduce the concept of 'robustness' of predictive models.

¹ Director, CoMarEng Advisory, Rua Atalaia 193, 1200-040 Lisbon, Portugal

² Retired Technical Director, HR Wallingford, Howbery Park, Wallingford, Oxon OX10 8BA, UK

UNCERTAINTIES IN SEDIMENT TRANSPORT MEASUREMENT

All data sets involving sediment and hydrodynamic interaction possess a certain amount of variability. The question needs to be asked how well data with inherent variability can actually be modelled. If the data were modelled it would be hoped that this variability is completely explained by the variations in the model inputs. However, no modelling studies give perfect agreement between the data and model output. Sometimes an exact prediction is made but then for a seemingly identical situation a different observation may be made. The same model will be unable to correctly predict both observations because a process-based model will have a unique output for a unique set of inputs, as shown schematically below.

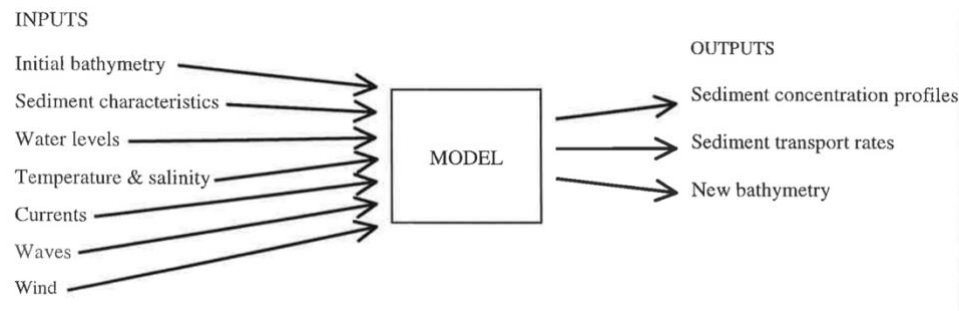


Figure 1. Conceptualisation of inputs and outputs in sediment modelling

While some of the variability can be accounted for by the variation of the parameters used as standard model inputs, this may still leave appreciable scatter, which is due to one or more different causes. The possible sources of explainable scatter are:

- Instrument errors in measuring the inputs or the results (e.g., calibration errors, electronic noise, logging data with insufficient accuracy, spikes in data)
- Statistical sampling errors (e.g., record length too short, such as too few waves; sampling rate too slow, missing high frequency contributions thus causing aliasing)
- Poor analysis techniques (e.g., not removing spikes; not removing trends)
- Omitting to measure some critical processes (e.g., temperature, biological processes, mud in water disturbing optical measurement of sand concentration, wave breaking)
- History effects (e.g. sediment left in suspension at slack water, relic bedforms following spring tides or storms, consolidation of mud beds)

Firstly, much of the scatter may be *predictable* if we include more input parameters within a model. For example, when predicting suspended concentrations of sediment, the water viscosity is sometimes taken as a default value (e.g., $10^{-6} \text{m}^2/\text{s}$) but actually varies strongly with temperature and salinity, which will significantly affect the settling velocity of the sediment. This source of scatter may be reduced by the inclusion of some additional processes within models, although including more detailed processes can sometimes perversely lead to greater volatility of outputs.

Secondly, the scatter may be *unpredictable but explainable*. This can include measurement errors, or temporal and spatial variability, which are not, or possibly cannot, be modelled. This variability includes history effects: e.g. a large quantity of suspended sediment entrained by strong tidal currents may remain in the water column at slack water, and hence is not in equilibrium with the instantaneous forcing. The use of more advanced modelling techniques that capture time-dependent advection could address this but such a high level of modelling is often not merited for the calculation of suspended sediment at a single position.

Thirdly, some of the scatter may be *unpredictable and unexplainable*; perhaps due to processes of which we presently have an incomplete understanding.

All predictors of sediment transport require inputs of the hydrodynamic forcing and the sediment properties. There is an element of unpredictability in these inputs due to experimental errors: two experiments could be stated as being identical whereas in truth there are small differences. The above processes are most readily assessed in terms of suspended sediment concentrations. Sediment transport rates themselves are more difficult to measure and are usually derived by integrating the sediment flux (the product of velocity and concentration) over the vertical, which involves making assumptions and extrapolations, hence introducing uncertainty.

This study looks at three data sets of suspended sediment concentration measurements under waves and/or currents. The experiments are presented in order of decreasing control of the hydrodynamic variables. The first and second experiments were performed in oscillatory water tunnels, the third in a large wave flume. Previously we have also examined field data sets, and some results are included, but for the purposes of this paper we mainly restrict ourselves to laboratory experiments.

Emphasis has been placed on finding experiments in which the hydrodynamic and sediment characteristics are *similar*. In the controlled laboratory experiments this means that the sediment on the bed and the flow conditions for repeat tests are stated to be identical. The variability between results with *similar* forcing is then analysed in terms of predictable scatter, unpredictable explainable scatter and unpredictable unexplainable scatter.

In order to introduce some rigour in the quantification of uncertainties and errors in predictions, we will apply a description along the lines of “the formula/model agrees with X% of the data to within Y%”.

Statistical measures, such as standard deviation, for calculating the variability of concentrations with similar forcing require the availability of several data points. This was not always possible with the data available for this study, so a simple description of the scatter has been adopted which is equally valid for only two data points:

$$S = \frac{c_{max} - c_{min}}{c_{max} + c_{min}} \quad (1)$$

The scatter parameter, S , is the difference between maximum and minimum concentration (c_{max} and c_{min} , respectively) normalised by twice their average, and $S = 0$ for $c_{min} = c_{max} = 0$. Values of S must lie between 0 and 1. The following values give a feel for the interpretation of S values:

$S = 0.00$	perfect agreement	$c_{max} = c_{min}$
$S = 0.25$	spread = mean \pm 25%	$c_{max} = 1.7c_{min}$
$S = 0.50$	spread = mean \pm 50%	$c_{max} = 3c_{min}$
$S = 1.00$	complete disagreement	$c_{min} = 0$

Laboratory experiments of sediment concentrations

All three laboratory data sets investigated here were conducted by meticulous experimenters in some of the most experienced hydraulic laboratories, so their experimental techniques will be of the highest available quality.

Steetzel (1984) and Van der Velden (1986) performed sinusoidal oscillatory flow tests in the Large Oscillating Water Tunnel at Delft Hydraulics (14m long, 1.1m high, 0.3m wide). The two experimental programmes differed only in the mean grain size of the sediment used (Steetzel (1984): $d_{50} = 220 \mu\text{m}$ and Van der Velden (1986): $d_{50} = 100 \mu\text{m}$). Profiles of concentration under nominally identical forcing were measured five times by suction sampling for a duration of 6 to 7 minutes, but only the maximum and minimum profiles were published. A total of 54 test conditions are available, and all concentration profiles are ripple-averaged. The range of flow conditions was: maximum oscillatory flow velocities of 0.1 to 0.9m/s and wave periods of 1 to 7s. The concentrations range over three orders of magnitude.

Each pair of observations (A and B), with nominally identical forcing, has been plotted in Fig. 2, together with the scatter parameter values $S = 0.25$ and $S = 0.5$. It can be seen that the majority of the data lies within $S \leq 0.25$ and all of the data lies within $S \leq 0.5$.

It was found that:

50% of the values had $S \leq 0.10$

90% of the values had $S \leq 0.23$

Reports on the performance of models often present a plot of model predictions versus observations. Clearly, any model that predicts correctly the concentration from one realisation could not possibly predict correctly the concentration from a second realisation (if $S \neq 0$), because the input parameters are identical for any pair of observations. Thus we cannot expect such plots to display any less scatter than that seen in Fig. 2.

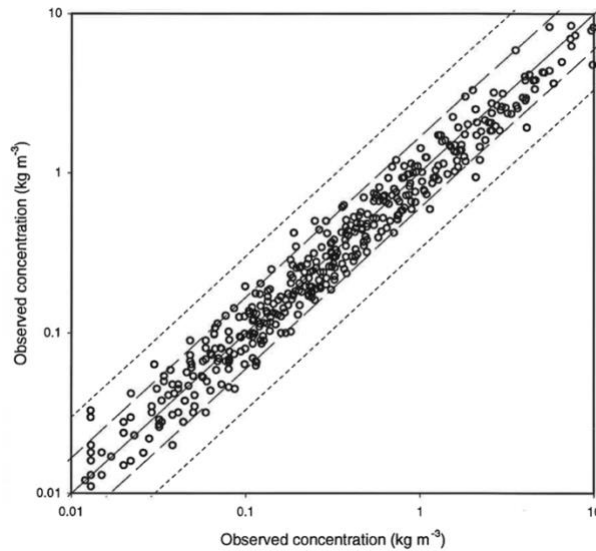


Figure 2. Suspended concentrations from two realisations (A and B) of the same input conditions in experiments of Steetzel (1984) and Van der Velden (1986). Concentration B versus concentration A. Long-dash lines: $S = 0.25$, short-dash lines: $S = 0.5$.

There are no causes of predictable scatter within this very controlled data set. There are a few possible explainable sources of scatter, such as experimental error, especially in the exact location of the bed. The tests were performed above a rippled bed, although the instruments were moved horizontally continuously so as to give ripple-averaged concentrations. The errors in height would have to be approximately 10mm in some cases in order for the concentration profiles to overlie each other. The heights were given to an accuracy of 1mm and so this degree of experimental error seems unlikely. Another possibility is that the time over which the suspended sediment was sampled was not long enough to minimise the statistical sampling error sufficiently. When a shorter sampling period is used, the sample mean will differ from the true mean by a greater amount for a shorter sampling period. The remaining scatter that cannot be accounted for by measurement errors is, therefore, unexplainable.

Rance (1984) conducted sinusoidal oscillatory flow tests in the Pulsating Water Tunnel at HR Wallingford (working section 10m long, 2.4m high, 0.6m wide). The same experiment was performed ten times with concentration measurements obtained at 5 heights between 1 and 5cm, and five times with measurements at 6 and 7cm. The measurements were made by pump sampling for a duration of 4 minutes. Flow conditions were: maximum oscillatory flow velocity of 0.42m/s and wave period of 8s. The sand had $d_{50} = 165 \mu\text{m}$.

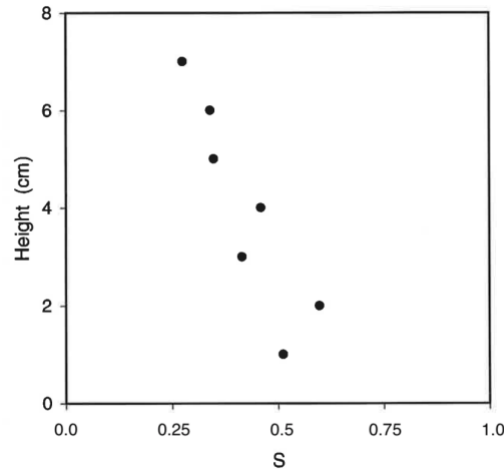


Figure 3. Scatter parameter for the Pulsating Water Tunnel tests

Figure 3 shows the scatter parameter is greatest near the bed, $S = 0.5$, decreasing to about 0.25 at a height of 7cm. In these experiments the bed was rippled but measurements were only taken at one location. Each result applies to a specific location above a ripple wavelength, and not a ripple averaged value. The ripples would not have migrated far, if at all, during a single test. The ripples will however have moved between tests, occurring in random locations, and therefore scatter would have been introduced.

It was found that:

50% of the values had $S \leq 0.41$

90% of the values had $S \leq 0.51$

In this case some of the scatter will be predictable. If information is known about the location over the ripple, then it is possible to account for some of the scatter by using a model that resolves the spatial concentration field across a ripple. If this is the case it would be expected that the greatest scatter occurred near to the bed, as was observed.

The explainable sources of scatter are likely to be dominated by uncertainties of the exact bed height and the position relative to the ripple crest, but also due to the non-uniformity of ripples. If the ripple pattern is not completely uniform then a model that assumes all ripples are identical would not correctly predict suspended sediment advected from a neighbouring ripple. The remaining unexplainable scatter at heights above the immediate influence of position on ripple is about $S = 0.25$, similar to that for the Steetzel (1984) and Van der Velden (1986) dataset.

Raudkivi and Dette (1991) performed regular and irregular waves tests on a plane sloping beach in the Grosse-Wellen-Kanal at Hannover University, which is a wave-flume 320m long, 7m deep and 5m wide. Each test was repeated four times, the bed being levelled before each one. The profiles were measured outside the surf-zone by pump sampling for a duration of 20 minutes. The sand used had $d_{50} = 250 \mu\text{m}$. The range of flow conditions was: wave heights of 0.7 to 1.4m and wave periods of 4 to 9s.

Figure 4 shows the large range of the scatter parameter at each height, between about 0.1 and 0.9. Interestingly there appears to be no consistent additional increase of scatter under irregular rather than regular waves, and no relationship could be detected between the scatter and the measurement height, wave period, or wave height.

It was found that:

50% of the values had $S \leq 0.36$

90% of the values had $S \leq 0.67$

There are more sources of predictable scatter within this experimental set-up than in the previous tunnel experiments. For example, the exact position down the flume will be of some importance in terms of water depth and reflected wave energy, as well as the previously mentioned position over any bed forms present.

In this case there are several explainable sources of unpredictable scatter. The main difference, in terms of scatter, between this experiment and the tunnel experiments is both the free surface and the presence of a surf-zone. Although the measurements were made outside the surf-zone, some residual undertow or turbulence may well have been diffused or advected from the surf-zone to the test position. The additional scatter is introduced by the non-repeatability of wave breaking, as demonstrated using Particle Image Velocimetry by Quinn et al, (1996). The mean flows and bed slope present may sort the bed material over the experimental programme, which may result in unpredictable advection processes. The other causes of unpredictable scatter mentioned in the other experiments above remain in addition to these.

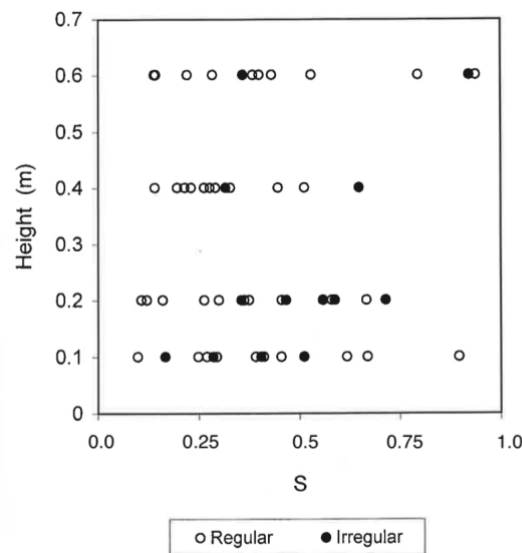


Figure 4. Scatter parameter for the Grosse Wellen Kanal tests

Table 1 summarises the values of the scatter parameter for the three data sets of suspended sediment concentration. The most important observation to be made is that even under the most controlled of experimental conditions there is a significant scatter within the data. In the original study, an extensive set of field measurements in the Outer Thames Estuary, UK, was also considered. The details are outside the scope of this paper, but the resulting values of S are included in Table 1. The main (surprising) conclusion was that the scatter in the field data between nearly-identical forcing conditions was not appreciably larger than was found in the laboratory measurements described above.

Table 1 Scatter parameters, suspended sediment concentration measurements

		Data set			
		LOWT	PWT	GWK	Thames
50%	$S =$	0.10	0.41	0.36	0.25
90%	$S =$	0.23	0.51	0.67	0.48

The case studies presented above have illustrated the differences between the different forms of scatter. The predictable scatter that can be modelled by the inclusion of additional inputs might only be included in models if it is considered important enough.

Explainable scatter can potentially become predictable if it is due to physical, chemical or biological processes.

The fundamental question remains to be answered: is the scatter observed under the most controlled conditions experimental error or unexplainable scatter? In other words, is the experimental variability present in all experiments, due to deficiencies in instruments (e.g. electronic noise, zero drift) and to sampling errors (e.g. too short a record, too slow a sampling rate), or would it still be found if perfect instruments and sampling schemes were used?

Quantification of experimental error

Instrument errors: All the experiments measuring suspended sediment concentration used suction sampling to obtain the concentration. Here we quantify the potential errors in the data sets so that the size of the natural variability can be established. A general analysis can be used for all of the data sets, quoting typical errors.

(a) Hydrodynamical (input) measurements

The water velocities measured in the water tunnels are accurate to within 2%. The wave heights and periods within laboratories will similarly be accurate to within 2%.

(b) Systematic error due to suction sampling

The water sampled may not be truly representative of the water in situ because grains may be preferentially sucked in. The error due to this effect was given by Bosman et al (1987) as 3%.

(c) Error in bed/measurement level

A 1mm error in the measurement height relative to the bed has been shown by Bosman et al (1987) to give a 10% error in concentration.

(d) Error in water volume and sediment weight

The errors in measuring the volume of the water sample and the weight of the dried sediment are within 1%.

Statistical sampling errors: The random errors of an estimate of mean concentration can be reduced by increasing the record length, T . However, the stationarity of the problem is also important. In a field situation the flow conditions can only be considered quasi-stationary for a limited period of time, typically no more than one hour.

The method of calculation of this sampling error based on the record length of sample taken is outside the scope of this paper but previous work conducted at HR Wallingford demonstrates that, in the extreme case, the sampling error for the laboratory experiments discussed in this paper will be of the order 5%.

Total experimental errors: The instrument errors of the section prior to the section above can be added to the sampling error in the section above to give a maximum experimental error of $e = 11.8\%$. This arises from: hydrodynamical forcing (2%), systematic suction sampling (3%), height error (10%), water volume (1%), sediment weight (1%), sampling error (5%), hence $2^2 + 3^2 + 10^2 + 1^2 + 1^2 + 5^2 = 11.8^2$. Thus if $c_{\max} = c_{\text{mean}}(1 + e)$ and $c_{\min} = c_{\text{mean}}(1 - e)$, then $S = e$, leading to a scatter parameter $S = 0.118$.

The total experimental error of 11.8% can be compared with the most controlled experiments, which had a median scatter of $S = 0.1$ corresponding to $\pm 10\%$, i.e. about equal to the expected spread due to the experimental errors. Conversely, about half of the test conditions contained variability that cannot be explained by experimental error. Any scatter parameter greater than $S = 0.118$, under the present experimental conditions, will contain unexplainable variability.

SEDIMENT TRANSPORT PREDICTION

An intercomparison of seven sediment transport ‘research’ models was made as part of the EU-funded MASTIII SEDMOC research project (1998–2001). The results of the intercomparison were described by Davies et al. (2002). One of the intercomparisons was a blind test where the various modelling teams were given 36 sets of field conditions and asked to predict the sediment transport rates. There was a large variation between the predicted lowest and highest transport rates, ranging from a best case of factor five to a worst case of factor 10,000. Admittedly, the latter case was for a very small sediment transport rate, and there were distinct outliers, but the degree of variation between models is still larger than would be expected in many other fields. We refer interested readers to study the other insights and conclusions of the paper. It may be that the predictive capabilities of sediment transport models have improved since the intercomparison was done but the authors of this paper are not aware of a recent, in-depth comparison exercise similar to the one undertaken then.

Other fields of science operate with the concept of robustness of models, i.e. how well a model works on alternative data. Segura-Lepe et al. (2019) defined predictive robustness as a model’s capacity to maintain predictive accuracy in the face of uncontrolled variation. Importantly, robustness of a model is not a reflection of how accurate the predictions of the model are, rather it is a measure of the sensitivity of the model to variations in the input parameters. However, sediment transport is by its very nature highly sensitive to the inputs, due to the strong nonlinearity of its governing equations. This is what models need to reproduce, without becoming unrealistically over-sensitive.

As an alternative definition of robustness, more appropriate to sediment transport, we might include the following factors in assessing the robustness of a model:

- how accurate is a model compared with field data, outside of any data used to calibrate the model?
- how sensitive is the model to small changes in the input parameters? If there are large corresponding changes in the output values, are they realistic?
- how well do different models agree with each other? Especially if they use very different conceptual approaches (e.g a detailed numerical model compared with a heuristic ‘geological’ model).
- accuracy needs to be stated in well-defined statistical terms. For morphodynamic models, the Brier Skill Score is an accepted metric (Sutherland et al., 2004), based on methods used in weather forecasting to check how good forecasts are compared with actuality.

So what is the solution? In the following we will discuss a few important coastal engineering applications and consider the implications of the preceding arguments.

Morphological response to engineering interventions is a common application of sediment transport predictors. These could involve designing control structures for an eroding coast or assessing the shoreline impact of a new development (port, real estate, dredging, etc.). As mentioned before, a sediment transport predictor sits at the heart of any such morphodynamic simulation. In relation to the preceding arguments, we know that the sediment transport data we compare our simulation against most likely will contain appreciable unexplained variation. We all know that many of our models are not particularly robust, using the definitions explained above. But all is not lost. Since the morphological responses are based on the gradients in transport rates, rather than the rates themselves, there is an element of dampening (there are inherent instabilities in the numerical solution of the hyperbolic equations governing the bed-updating (see e.g. Hudson et al., 2005) but that is outside the scope of this paper). Furthermore, since the sought output is shoreline response, it is prudent to calibrate model results against historic bathymetric changes. If that is not possible, then the model can really only be applied in a relative sense. Conversely, if sound calibration and validation is indeed possible, then the inherent uncertainties discussed in this paper can be addressed sensibly.

Ports and harbours can be prone to sedimentation if they are located, for example, near a river mouth or along a coast with a high littoral drift. The most common cause of harbour siltation is transport of suspended fine sediment from a dynamic flow regime outside the harbour to the quiescent water inside. In the extreme (but not practically unrealistic) case, all the suspended sediment transported into a basin

will be trapped. Any uncertainties in suspended concentrations will impact the siltation calculation proportionally and we now know that there most likely will be unexplainable variations. That can have severe commercial ramifications for a port operator (will the maintenance dredging requirements over the design life be, say, X or $1000X$ m^3 ?). In this situation, the prudent engineer will, again, compare and adjust siltation predictions with observations of actual siltation rates. That can at least help get a handle on predictable and unpredictable but explainable variations. If a sufficient number of observations can be obtained, then an attempt can be made to quantify the unexplainable variation too. If observations are not available, then siltation simulations must include an extensive sensitivity analysis to yield a confidence interval that can be used in a commercial risk management plan.

Many power plants and refineries depend on seawater for their process cooling, and desalination plants also require seawater intakes. In the design of a once-through seawater cooling system, it is of paramount importance to reduce the ingress of suspended sediment. Firstly, sediment coarser than, say, $60\ \mu m$ can clog the condensers in the heat exchange system; secondly, sediment can settle in the intake basin or the pumphouse forebay to the detriment of operability; thirdly, excessive sediment ingress can cause the intake pipes to clog, resulting in a plant shutdown. The cooling water intake structure will often be located on the seabed, offshore from the plant. The openings are at the top of the intake structure (or Velocity Cap) and the vertical distance from the seabed of these openings is one of the key design parameters: the hydrodynamic forces on the structure increase with distance from the seabed whereas the sediment ingress decreases (exponentially). An incorrectly designed intake height can result in poor operation of the plant or, in the extreme case, inoperability.

So, a major design decision that can have important commercial implications hinges on the determination of the suspended sediment concentration, which is fraught with the challenges discussed above. The only way to proceed for the coastal engineer is with caution. On the design side, a probabilistic approach has to be adopted whereby the joint probability of waves and currents has to be assessed and the resulting sediment ingress calculated. This entire simulation then has to be repeated a number of times to test the sensitivity of the ingress predictions to variations in the suspended sediment concentration. Then this range of probabilistic simulations can feed into an operational risk management exercise that must be conducted in collaboration with the plant operators. In addition to informing design decisions, the ingress results may influence operation and maintenance procedures, for example by dictating that pumps (counter-intuitively) must be run at full power during high ingress situations to avoid clogging of the pipes.

As a final comment, we refer interested readers to the results of the EU-funded COAST3D project (see e.g. Soulsby, 1998). The project was aimed at improving modelling outputs based on field observations. Large-scale field measurements were conducted at two sites: a relatively simple uniform straight coastline in Netherlands, and a much more complex coastline in UK. In both cases, numerical modelling predictions were compared with field measurements.

CONCLUSIONS

We have defined predictable, explainable and unexplainable variability. Measured values of suspended sand concentration from laboratory measurements showed considerable variability between nominally exact repeat experiments. A scatter parameter, S , was defined in Equation (1) as a measure of this variability. The most controlled of the experiments gave a median value of $S = 0.1$, and 90% of the data had $S \leq 0.23$. Explainable causes for this include uncertainty in the bed level, errors in measurements, and statistical sampling error. However, these errors are much smaller than frequently observed variabilities, leaving a large unexplained contribution to the variability.

The concept of 'robustness' in predictive models has been discussed and a set of criteria to assess robustness of sediment transport models proposed.

The study leads to the following conclusions regarding prediction of sediment transport and morphodynamics for coastal management purposes:

1. Variability in suspended sediment concentration measurements is much larger than for many other parameters in coastal science and engineering. The most tightly controlled laboratory experiments give variability of about $\pm 10\%$ typically, and up to $\pm 25\%$, for the range about the mean of a number of repeat experiments. Other laboratory experiments considered had 90% exceedance values of S up to 0.67, and field experiments did not have greater scatter than laboratory experiments (Table 1).

2. The accuracy of prediction formulae and models for sediment suspension and transport has to be viewed in comparison with the variability of repeat measurements. If two repeat experiments with identical input parameters yield measured concentrations which differ by 50% ($S = 0.33$), then no prediction method which correctly predicts the first value can also predict the second value correctly.
3. Changes in morphology result from spatial variations in sediment transport rate. Hence if concentration exhibits large variability, as has been demonstrated above, so will sediment transport and morphology. For practical coastal engineering applications it is prudent to supplement advanced sediment transport modelling with simple formulae and/or empirical relationships. This can provide a benchmark against which the modelling results can be assessed.
4. If, as at present, the large variability in both data and prediction methods is unavoidable, then the expectations of accuracy of coastal sediment/morphology predictions need to recognise this. Scopes-of-work and outputs from projects need to be worded accordingly.

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REFERENCES

- Bosman, J.J., Velden, E. van der & Hulsbergen, C.H., (1987) "Sediment concentration measurement by transverse suction", *Coastal Engineering*, 11: 353-370.
- Davies, A.G., Van Rijn, L.C., Damgaard, J.S., Van de Graaff, J. & Ribberink, J. (2002) "Intercomparison of research and practical sand transport models", *Coastal Engineering*, 46 (1): 1-23.
- Hudson, J., Damgaard, J., Dodd, N., Chesher, T. & Cooper, A. (2005) "Numerical approaches for 1D morphodynamic modelling", *Coastal Engineering*, 52 (8): 691-707.
- Quinn, P.A., Barnes, C.D., Lloyd, S.T., Greated, C.A. & Peregrine, D.H., (1996) "Velocity measurements of post-breaking turbulence generated by plunging breakers", *Proceedings of Coastal Dynamics '95*, ASCE, Gdansk, Poland.
- Rance, P.J., (1984) "Sediment transport by waves acting on a horizontal bed", HR Wallingford Report IT269. pp.26.
- Raudkivi, A.J. and Dette, H., (1991). "Ein vereinfachtes Verfahren zur Ermittlung der Suspensionsfracht ausserhalb der Brandung", Sonderdruck aus Heft 111 der Mitteilungen des Leichtweiss-Instituts für Wasserbau der Technischen Universität Braunschweig.
- Segura-Lepe, M.P., Keun, H.C. & Ebbels, T.M.D. (2019) Predictive modelling using pathway scores: robustness and significance of pathway collections. *BMC Bioinformatics* 20, 543.
- Soulsby, R.L. (1997) *Dynamics of Marine Sands*. Thomas Telford Publications, London.
- Soulsby, R.L. (1998). "Coastal Sediment Transport: the COAST3D Project". *Coastal Engineering Proceedings*, 1(26).
- Steezel, H.J., (1984). "Sediment suspension in an oscillating water motion close to the sand bed". Coastal Engineering Dept., Delft Univ. of Technology, Delft, The Netherlands.
- Sutherland, J., Peet, A.H. & Soulsby, R.L., (2004) "Evaluating the performance of morphodynamic modelling". *Coastal Engineering*, 51 (8-9): 917-939.
- Velden, E. van der (1986) "Sediment suspension in an oscillating water motion close to the sand bed". Coastal Engineering Dept., Delft Univ. of Technology, Delft.