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Sediment transport processes within coral reef and vegetated coastal ecosystems: a review

Ryan Lowe[1,2,4] Marco Ghisalberti[3,4]

[1] School of Earth and Environment and UWA Oceans Institute, The University of Western Australia, Perth, Western Australia, Australia

[2] ARC Centre of Excellence for Coral Reef Studies, Townsville, Queensland, Australia

[3] School of Civil, Environmental and Mining Engineering, The University of Western Australia, Perth, Western Australia, Australia

[4] Western Australian Marine Science Institution, Perth, Western Australia, Australia

WAMSI Dredging Science Node

Report

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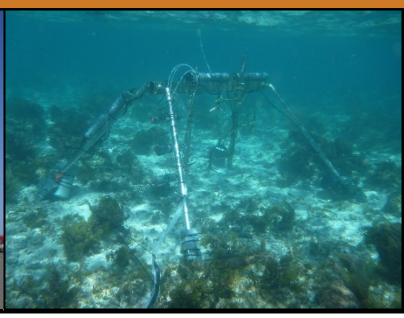
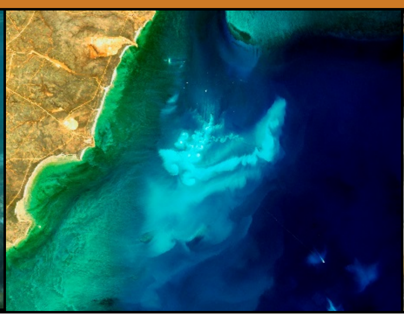
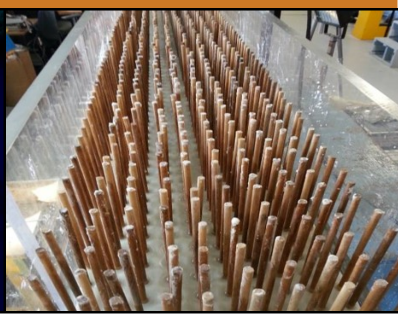

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WAMSI Dredging Science Node

The WAMSI Dredging Science Node is a strategic research initiative that evolved in response to uncertainties in the environmental impact assessment and management of large-scale dredging operations and coastal infrastructure developments. Its goal is to enhance capacity within government and the private sector to predict and manage the environmental impacts of dredging in Western Australia, delivered through a combination of reviews, field studies, laboratory experimentation, relationship testing and development of standardised protocols and guidance for impact prediction, monitoring and management.

Funding Sources

The $20million Dredging Science Node is delivering one of the largest single issue environmental research programs in Australia. This applied research is funded by **Woodside Energy, Chevron Australia, BHP Billiton and the WAMSI Partners** and designed to provide a significant and meaningful improvement in the certainty around the effects, and management, of dredging operations in Western Australia. Although focussed on port and coastal development in Western Australia, the outputs will also be broadly applicable across Australia and globally.

This remarkable **collaboration between industry, government and research** extends beyond the classical funder-provider model. End-users of science in regulator and conservation agencies, and consultant and industry groups are actively involved in the governance of the node, to ensure ongoing focus on applicable science and converting the outputs into fit-for-purpose and usable products. The governance structure includes clear delineation between end-user focussed scoping and the arms-length research activity to ensure it is independent, unbiased and defensible.

And critically, the trusted across-sector collaboration developed through the WAMSI model has allowed the sharing of hundreds of millions of dollars' worth of environmental monitoring data, much of it collected by environmental consultants on behalf of industry. By providing access to this usually **confidential data,** the **Industry Partners** are substantially enhancing WAMSI researchers' ability to determine the real-world impacts of dredging projects, and how they can best be managed. Rio Tinto's voluntary data contribution is particularly noteworthy, as it is not one of the funding contributors to the Node.

Funding and critical data

Critical data

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Corresponding author and Institution: R. Lowe (UWA). Email address: ryan.lowe@uwa.edu.au

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Front cover images (L-R)

Image 1: Trailer Suction Hopper Dredge *Gateway* in operation during the Fremantle Port Inner Harbour and Channel Deepening Project. (Source: OEPA)

Image 2: Sediment transport field study - sawhorse instrument frame deployed at Ningaloo Reef with hydrodynamic and sediment transport instrumentation. (Source: Andrew Pomeroy)

Image 3: Dredge plume at Barrow Island. Image produced with data from the Japan Aerospace Exploration Agency (JAXA) Advanced Land Observing Satellite (ALOS) taken on 29/08/2010.

Image 4: Laboratory experiments of sediment transport through artificial canopies. (Source: Andrew Pomeroy)

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Executive summary

Modern sediment transport theory and models, including those used to predict the impact of dredging plumes, are still based entirely on the mechanics of how sediment is transported over open (bare) sediment beds. However, many coastal ecosystems contain large and complex bottom roughness (or canopies) on the seafloor that can dramatically influence both the near-bed hydrodynamics, and in turn, how sediment is transported. These ecosystems, which include coral reefs, seagrass meadows and other aquatic vegetation, are also structurally and functionally important and considered to be sensitive to major turbidity and sediment deposition events (e.g. from dredging) and hence often prioritized in dredging management efforts.

Presently, mechanistic models of sediment transport in the presence of submerged canopies are severely lacking, with only a limited number of mostly qualitative studies providing insight into these dynamics. While there have been some significant advances over the past decade in our understanding of how submerged canopies modify near-bed hydrodynamics, which is an important foundation for sediment transport predictions, how these hydrodynamics influence sediment transport (including controlling rates of sediment erosion and deposition) are still poorly understood. It is clear that new observations of sediment transport within environments such as coral reefs and seagrass meadows are needed to (1) provide the missing quantitative insight needed to better understand these processes, (2) incorporate these dynamics into new predictive sediment transport formulations applicable to these environments, and (3) finally embed these dynamics in process-based numerical models that can eventually be applied within predictive models.

In this review we summarize the current state of knowledge and gaps in the various components required to predict sediment transport within coral reef and vegetated coastal ecosystems. Although many knowledge gaps still remain, we review the existing framework for predicting canopy flows and how this can serve as a foundation for developing new sediment transport models. Specifically we review:

- The hydrodynamic interactions of currents and waves with submerged canopies, including the influence on bed stresses (Section 2);
- The traditional approaches and models used to predict near-bed sediment transport in the coastal ocean (Section 3);
- Existing observations of sediment transport within aquatic vegetation and over coral reefs (Section 4);
- Measurement techniques for quantifying and monitoring near-bed sediment fluxes (Section 5); and
- Prospects for upscaling these dynamics with numerical models to improve predictions of the transport and fate of natural and dredging-derived sediments in these environments (Section 6).

Considerations for predicting and managing the impacts of dredging

To improve predictions of the impacts of dredging, it is important to move beyond traditional sediment transport models that have been developed for open (bare) sediment beds. Coral reefs, seagrass meadows and mangrove forests are ecologically important and prominent features along Australia's coastline, and considered to be particularly sensitive to dredging-related pressures. As a result, these ecosystems are often prioritised in dredging monitoring and management programs. Unfortunately, sediment transport formulations that have been derived for bare sediment beds are known to severely break down when applied to coral reef and vegetated coastal areas, despite still being regularly applied to these environments. As a consequence, existing dredging model predictions that are required for Environmental Impact Assessments (EIAs) will generally break down when applied to these coastal systems. This is due to the substantial reduction of bed shear stresses by the large roughness (canopies) formed by coral reef communities and aquatic vegetation, which can dramatically increase rates of sediment deposition, reduce rates of resuspension, and reduce net transport rates. Consequently, important predictions of, for example, Zones of Influence (ZOI) surrounding dredging operations, can be grossly in error when applying existing engineering models to these ecosystem types. Based on this review, the following issues should be considered when making predictions of dredging impacts in these environments:

- Detailed habitat maps prior to dredging projects should not only be used to assess potential biological impacts, but also the role that habitat type may have on physical sediment transport processes, especially rates of sediment deposition. Although habitat assessments traditionally focus on biological classifications, additional estimates of associated bottom roughness characteristics (or rugosity) would help improve sediment transport estimates.
- The main challenge with developing accurate predictive models for sediment transport over benthic canopies is how to account for the complex and varied bottom roughness of natural coastal ecosystems. While significant advances are being made in predicting near-bed hydrodynamics associated with large bottom roughness (as detailed in this review below), at present there are still major knowledge gaps in how this controls sediment transport rates. Although there are research efforts to address these knowledge gaps, currently only crude estimates of these modified transport rates can be made.
- Due to this large uncertainly in sediment transport rates over benthic canopies, model predictions over areas that include coral reefs and aquatic vegetation should be treated with extreme caution. For these regions, it is important to conduct a very conservative uncertainty analysis of these transport predictions, ideally through model sensitivity scenarios that consider only order of magnitude (or greater) knowledge of sediment transport rates. Once further field and laboratory data of sediment transport over benthic canopies become available, these large uncertainties can be reduced.
- Within and adjacent to benthic ecosystems such as coral reefs and seagrasses, sediments are usually biogenic-derived (comprised of calcium carbonate) that can have physical characteristics that differ substantially from most traditional siliciclastic coastal sediments used in sediment transport research. Depending on the biological source, these sediment grains can have markedly different shapes and effective densities that can modify their transport rates. This poses challenges when relating sediment grain size distribution characteristics (e.g. obtained by sieve or laser diffraction) to settling velocities, the latter being a key parameter in sediment transport formulations. Ideally transport predictions of carbonate sediments should be based on *in situ* measurements of sediment characteristics, nominally using directly measured settling velocities (i.e. as obtained in settling tubes).
- Likewise, suspended sediment monitoring instrumentation based on optical or acoustic sediment properties may show very different responses to carbonate sediments. Instrument calibration should nominally be conducted with *in situ* water samples obtained on a site-by-site basis.

1. Introduction

A common feature of many coastal systems is the presence of large and complex bottom roughness (or canopies) on the seafloor that are formed by a wide range of different marine communities, including seagrasses, coral reef organisms, sponges and mangroves. Through light reduction and the direct impacts of sediment deposition, the health and function of these ecosystems can be significantly compromised by dredging activities. In predicting zones of impact and influence in dredging operations, it is therefore critical that we develop a mechanistic understanding of the transport and fate of dredging-derived sediments in these systems. This level of understanding is important, as observations suggest there are often complex and highly nonlinear relationships between community impact/mortality and both the concentration and exposure time of dredging plumes.

Importantly, benthic canopies have a profound impact on coastal hydrodynamics by imposing substantial drag forces on the flows generated by waves and currents. This, in turn, results in substantial modifications to the mean and turbulent flow structure near the seafloor. Consequently, the transport of both natural and dredging-derived sediments (which is closely coupled to the hydrodynamics), including rates of sediment deposition and suspension, can be dramatically altered in these environments. Therefore, existing sediment transport models (typically derived for bare, sandy substrates) have little to no quantitative applicability to these systems.

The complex interaction between these benthic systems, the near-bed flow and the resultant sediment transport cannot currently be resolved with existing sediment transport models; direct observations are still severely lacking and must form the foundation for the development of new models. This review of the current understanding suggests a clear path for the WAMSI DSN Theme 3.1.2 project. Namely, new observations of sediment erosion and deposition within environments such as coral reefs and seagrass meadows are critically needed to (1) provide the missing quantitative insight needed to develop process understanding of sediment erosion and deposition in these systems, (2) incorporate these dynamics into new predictive sediment transport formulations applicable to these environments, and (3) finally embed these dynamics in process-based numerical models that can eventually be applied to enable predictions of the impacts of dredging activity on these critical ecosystems. Without this fundamental information, it is impossible to predict the fate and impact of sediment dredging plumes on these often sensitive environments with any confidence.

2. Flow within and above submerged coral reef and vegetation canopies

The flow structure in and around reef organisms depends on the complex interaction between the overlying water motion and the typically large, three-dimensional bottom roughness (or canopies) formed by benthic organisms such as coral reef communities and seagrasses (Figure 1). The common challenge for understanding the flow dynamics in all natural canopies is how to properly account for the highly variable spatial flow structure that arises within even the simplest morphologies. There have been some attempts to directly observe or simulate the full three-dimensional turbulent flow structure through e.g. individual branching coral colonies using numerical simulations (Kaandorp et al. 2003, Chang et al. 2009, Chindapol et al. 2013); however, such efforts are extremely expensive computationally, requiring flows to be resolved down to scales of order mm. Thus, for now and the foreseeable future, it remains impractical to resolve the roughness geometries of natural communities of reef organisms, let alone at the ecologically-relevant scale of a whole coral reef landscape (scales of 10s to 1000s of m), with this kind of resolution.

2.1 Momentum balances and governing equations

To account for how unresolved small-scale hydrodynamic processes influence the larger-scale macroscopic properties of a canopy flow (e.g. mean velocity profiles), the traditional Reynolds Averaged Navier Stokes momentum equations are spatially-averaged over a horizontal plane excluding the solid canopy elements that is valid both within and above the canopy region (Raupach & Shaw 1982):

$$\frac{D\langle u\rangle}{Dt} = -\frac{1}{\rho}\frac{\partial\langle p\rangle}{\partial x} + \frac{1}{\rho}\frac{\partial\tau_{xy}}{\partial z} - f_x \qquad (1)$$

where *x* denotes the streamwise direction, *z* denotes the vertical, ρ is the seawater density, *u* is the streamwise velocity, *p* is pressure, τ_{xy} is the shear stress and the brackets represent spatially-averaged variables. Importantly, the term f_x represents a spatially-averaged 'canopy resistance term' that arises from forces exerted by the canopy onto the surrounding flow.

The fundamental challenge in predicting flow through submerged canopies via Equation (1) remains how to most accurately relate f_x to the complicated three-dimensional structure of natural canopies, especially given their abundant variation in morphologies and roughness scales. For canopies with simple morphologies (e.g. seagrasses), these form drag forces have been successfully parameterized using a quadratic drag law that depends on the local in-canopy velocity, the integrated frontal area of the canopy elements per unit area of seafloor (λ_f), and an empirical drag coefficient ($C_{d,c}$) (see Nepf 2012 for details). Such approaches have also been applied to e.g. coral reef canopies with well-defined branch geometries such as in Figure 1a; however, the complex morphologies of most natural canopies make assigning a representative λ_f difficult or even impossible due to the challenge of identifying these single, well-defined geometric parameters. As an alternative approach to account for this issue, Lowe et al. (2008) used turbulent porous media flow theory to parameterize f_x. The advantage of this approach is that it has been applied to a number of complex geometrical arrays and tested with a wealth of empirical data (Macdonald et al. 1979). Although this approach worked well for predicting flow through a community of the coral *Porites compressa* (Lowe et al. 2008), additional work is still needed to parameterize flow resistance across a broader spectrum of natural reef canopy types.

Figure 1. Examples of coastal canopies. (Top) canopies formed by the roughness of coral reef communities, (Bottom) canopies formed by aquatic vegetation.

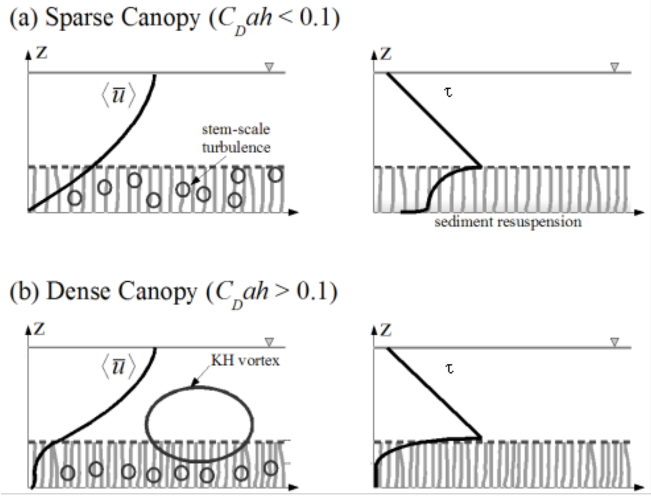

Figure 2. Flow within and above a submerged canopy; profiles for mean velocity ū and turbulent stress τ are shown (Luhar et al. 2008)

2.1.1 Mean and turbulent flow structure

For a unidirectional current over a submerged canopy, the discontinuity in form drag f_x near the top of the canopy generates a region of strong shear in the mean velocity profile (Equation (1)), resulting in a local peak in the turbulent shear stress τ_{can} (Figure 2) (Ghisalberti 2009). This shear layer transfers momentum from the overlying water column down into the canopy, thus driving flow inside the canopy. This is the dominant form of momentum transfer that occurs when the flow is 'unconfined', or when the canopy height h_c occupies only a small fraction of the total water depth *h*.

Particularly in dense canopies, the shear layer often does not penetrate completely to the bed. This separates the canopy vertically into two zones (Nepf & Vivoni 2000). The upper zone (termed the 'exchange zone') is a region of rapid vertical transport and is driven by both the turbulent stress and the pressure gradient. The lower zone (termed the 'wake zone') is governed by a simple balance of drag and pressure gradient, much like classical porous medium flow. The turbulent stress in the wake zone is very small, except in the very thin boundary layer at the bed. The extent of shear layer penetration into a submerged canopy is inversely proportional to the drag length scale of the canopy, $L_D = (C_{d,c}a)^{-1}$, where *a* is the canopy frontal area per unit volume. Consequently, $C_{d,c}ah_c$, the scale ratio of canopy height to exchange zone depth, is a key dimensionless parameter in the description of bed stress and sediment transport in canopy flows (Nepf et al. 2007). For a sparse canopy ($C_{d,c}ah_c > 0.1$), turbulent transport in the shear layer penetrates fully to the bed, maximizing the potential for sediment transport (Figure 2). Denser canopies reduce the turbulent stress at the bed and are therefore thought to promote sediment deposition.

When h_c becomes an appreciable fraction of the water depth, the underlying canopy flow becomes 'depth-limited' and the background pressure gradient driving the overlying flow also starts to dominate the driving force within the canopy itself (Nepf & Vivoni 2000). As h_c / h increases, the pressure gradient term continues to increase the in-canopy flow, reaching a limit where the reef canopy becomes 'emergent' ($h_c \sim h$) such that the shear layer is no longer present and flow is driven entirely through the canopy by the external pressure gradient (Nepf 2012). With typical canopy heights ranging from centimetres to metres, many or most flows over aquatic canopies (*h* typically *O*(m), due to light requirements) must experience some degree of depth limitation. This seemingly 'local' effect can also have important consequences on the broader circulation patterns (100s to 1000s of m), since the larger drag forces that arise from more water being driven though a canopy under depth-limited conditions increases the resistance experienced by the overlying flow. This was well illustrated by McDonald et al. (2006), who found that the community bottom drag coefficient C_D, relating the total drag force to the overlying flow speed (not to be confused by the canopy element drag coefficient $C_{d,c}$ above), increased by roughly two orders of magnitude (~0.01 to 1) as the depth over a canopy of *Porites compressa* coral approached the emergent limit (see Figure 3 in that paper). Furthermore, there appears to be a relatively abrupt transition to high (order

0.1 to 1) values of C_D when h_c / h increases above ~0.3 (McDonald et al. 2006, Lowe et al. 2008). Collectively these recent studies emphasize that careful consideration of the in-canopy momentum dynamics is critical to accurately parameterize bottom drag on reefs and vegetated coastal areas; factors that have largely been ignored in traditional coastal ocean models (Rosman & Hench 2011).

While the existence of strong vertical hydrodynamic gradients in canopy flow is well established, there is also significant *horizontal* variability in the flow, both instantaneously and in the mean. A submerged canopy can impart hydrodynamic variability on three separate scales. The smallest scale is that of the canopy element diameter (*d*), typically $O(10^{-3}–10^{-2}$ m); the velocity immediately behind an element will assuredly be lower than that at adjacent locations. The intermediate variability occurs on the drag length scale of the canopy, typically $O(10^{-2} – 10^{0}$ m). The largest scale is that of the width of the canopy 'patch'. The impact of patchiness on the hydrodynamics, in particular the propensity of the flow to be diverted around, rather than over, the canopy, is summarised nicely by Fonseca and Koehl (2006). Experimental studies (e.g. White & Nepf 2007, Ghisalberti 2010) have observed and quantified variability in the flow on all three scales.

2.1.2 Implications for bed shear stresses

Due to the drag they exert, aquatic canopies typically result in a reduction in near-bed velocity and bed shear stress. Consequently, aquatic canopies are conventionally viewed, relative to surrounding areas, as regions of enhanced net sediment deposition. Dimensional reasoning suggests that (in unidirectional flow through a rigid canopy), the spatially-averaged bed stress (τ_b) is related to flow and canopy properties according to:

$$\frac{\tau_b}{\rho u_*^2} = f\left(C_{d,c} a h_c, \frac{h}{h_c}, \frac{d}{h_c} \right) \qquad (2)$$

where ρu_*^2 denotes the local bed shear stress in the absence of the canopy. The three terms on the right hand side indicate, respectively, (a) whether the canopy shear layer extends fully to the bed, (b) the constraining effect of the depth, and (c) the contribution of wake turbulence to the near-bed flow.

However, the bed shear stress in aquatic canopies, and its role in driving sediment transport, has largely eluded quantitative description. Firstly, it is difficult to predict the shear stress on the sediment bed in an aquatic canopy. Traditional application of a bulk momentum balance to determine the bed stress is likely to be wildly inaccurate as the flow resistance component of interest (the bed stress) is typically dwarfed by the other component (canopy drag), which is difficult to estimate with any certainty (Nepf 2012). Secondly, even if bed stress could be readily predicted, it is unlikely to be the only flow descriptor relevant to sediment transport; the structure of the turbulence in the flow is almost certainly important as well (see for example, Celik et al. 2010). Over a bare bed, the situation is simplified, as the mean bed stress and turbulence strength are linked. However, in canopy flow, turbulence is generated primarily by shear at the top of the canopy and in the canopy element wakes, not by the boundary layer at the bed. Therefore, predictive tools of sediment transport based entirely on the mean bed stress (as are common in open-channel flows) are unlikely to be quantitatively relevant (Yager & Schmeeckle 2013). Finally, as previously indicated, spatial variability of the near-bed flow and bed stress is significant on all scales; single-point observations may not be at all representative of the spatially-averaged bed stress.

2.2 Dynamics of wave-driven oscillatory flows

The dynamics of wave-driven flows through canopies have historically received limited attention, largely due to the lack of analogous terrestrial canopy models on which to build. While the momentum equations describing water motion in canopies under oscillatory and unidirectional flows are fundamentally similar, there are two key differences: (1) surface waves can generate large oscillatory pressure gradients at the dominant wave period *T*, and (2) flow accelerations inside the canopy can add inertial forces that increase the overall flow resistance f_x in Equation (1). To account for these effects, Lowe et al. (2005) developed a simple model describing the momentum dynamics within submerged canopies under wave-driven oscillatory flow by depth-integrating Equation (1) over the canopy region:

$$\underbrace{\frac{d\hat{U}}{dt}}_{\text{acceleration}} = \underbrace{-\frac{1}{\rho}\frac{dP}{dx}}_{\text{pressure}} + \underbrace{\frac{C_f}{2h_c}\left|U_\infty\right|U_\infty}_{\text{shear stress}} - \underbrace{\beta\left|\hat{U}\right|\hat{U}}_{\text{form drag}} - \underbrace{\frac{C_M\left(1-\phi\right)}{\phi}\frac{d\hat{U}}{dt}}_{\text{inertial}} \tag{3}$$

Here $\hat{U}$ denotes the spatially-averaged in-canopy velocity, C_f is a friction coefficient that relates the magnitude of the shear stress at the canopy interface to the free stream velocity U_∞, β is a dimensional drag parameter based on a porous media formulation that depends on the internal bed geometry, and C_M is an inertial force coefficient (see Lowe et al. 2008 for details). Equation (3) predicts that the acceleration of the in-canopy flow (term 1) depends on the pressure gradient and shear stress terms responsible for driving the flow (terms 2 and 3) and the form drag and inertial forces that oppose it (terms 4 and 5). Lowe et al. (2005) further defined a 'flow attenuation parameter' $\alpha \equiv \hat{U}^{rms} / U_\infty^{rms}$ to be the ratio of the root-mean-squared (rms) wave velocity inside the canopy $\hat{U}^{rms}$ to that in the free stream U_∞^{rms}. Above the canopy where the wave-driven flow is assumed to be inviscid (i.e. above a wave boundary layer), the wave-driven pressure gradient is related solely to the acceleration of the free stream oscillatory flow. Simple scaling arguments show that the importance of this pressure gradient term to the shear stress term increases with the ratio of the wave excursion orbital amplitude (A_∞^{rms}) to the roughness height of the canopy (Lowe et al. 2005):

$$\frac{\text{shear stress}}{\text{pressure}} \sim \frac{U_\infty^{rms}T}{h_c} \sim \frac{A_\infty^{rms}}{h_c} \tag{4}$$

Thus, similar to the case of severely depth-limited unidirectional flow, the pressure gradient imposed by waves substantially enhances flow inside a reef canopy over a pure unidirectional flow of the same magnitude. This theory has been supported by experimental studies using both idealized reef canopies and experimental assemblages of real branching coral reef canopies (Reidenbach et al. 2007, Lowe et al. 2008), which have all shown that unsteady wave motion substantially enhances the in-canopy flow (by a factor of 5-10 in these particular studies).

Bed shear stresses in wave-driven canopy flows remain largely unquantified. The lack of predictive capability is due, in part, to two important deviations from the steady flow condition. Firstly, the limited development (before flow reversal) of wave boundary layers over a bare bed results in a bed stress that is *lower* than that of a steady flow of the same magnitude. Secondly, and conversely, the substantially increased in-canopy velocity of an oscillatory flow (again, relative to a steady flow of the same magnitude) is likely to serve to *increase* the bed shear stress. The absence of direct measurements of bed stresses in oscillatory canopy flows means that this study has the capacity to fill a significant gap in the current understanding, one which greatly limits our ability to understand sediment transport in these complex benthic systems.

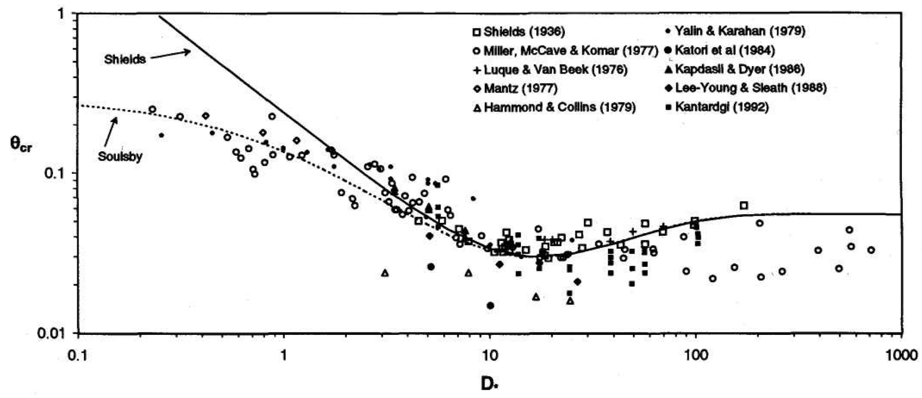

Figure 3. Shields diagram for initiation of sediment motion, derived from a compilation of experimental data sets (Soulsby and Whitehouse, 1997).

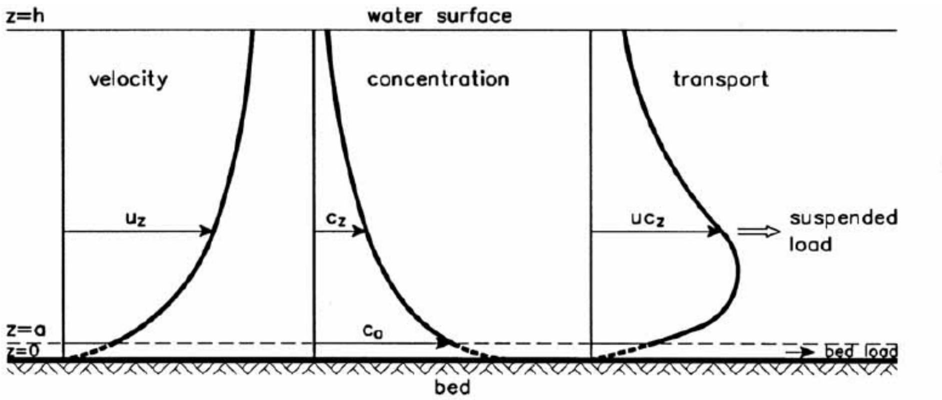

Figure 4. Conceptual model of sediment transport separating bedload and suspended load (van Rijn 2007a).

3. Sediment transport in the bottom boundary layer

3.1 The traditional conceptual framework

Studies of the dynamics of sediment movement in coastal systems have predominately focused on coastal systems with homogeneous sediment beds that lack benthic canopies, as well as systems where the sediment is mostly comprised of siliciclastic material (i.e. typically quartz-based sediments ranging from sand- to fine-grain fractions). From this work, a large body of experimental data (both laboratory and field based) has led to the development of numerous semi-empirical formulations that are designed to predict sediment transport rates under a wide range of different current and wave conditions (e.g. Soulsby 1997). These formulations have thus become the foundation for a number of predictive sediment transport approaches, ranging from simple empirical models to those implemented in complex process-based coupled hydrodynamic-sediment transport numerical models.

A key challenge in predicting sediment transport, even over the most simple homogeneous sediment bed, is first how to relate the mean and turbulent flow structure, as derived from field observations or a hydrodynamic model, to the entrainment (mobilization) of sediment that was initially at rest on the seafloor. Ultimately these relationships (e.g. Shields 1936) rely on predicting the hydrodynamic forces (i.e. the critical bed shear stresses) that are required to overcome sediment resistive forces (i.e. their weight, interactions between grains, etc.) and hence lead to the initiation of sediment transport in the bottom boundary layer. Dimensional analysis shows that this relative balance between hydrodynamic mobilizing forces and deposition forces can be parameterized with the so-called Shields parameter θ_{cr} :

$$\theta_{cr} = \frac{\tau_{b,cr}}{(\rho_s - \rho) g d_s} \tag{5}$$

where $\tau_{b,cr}$ is the critical bed shear stress leading to the initiation of sediment motion, ρ_s is the sediment grain density, ρ is the seawater density, and d_s is a representative sediment grain diameter. For uniform sediment beds without canopies, a wealth of historical data has been used to develop predictive empirical formulas (e.g. Figure 3) to determine these critical shear stresses as a function of basic properties of the sediment (generally just a representative 'spherical' grain size and a representative sediment density), as well as in some more complicated cases simple geometrical properties of bedforms if they are present (e.g. ripple heights, lengths, etc.).

Once sediment transport is initiated, the horizontal transport is then (somewhat arbitrarily) decomposed into two components: 1) suspended load - sediment that is transported in suspension in the water column; and 2) bedload - sediment transport in which grains remain in regular contact with the seabed (Figure 4). Thus, rates of total sediment transport S_{total} (volume of solid grains of sediment per second per m width, m^3/m/s) are linearly separated as:

$$S_{total} = S_b + S_s \tag{6}$$

where S_b and S_s denote the bedload and suspended load contributions. Numerous transport formulations have been proposed to predict these separate rates of suspended load and bedload, and these have been implemented in a variety of different predictive models.

The partitioning of sediment transport into suspended loads and bedloads is dependent on the Rouse number, a ratio of the sediment grain fall velocity (w_s) to the shear velocity (u_*, a measure of the bed shear stress).

$$P = \frac{w_s}{u_*} \tag{7}$$

For non-cohesive sediment beds lacking a benthic canopy, when $P > 1$, the majority of the sediment transport is in the form of bedload. As the flow intensity increases, and P becomes less than approximately 0.5, the majority of the sediment transport is in the form of suspended load. In the intermediate range, both bedload and suspended load can make significant contributions to the total flux.

Finally, while the discussion above has focused on the dynamics necessary to mobilize or erode sediment initially at rest on the seafloor, i.e. based on critical shear stress thresholds, it is worth noting that these concepts are also used to describe the converse case; that is conditions that will lead to deposition of sediment, for example, the settlement of sediment suspended in a dredging plume. Thus when the Shields parameter θ based on the local hydrodynamic conditions falls below the critical threshold θ_{cr} sediment deposition is assumed to occur.

3.2 Traditional bedload transport models

There are several commonly-used formulations for bedload transport of non-cohesive sediment driven by unidirectional flow, based on decades of experimental and field data of fluvial transport of (primarily) fine to coarse-grained sands (62.5 μm to 2 mm). These formulations are too numerous to discuss in detail; however, Van Rijn (2007b) provides a good recent summary. Importantly, however, modern bedload formulations have several features in common; the majority can typically be expressed as relating a dimensionless measure of bedload transport:

$$\phi_b = \frac{S_b}{\sqrt{\left(\frac{\rho_s}{\rho} - 1\right) g d_s^3}} \qquad (8)$$

to the excess Shields parameter (i.e. the Shields parameter minus the critical value in Figure 3). That is, a general relationship is of the form

$$\phi_b \propto \left(\theta - \theta_{cr}\right)^{\beta} \qquad (9)$$

where β is an exponent typically in the range 1 – 2. The form of Equation (9) highlights the importance of accurate bed shear stress estimates in the prediction of bedload transport rates. The formulations summarised in van Rijn (2007b) all have defined ranges of 'optimal' applicability, in terms of the sediment size, the flow conditions and the validity of implicit assumptions. Within typical ranges encountered in coastal and estuarine environments, these formulations provide estimates of bedload transport that typically agree within a factor of 2 (van Rijn 2007b); in the context of sediment transport, this is considered good agreement.

The extension of steady flow formulations to oscillatory (i.e. wave-driven) flow presents an additional level of uncertainty. Oscillatory flow adaptations fall into two categories: 1) those that determine the wave-averaged transport rate, typically by employment of the maximal (or crest) value of the Shields parameter in an equation of the form of Equation (9), and 2) those that estimate the instantaneous transport based on instantaneous flow conditions (requiring integration over the wave cycle to estimate the wave-averaged transport).

3.3 Traditional suspended load transport models

Suspended sediment transport is defined as the depth-integrated product of flow velocity (*u*) and suspended sediment concentration (*c*). Models of suspended sediment transport (S_s) are all based on the conservative advection-diffusion equation. In a one-dimensional (i.e. horizontally-uniform) system, this takes the form:

$$\frac{\partial c}{\partial t} + w_s \frac{\partial c}{\partial z} + \frac{\partial \langle c' w' \rangle}{\partial z} = 0 \qquad (10)$$

where w_s is the sediment fall velocity, and $\langle c' w' \rangle$ represents the vertical (upward) turbulent sediment flux that is responsible for maintaining the sediment in suspension. However, solution of Equation (10) and subsequent calculation of suspended load relies on the following to be known or assumed: (1) a 'reference' concentration of suspended sediment near the bed, typically derived from empirical relationships, (2) the velocity profile $u(z)$, and (3) closure for the turbulent term, typically via a turbulent diffusivity. The turbulent diffusivity for sediment is typically assumed to be equal to the turbulent eddy viscosity of momentum. A range of turbulence closure schemes are used to predict eddy viscosities, ranging from simple analytical approaches (e.g. giving the classic Rouse concentration profile) to those embedded in numerical models based on the turbulent kinetic energy equations.

Importantly, the theory underpinning the prediction of both bedload and suspended load has been developed based on smooth wall boundary layer theory. The relevance of existing formulations in describing sediment transport in the complex benthic ecosystems considered here, which greatly modify the near-bed flow and vertical transport, still remain largely untested.

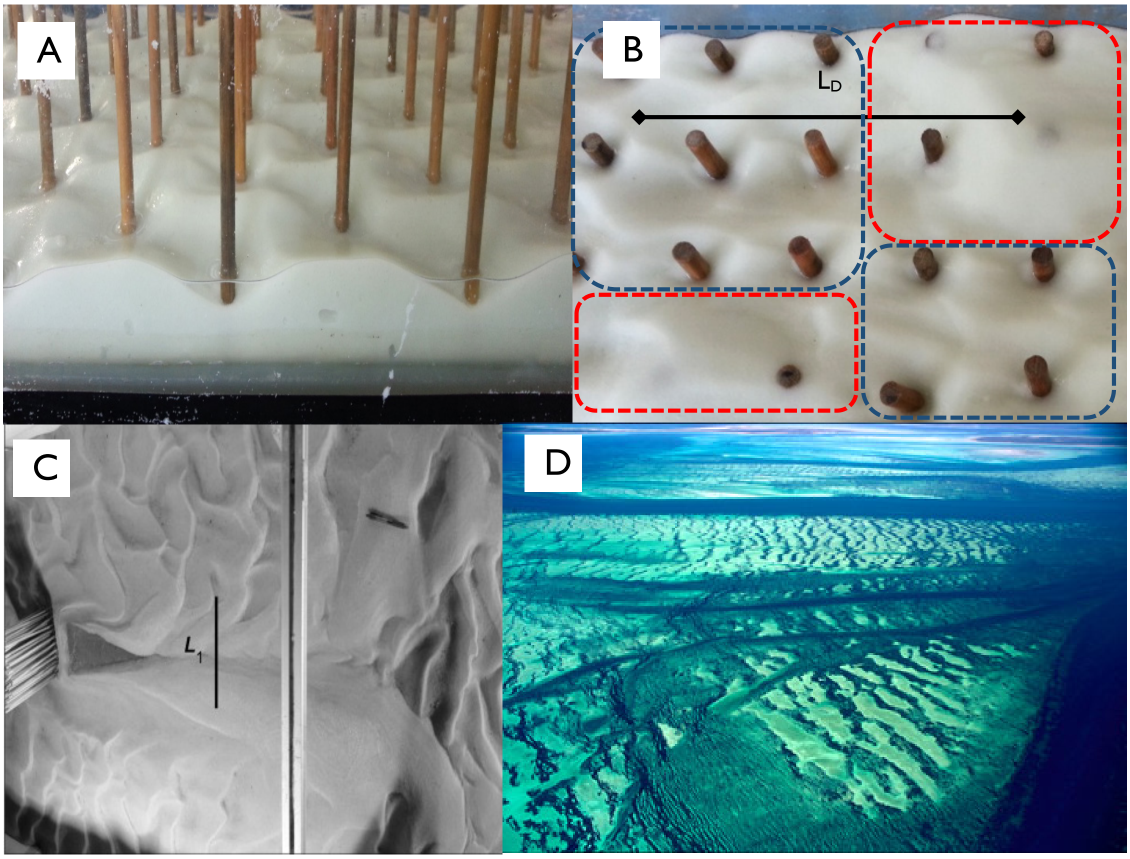

Figure 5. Sediment transport on the four spatial scales discussed here. (A) Stem-scale scour in the laboratory (Ng, 2013) (B) Canopy-scale heterogeneity of sediment transport in a uniform array in the laboratory (adapted from Ng, 2013). Alternating zones of strong sediment deposition (red zones, often burying canopy elements) and sediment erosion (blue zones), separated by a distance of the order of LD, are evident (C) Panoramic view of patch-scale sediment transport in the laboratory. The patch on the left-hand side (flow is from left to right) creates strong scour within the patch, deposition behind the patch and patch-driven bedforms (taken from Follett and Nepf, 2012) (D) Fauré Sill (500 km²) in Shark Bay, Western Australia, which has formed through thousands of years of sediment deposition within a seagrass meadow (Davies, 1970; image from WA Department of Parks and Wildlife).

3.4 Potential additional factors influencing fine-grain sediment transport

As discussed, the majority of sediment transport understanding has been derived from the study of non-cohesive sediment in the sand size fraction. Unlike sands, the transport properties of fine cohesive sediments may not be amenable to classification by grain size and distribution alone. With such fine sediments, which can comprise an important fraction of dredging plumes, electrostatic forces engender 1) flocculation of sediment particles into aggregates of a range of sizes and settling velocities, and, accordingly, 2) sediment properties that are highly sensitive to the physico-chemical environment. This can further complicate quantitative description of sediment transport; for example, the predictive capability for the threshold of incipient motion of cohesive sediment is limited (in contrast to the well-established relationship in Figure 3 for non-cohesive sediment).

While the effects of sediment cohesion have the capacity to quantitatively influence rates of sediment transport in dredging plumes, the substantial (i.e. primary) challenges in this research still relate to understanding the significant effects of benthic canopies on sediment transport. Accordingly, the focus will be on evaluating the applicability of conventional formulations for the transport of non-cohesive sediment in these complex ecosystems, which must be the first step to accurately predict these dynamics.

4. Sediment transport through canopies

4.1 Key issues and challenges

Given that existing sediment transport formulations have been developed for open sediment beds (see Fredsøe & Deigaard 1992 for a review), they cannot be directly applied to the vast regions in many coastal systems that contain canopies (e.g. seagrass meadows, coral reefs, macro-algal dominated reef ecosystems and mangrove forests). In contrast to systems with uniform sediment beds (e.g. sandy beaches and many shelf regions, etc.), where hydrodynamic forces (shear stresses) are mostly exerted directly on a sediment, in canopy environments the momentum transfer to the canopy via drag forces can dramatically reduce the forces that act on sediment within a canopy. Furthermore, the increased bottom roughness of canopies that enhance the drag encountered by waves and currents also leads to the increased dissipation of hydrodynamic energy in the water column. To account for this, numerical models of coral reefs and seagrass meadows for example must incorporate higher bottom drag forces (via increasing drag coefficients) that ultimately result in higher predictions of bottom shear stresses. As a result, application of standard sediment transport models based on smooth bed theory will actually predict greater rates of sediment mobilization and transport; in reality the opposite will generally occur, with bed shear stresses at the base of the canopy actually being substantially reduced.

4.2 Studies of sediment transport through aquatic vegetation

Studies quantifying rates of sediment erosion and deposition in vegetation canopies are comparatively rare (for a complete summary of existing studies into the relationship between flow, vegetation and sediment transport, see Table 1). Nevertheless, the impact of submerged canopies on sediment transport has been shown to be profound, relative to a corresponding bare bed. Rates of sediment accumulation can be so high that they result in changes in bed morphology that can further reinforce accumulation, as has been recorded in a variety of vegetation canopies (James et al. 2004). Gacia et al. (1999) demonstrated that particle retention in vegetated beds could be up to 15 times greater than the equivalent non-vegetated bed, and that the rate of deposition was strongly related to the projected surface area of the canopy.

The majority of studies (both experimental and field) point to vegetation canopies as regions of net sediment deposition (see extensive reviews of Baptist 2005, Järvelä et al. 2006, Kothyari et al. 2009, Jones et al. 2012, Montakhab et al. 2012). However, recent laboratory and field observations of sediment transport in aquatic canopies have been divergent. Several studies have brought into doubt the core idea that canopies (averaged over the patch-scale) are invariably zones of sediment deposition. Such studies include:

- Those that highlight the importance of the patch size: smaller vegetation patches have been shown to be zones of increased net erosion (relative to their surroundings), especially at the front of the patch (e.g. Fonseca & Koehl 2006, Chen et al. 2012, Follett & Nepf 2012, Ortiz et al. 2013).
- Those that highlight the importance of the canopy density: at low canopy densities, increases in net erosion (again, relative to their surroundings) have been observed (e.g. Van Katwijk et al. 2010, Lawson et al. 2011).

Accordingly, there exists no real predictive capability for sediment transport in vegetation canopies. Studies may provide system-specific descriptions for sediment retention capacity in vegetation canopies (perhaps relative to the corresponding bare bed), but it is unclear how this capacity varies with properties of the canopy and of the ambient flow.

Table 1. Compilation of existing research into sediment transport in vegetation canopies

Author	Notes	test environment	vegetation model		vegetation zone			sediment			rectangular channel			
			stem diameter (cm)	pattern	density Ø (otherwise stated)	length (cm)	width (cm)	ρs (g/cm3)	D (mm)	characteristc	flow depth (cm)	flow velocity (cm/s)	flume dimension (cm3)	bed slope
James et al. 2004	2 series of experiments: Expt A with constant water discharge and varying sediment supply rates (i.e. bed load transport rate), Expt B: constant sediment supply rates but varying water discharge;	lab	emergent, 0.5	staggered	0.0314	1500	38		0.45	sand	•3.6 to 4.3 in experiment A •2 to 11 cm in Experiment B	15.7 to 18.5	1500 (L) x 38 (W), glass sided	0.002-0.01
Tanino and Nepf 2008	Laboratory Investigation of Mean Drag in a Random Array of Rigid, Emergent Cylinders	lab	6.4	random	0.15-0.35	28.4	40		na				na	0
Kothyari et al. 2009	drag coefficient of emergent vegetation	lab	10	-	0.0022-0.0885	180	50		na				1600 x0.50	0-0.02
Kothyari et al. 2009	Effect of tall vegetation on sediment transport by channel flows	lab	0.2 to 0.4	staggered	0.0017- 0.011	1200	15 20	2.65	0.55 to 5.9	quartz sand	30	35 to 95	1200x15 (or 20) x 30	0.01 to 0.2
Jordanova and James 2002	modelling of flow-sedimnet-vegetation interactions in flume, effect on sediment transport rate when sediment supply is ceased	lab	emergent, 0.5	staggered	0.0314	10000	1250	2.65	0.45	sand	3.6-4.3	15 to 18	1500 x 38 (W) x	0.016
Baptist 2005	A flume experiment on sediment transport with flexible submerged vege	lab	submerged, flexible 0.2	square	401 stems/m2	1585		2.65	0.032 (9 cm thick)	quartz sand	26 to 30	38- 61	3501 (L) x 80 (W)	
Chen 2012*	Observations on flow and local scour around submerged flexible vegetation	lab	submerged, 1.8, mounted on a 3x3 cm board (with 16 bundles on each board). This is one N.	staggered	number of model plants ,N per unit bed area A (3^2* N /A)= 0.21 to 0.65	39 to 51	30	2.65	0.105	sand	18.7	27.3	800 x 30 x 60	
Monthakab and Yusuf 2011	effect of different density and arrangement of vegetation on sediment trapping capacity measured the TSS in water sample collected at 5, 10 and 15 min	lab	submerged, Real plant *Hydrilla verticillata*	concentrated in a band in the middle of the flume, only both sides of channel, over the whole cross section	24, 36 and 48 plant bunches (stem diameter not mentioned)	50	50	2.52	0.0815	clay	15	24	240 x 50 x 50	0
Shi et. Al 2000	lower suspended sediment concentrations in saltmarsh canopies compared to unvegetated mudflat	field	Scirpus mariquete and Spartina alterniflora, no diamater given	-	1000 stems/m2	continuous		2.65	-	-	-	up to 50	n/a	n/a
Leonard 2006	study of horizontal and vertical turbulent kinetic energy, velocity and suspended load in different densities of salt marshes	field	submerged	-	150 to 250 m/2	continuous		-	-	sand	45	2 to 6	n/a	n/a

4.2.1 A range of spatial scales

Just as the flow within aquatic canopies is highly spatially variable, so too is sediment transport. Four spatial scales that are demonstrably relevant to sediment transport are:

- The 'element scale' (typically O(mm-cm)) – significant erosion (as evidenced by scour holes) can occur around individual stems (Figure 5A), much as it does around pylons and pipelines. Sediment transport on this scale has tremendous implications for the stability of individual seedlings or shoots in seagrass recruitment or transplanting.
- The 'canopy scale' (LD, typically O(0.1-1 m)) – this represents the scale of turbulence induced by the flow resistance of the canopy. There is significant sediment transport on the canopy scale in aquatic canopies Figure 5B).
- The 'patch scale' (typically O(1-10 m), but highly variable) – sediment transport on the horizontal scale of a patch of vegetation (Figure 5C) will greatly impact patch growth and may dictate patch shape (Follett & Nepf 2012, Ortiz et al. 2013).
- The 'meadow scale' (typically O(0.1-1 km), but highly variable) – sediment transport on the scale of an entire seagrass meadow has the potential to create large-scale sedimentary structures, as in Figure 5D.

4.3 Studies of sediment transport on coral reefs

There are numerous data sets on the grain size distributions and composition of reef sediments, which include a wide variety of systems in the Indo-Pacific and Caribbean, as well as those incorporating a number of different reef types ranging from fringing reefs to atolls. However, most of these studies provide only a descriptive assessment of the distributions of sediment properties across reefs, thus lacking a process-level understanding of what controls these distributions, whether it be physical or ecological.

Field observations of suspended sediment concentrations (SSCs) have been obtained on a wide range of reefs, but accurate measures of sediment fluxes on reefs remain scarce. These tend to be based on point estimates of suspended sediment transport rates derived from co-located hydrodynamic measurements and logging sensors that provide a proxy for sediment concentrations (see below). No accurate direct measurements of bedload transport on reefs have been reported, which may be particularly important within low energy areas of reefs such as within sandy lagoons.

For reef environments, quantification of suspended sediment transport and deposition has been the primary focus of most studies. On the reef flat, the concentration of suspended sediment has been associated with the height of the waves that can propagate onto coral reef flats (Suhayda & Roberts 1977). Low suspended sediment concentrations have been measured in the water column at shallow water depths while larger concentrations have been measured with deeper water depths (e.g. higher tides or storm conditions) (Storlazzi et al. 2004). The increase in concentration has been attributed to larger shear stresses on the seabed that occur as larger waves propagate onto the reef often during periods of increased water depth such as during storm surges or higher tides (Suhayda & Roberts 1977, Ogston et al. 2004, Storlazzi et al. 2009). In the lagoon, attenuation of swell waves on the reef results in a low energy environment where currents and secondary waves have been suggested to not induce a large enough shear stress to suspend new sediment (Roberts et al. 1981). Sediment that has already been entrained into the water column may, however, be transported within the lagoon where it either settles out of the water column or is advected out of the system as the currents exit though the channels in the reef (Storlazzi et al. 2009). Although a simple conceptual understanding of sediment distribution within reef environments has been developed from many quantitative studies, a detailed study into the physical processes associated with sediment (re-) suspension, distribution and sedimentation, as well as how these processes are affected by relative differences in hydrodynamic processes in the presence of coral, has yet to be established for reef environments.

Overall, there is still very limited *quantitative* data presently available that can provide confidence in existing sediment transport models to accurately predict sediment transport in reef environments. Fundamental data on the transport of carbonate sediments is lacking, making it difficult to 1) understand how well existing semi-empirical sediment transport formulations originally derived with spherical siliciclastic sands perform in reef environments, and 2) to support the development of new formulations to improve these predictions.

5. Sediment transport measurement techniques

There are numerous approaches used to measure sediment concentrations and sediment transport rates in the coastal bottom boundary layer. Some of the primary approaches are briefly summarized here, including highlighting their potential advantages and disadvantages.

5.1 Existing technology

5.1.1 Optical

The primary sensors used to take measurements of the concentration of sediment in the water column use the backscatter or transmission of certain wavelengths of light. Transmissometers quantify the amount of light blocked across the sensor by suspended sediment particles (e.g. Wolanski et al. 2003). These sensors are very sensitive and are useful in optically clear waters but become saturated at relatively low particle concentrations and thus are not useful in highly turbid environments. Optical backscatter sensors measure the amount of light scattered by sediment back to the sensor and, although not as sensitive as transmissometers, can effectively operate at much higher SSCs (e.g. Storlazzi et al. 2009). Although both transmissometers and optical backscatter sensors are extremely reliable and the industry standards for assessing levels of suspended sediment, they only provide information on concentration of sediment in the water column and react differently to different sized particles. When information on sediment character, such as source (biogenic versus terrigenous) is desired, some studies have employed underwater camera systems to recover optical imagery of the material in suspension to provide insight into the origin of the sediment (e.g. Storlazzi et al. 2009). All of these optical sensors are negatively affected by fouling and typically can only provide clean data unbiased by biofouling for a few days to weeks in tropical coral reef environments unless the sensors' optics are cleaned regularly.

5.1.2 Sonar (single and multiple frequencies)

Sonars can provide information on SSCs similar to optical backscatter sensors by recording the amount of acoustic energy reflected back to the sensor, and are generally unaffected by fouling. Acoustic sensors, unlike optical sensors, are much more dependent on particle size and thus not as effective in locations with varying grain sizes. Given that sonar frequency is inversely related to the optimal size of particles measured, these approaches tend to target finer-grained sediment particles based on the higher frequencies (i.e. order megahertz) of typical oceanographic instruments. In some cases the acoustic backscatter recorded by acoustic Doppler velocimeters and acoustic Doppler current profilers developed to measure currents can be used to provide information on SSCs similar to dedicated acoustic backscatter systems (e.g. Storlazzi et al. 2004). Multi-frequency systems have also been developed to increase the number of grain sizes that can be measured by a single unit.

5.1.3 Samplers

A number of tools have been developed to take physical samples of suspended sediment for physical or chemical analyses. Simple traps, deployed both vertically and horizontally, have been used to collect sediment, but these tools often affect flow at the site and can provide spurious data on true sedimentation rates (Storlazzi et al. 2011). Designed surfaces and collection devices have more recently been developed to try to accurately measure sedimentation rates and provide sediment samples for analyses (Field et al. 2013). A number of pump sediment systems developed for river systems have been modified for use in shallow coastal systems (e.g. van Rijn 2007a); these systems are generally very cumbersome and not well suited for long-term autonomous measurements.

5.2 Summary of measurement challenges

Although there have been a number of measurements made of sediment dynamics in coral reef environments over the past decade, these are orders of magnitudes less than those made along sandy, siliciclastic coasts that have gentler bathymetric variations and are less hydrodynamically rough. The much greater bathymetric complexity of coral reefs and their greater hydrodynamic roughness means that there are extremely limited samples for a given reef configuration. Therefore, the primary need is for increased numbers of studies and data from varying reef types and shoreline configurations. Furthermore, most of the previous field studies have been of limited duration (weeks to a few months) and thus are insufficient to significantly contribute to the understanding of reef and reef-shoreline annual and longer term sediment budgets.

In addition, there is also great heterogeneity of grain sizes, shapes, and densities in coral reef sediment (Kench & McLean 1996). Because optical and acoustic sensors are dependent on grain size and calibration procedures that only relate to a particular (single) sediment type, it is apparent that much more information is needed on the effect of this heterogeneity on suspended sediment measurements. Time-series sampling of sediment in suspension is needed for time-varying calibrations of acoustic and optical sensors. At this time, the sediment transport formulas embedded in most hydrodynamic numerical models assume solid spherical sediment particles of a given size and uniform density, but many carbonate sediment particles are porous and of varying density due to dissolution and re-precipitation of calcareous material (Kench & McLean 1996). This means that new studies are required to understand how the various shapes, densities, and structures of carbonate sediment particles can be represented by uniform sizes and densities.

Most of the tools used to make time-series measurements of sediment fluxes in coastal environments specifically target the measurement of suspended sediment loads; there are very few direct measurements of bedload in any coastal environment, let alone in coral reef environments. Because the greatest volume of sediment is transported as bedload, the lack of data on this aspect of sediment dynamics on coral reefs currently limits our ability to accurately constrain net fluxes and sediment budgets on coral reefs and adjacent shorelines.

The processes of fine-scale deposition and resuspension on hydrodynamically-rough corals and carbonate surfaces that affect biological and chemical processes relevant to reef health (reef morphology, roughness, and sediment production) are poorly understood. Understanding of such fine-scale processes are relevant to not only better constrain predictions of the impact to natural sediment transport events such as river flood plumes, but also anthropogenic events such as the impact of dredge disposal in the vicinity of coral reef environments.

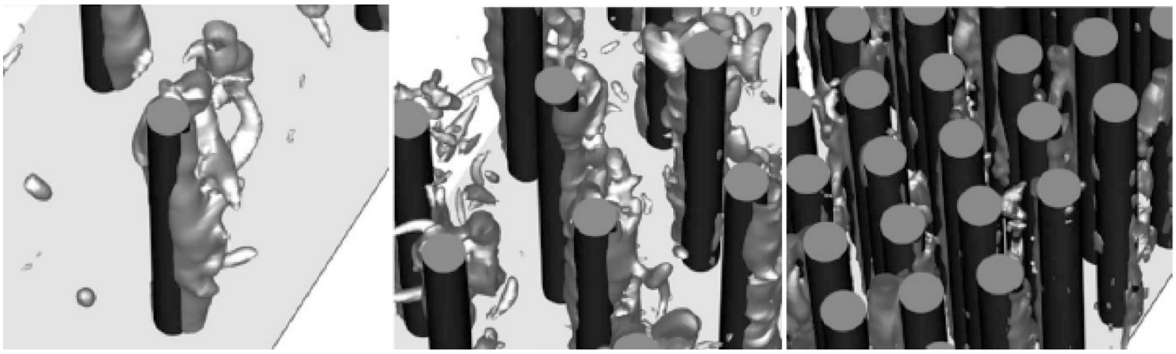

Figure 6. The complex turbulent flow structure resolved through an idealised canopy of vertical cyclinders using highly-resolved computational fluid dynamics (CFD) models. The figure adapted from Stoesser et al. (2010) shows instantaneous pressure contours for three canopy densities.

6. Prospects for numerical modelling

As summarised above, one of the greatest challenges to predicting sediment transport through canopies remains how to accurately describe the mean and turbulent flow structure both within and above the canopies, and how this varies as a function of canopy type, canopy density and properties of the overlying flow. In particular, accurate modelling of the hydrodynamics is critical to robustly predict the bed stresses that will entrain or deposit sediment, as well as to predict rates of bedload. Predicting the detailed turbulent flow structure within and near canopies is also essential to being able to accurately model rates of suspended sediment transport through the entire water column.

There is a growing literature that attempts to model the mean and turbulent flow structure through aquatic canopies under *unidirectional flow* conditions. These modelling studies loosely fall into two model classes: 1) very high resolution computational fluid dynamic (CFD) studies conducted on very small scales, which attempt to directly resolve the turbulent flow structures through the canopies, and 2) parametric models that attempt to model the mean and turbulent flow profiles or bed stresses, using semi-empirical formulations.

Detailed CFD models of flow through aquatic vegetation are becoming more prevalent and increasingly refined. One of the earliest studies was conducted by López and García (1998), who did not attempt to resolve the detailed flow around each canopy element in the flow, but rather applied the Reynolds Average Navier Stokes (RANS) equations with a $k-\varepsilon$ turbulence closure scheme to parameterise the turbulent flow structure as a function of the local form drag exerted by the canopy. The accuracy of all of these RANS based modelling approaches largely depends on how well the turbulent flow field can be modelled with a turbulent closure scheme. There have been a number of new advances in turbulent closure schemes applicable to canopy flows, which have been found to predict the spatially-averaged flow structure fairly accurately for both emerged and submerged cases (see King et al. 2012 for a recent summary). Most recently, due to the exponential growth of modern computational power, there has been a growing number of CFD modelling studies that attempt to directly resolve the fine-scale flow interactions directly with canopy elements, albeit still relying on turbulence closure schemes based on Turbulent Kinetic Energy (TKE) and Large Eddy Simulation (LES) schemes (e.g. Cui & Neary 2008, Stoesser et al. 2009, Okamoto & Nezu 2010, Stoesser et al. 2010, Kim & Stoesser 2011, Marjoribanks et al. 2014, Marsooli & Wu 2014) (e.g. see Figure 6). Although these CFD modelling approaches provide valuable insight into the hydrodynamic transport mechanisms within canopies that ultimately drive small-scale sediment transport, due to their very large computational demands (i.e. requiring turbulent flows down to scales of a mm or less), their use is still practically limited to relatively small-scale domains of the order of metres, which precludes their use in broader scale applications of sediment transport through coastal ecosystems.

In practice, for field scale applications of hydrodynamic and sediment transport models, parametric models can only directly be used. These models generally attempt to model the flow structure and bed shear stresses within canopies by considering the momentum balances that are established within the canopy. These tend to be based on an algebraic set of equations that can predict, for example, bed shear stresses as a function of the overlying flow and geometric properties of the canopy. Vargas-Luna et al. (2014) have recently provided an excellent review of the current state of knowledge of these parametric models, including a comparison with some (albeit limited) data sets. We note that while the Vargas-Luna et al. (2014) review summarises some simple models that may be applicable to predicting bed shear stresses for both emerged and submerged canopies, due to the lack of bed shear stress data for the submerged case, they only compare model performance for emerged canopies. It is clear that new data on bed shear stresses for submerged canopies are critically needed to test new models that have been proposed, as well as further develop and refine them. In addition, all of this work has focused solely on unidirectional flows, thus neglecting wave-driven flows that often dominate these coastal zone. New models will need to be developed to include this other important class of flows.

Numerical modelling studies of sediment transport through canopies tend to be even more limited, and again these have almost exclusively focused on transport driven by unidirectional flow. There is a vast literature on sediment transport over non-vegetated sediment beds (see Section 3), which require predicting the critical bed shear stresses that initiate sediment motion (whether it be bedload or suspended load), and the mean and turbulent flow structure to predict rates of suspended load transport. Although still not adequately evaluated in the literature, a working hypothesis could be that these same sediment transport formulations could provide some foundation for sediment transport through canopies, if they are modified to account for the reduction in bed shear stresses arising from the canopy, as well as changes to the mean and turbulent flow structure. Again focusing only on the simpler case of sediment transport through emergent canopies, Vargas-Luna et al. (2014) assessed the performance of these modified sediment transport models by comparing with bedload transport measurements from Jordanova and James (2003) and Kothyari et al. (2009) (refer to Figure 7). While these results show some promising agreement, it must be emphasised that these are based on predictions of bedload only as well as for emergent canopies. With most coastal canopies (e.g. seagrasses meadows and coral reefs) being completely submerged, and given that fine sediments associated with dredge plumes will generally be transported initially as suspended load, these existing formulations may be of questionable utility in some applications. New data are critically needed before these models can be further developed and tested. However, there is clearly a sound theoretical basis that can be the foundation for these new sediment transport formulations. Once such sediment transport formulations are developed, they can then be readily incorporated into existing coastal models, which would be a vast improvement in the modelling of sediment transport for a wide range of coastal ecosystems.

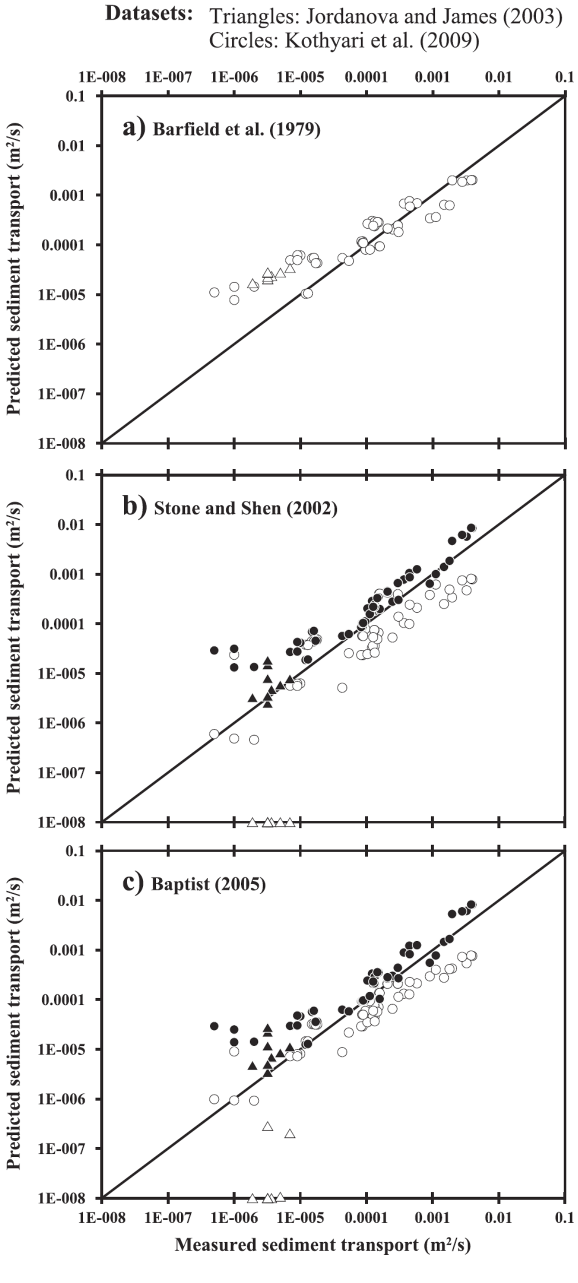

Figure 7. Comparison of sediment transport rates using data from Jordanova and James (2003) and Kothyari et al. (2009), using three different parametric hydrodynamic models (a-c) to predict bed shear stresses. Adapted from Vargas-Luna et al. (2014).

7. Summary

We have reviewed the existing literature on how sediment transport is modified by the presence of aquatic canopies, particularly canopies that are formed by coral reef communities and aquatic vegetation such as seagrasses. This has highlighted numerous knowledge gaps that presently preclude accurate predictions of sediment transport within these coastal ecosystems. From this review we identify the following summary points:

- There is a well-established literature on the mean and turbulent flow structure through both submerged and emerged aquatic canopies driven by *unidirectional flow*. These models are designed to predict the bulk (macroscopic) flow through a canopy as a function of both the overlying flow and representative geometrical properties of the canopy that can be quantified. On this basis, predictive models have been developed to predict the flow structure through canopies, which have been proven to be accurate in many cases. While there is some literature on canopy flows driven by wave-driven *oscillatory flows*, and some models have been proposed, these have received nowhere near the same degree of testing.
- Some attempts have been made to measure bed shear stresses within submerged and emerged canopies, but data remain very limited. Given that sediment transport depends critically on accurate knowledge of these bed shear stresses, this gap in the hydrodynamics poses a major barrier to establishing predictive sediment transport models through canopies. There needs to be more research focus on how in-canopy hydrodynamics are related to bed shear stresses, and how bed stresses change under different flow conditions (unidirectional vs oscillatory) and for different canopy types.
- For open sediment beds lacking any canopy, there is already a large body of literature on the mechanics of sediment transport driven by both currents and waves, including well-established models for predicting both bedload and suspended load. All of these predictive formulas contain a great deal of empiricism. With historical sediment transport studies focusing almost exclusively on siliciclastic sands, there are many questions on how well these traditional formulations will perform for biogenic carbonate sands that are more typical of many or most coastal ecosystems (e.g. coral reefs, seagrass meadows, etc.).
- A number of techniques now exist to measure suspended sediment transport in the bottom boundary layer, with most instrumentation relying on either optical or acoustic sensors. As these instruments were not necessarily designed and tested for applications with carbonate sediments, there remain questions on how well these instruments will perform, for example, in sites such as coral reefs where the sediments tend to be dominantly carbonate.
- There have been some field observations of sediment transport through both coral reef and seagrass canopies; however, these tend to be largely qualitative descriptions of SSCs or rough estimates of transport rates. Due to the lack of detailed quantitative data, this is restricting the development of predictive models applicable to these type of coastal ecosystems. There have been some recent measurements of sediment transport through emergent canopies in controlled laboratory experiments, which suggest that existing sediment transport formulations potentially can be used if they are modified to account for substantial hydrodynamic modifications to the flow by a canopy. However, observations of sediment transport through submerged canopies, the most relevant case for most coastal applications, are severely lacking.
- A wide range of numerical modelling techniques exist to predict flow through aquatic canopies, ranging from very advanced and computationally expensive CFD models that resolve the details of the fine-scale flows, to parametric models that consider the main momentum balances but in principle can be readily implemented in larger (field scale) numerical models. The major barrier to developing and applying these numerical models is the lack of existing laboratory and field data to aid in their development and provide validation.

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