Sediment transport over benthic habitats – corrections for sediment transport models

DREDGING SCIENCE NODE

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Benthic ecosystems (with canopies) modify sediment transport

• Most coastal ecosystems have benthic canopies (e.g., coral reefs, seagrass meadows, mangroves, etc.)

• Reduced near-bed flows in canopies → reduced sediment transport (and enhanced deposition)

• Sediment transport formulations accounting for benthic ecosystems are lacking

• Applying existing sediment transport models based on bare sediment lead to major errors
Background: conventional approaches to predict sediment transport (bare beds)

- Sediment transport predictions are based on predicting bed shear stresses ($\tau_{\text{bed}}$)
- Determines whether sediment will be eroded or deposited at a bed (critical shear stresses)
- Assume that $\tau_{\text{bed}}$ applied to the bed is equivalent to the resistance experienced by the overlying flow ($\tau_{\text{flow}}$)
The conundrum: bed shear stresses with canopies

- Hydrodynamic (circulation) models conventionally focus on predicting “bottom” stresses that parameterize total flow resistance ($\tau_{\text{flow}}$).
- But sediment transport driven by bed shear stresses exerted on the sediment ($\tau_{\text{bed}}$).
- Problem: bottom friction tends to be enhanced in models over canopies (e.g. reefs, seagrass meadows) predicting that sediment transport is enhanced -> the opposite occurs.

\[
\tau_{\text{flow}} = \tau_{\text{drag}} + \tau_{\text{bed}}
\]

Total stress = Canopy drag + Bed shear stress

\[
\tau_{\text{drag}} \quad \tau_{\text{bed}}
\]
This has major implications for sediment transport

An illustrative example: (Le Bouteiller et al. 2015)

Prior experimental studies have only highlighted major discrepancies ... up to 3+ orders of magnitude errors in sediment transport!
Project objectives and research components

(1) Obtain direct observations of sediment fluxes, deposition and resuspension rates within benthic canopies.

(2) Develop new empirical relationships of sediment deposition and erosion rates applicable to a range of habitat types (e.g. coral reefs, seagrasses, etc.).

(3) Provide a framework for embedding new sediment transport routines applicable to a range of habitat types within a practical hydrodynamic-sediment transport models

Integration of field, laboratory and numerical modelling components
Sediment transport over reef roughness (example field study)

- Detailed field measurements of:
  - Turbulence (bed stresses), sediment concentrations, and sediment fluxes across reef canopies
  - Broad (reef-scale) observations sediment concentrations and reef hydrodynamic processes


Bed shear stresses

- Measurements both above the roughness / canopy) (τ_{flow}) and at the bed (τ_{bed})

Friction velocity:

\[ u_* = \sqrt{\frac{\tau}{\rho}} \]
Suspended sediment properties and transport thresholds

- Existing sediment transport models predict **bed** sediment (medium-coarse sand) should be mobilised for the $\tau_{\text{flow}}$
- Only much finer sediment (coarse silt) is transported $\rightarrow$ consistent with much lower $\tau_{\text{bed}}$
- Reef roughness substantially reduces sediment transport
Improving model predictions of sediment transport

1D suspended sediment transport (advection-diffusion equation)

\[
\frac{\partial (uc)}{\partial x} - \frac{\partial (w_s c)}{\partial z} - \frac{\partial}{\partial z} \left( \frac{\varepsilon_s}{\varepsilon_z} \frac{\partial c}{\partial z} \right) = 0
\]

Reference concentration

\[ c_0 = A \left[ \frac{\theta u_s}{w_s} \right]^B \]

Comparing observed versus predicted suspended sediment fluxes (\(uc\))

Conventional approach (\(\tau_{flow}\))

Reduced bed stress model (\(\tau_{flow}\))

Reference concentration

\[ c_0 = A \left[ \frac{\theta u_s}{w_s} \right]^B \]
Laboratory experiments

- Experiments conducted in a large-scale wave-current flume at UWA
- Model canopy – array of rigid cylinders (variable packing density), emergent & submerged
Canopy effects on near-bed velocity

- Attenuation of near-bed velocity significant at realistic densities (up to an order of magnitude)
- Identifies a “roughness density” ($\beta$), as key descriptor of canopy flow reduction

\[
U_b = \frac{U_\infty}{\lambda} \left( \frac{a h}{2} \right)^{1/2}
\]

$\lambda = \text{canopy solid fraction}$

$\alpha = \text{frontal area per unit volume}$

Bare bed

Increasing canopy height, density

\[
\beta = \lambda (a h)^{1/2}
\]
Canopy effects on bed shear stress

- Bed stress measured with high-resolution ADV profiler
- Bed stress ($u_{\ast,bed}$) directly linked to near-bed velocity, but ratio higher for denser canopies

\[
\frac{u_{\ast,bed}}{U_b} \approx 0.038 \left(1 + (ad)^{1/8}\right)
\]
Sediment transport

- Canopies reduce the threshold near-bed velocity required to mobilise sediment, due to the addition of turbulence in the element wakes.
- However, canopy presence greatly reduces the near-bed velocity, so net effect is diminished transport (by up to factor of 3).
CFD modelling of bed shear stresses

- Developed predictive model for bed shear stress in canopy flows that integrates experimental and numerical data

Conclusions

• Unique field observations of sediment transport over coral reef and seagrass canopies -> supported by lab and CFD studies of the fundamental sediment transport processes

• New models developed to predict the modification of bed shear stresses and near bed flows in the presence of benthic ecosystems

• A new framework for improving sediment transport predictions (including deposition and resuspension in sensitive benthic ecosystems

Continuation of this work:

Implications for management

Given ambient wave and current conditions (hydrodynamic models), properties/concentrations of dredged sediments (other projects in this theme) and basic ecosystem properties (habitat mapping), we can identify:

• Ecosystems that are at risk of extreme rates of particle deposition

• The wave/current conditions required for removal of this deposited sediment (what is likely timescale of effects of dredged sediment?)

Overall, this should assist in providing a more complete definition of potential ‘Zones of Impact’ of dredging activities.
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Project publications (to date...)

**Journal papers**


**Phd Theses**

Andrew Pomeroy, Mike Cuttler, Vahid Etminan
Miscellaneous figures

(Chen et al., Adv. Water Resour., 2012)
Sediment transport over seagrass meadows

• ~3 week experiment over *Posidonia* meadows
• Similar setup to Ningaloo Reef (ADVs, OBS, suction sampling, LISST)
• Relocated over dense meadow, sparse, and bare bed