

Hydraulics and Sediment Transport in a Creek — Mangrove Swamp System

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SUMMARY A finite-difference implicit numerical model is used to calculate the movement of water and sediments in a tidal creek surrounded by thickly vegetated mangrove swamps in Missionary Bay, North Queensland. A net downstream water current through the swamps exists which enhances the export of nutrients from mangrove swamps. Mangroves are responsible for maintaining a deep self-scouring drainage channel.

1 INTRODUCTION

Hinchinbrook Island is located in North Queensland, approximately 18°25' South, 146°20' East, 100 km North of Townsville. As will be shown in slides, large areas of its western and northern shores are densely vegetated mangrove swamps in a relatively pristine condition. In 1979, a study was undertaken of the hydrodynamics of Coral Creek and its surrounding mangrove swamps, to link with other investigations on sediment and nutrient budgets, as well as to help understand further the role of mangroves in coastal processes.

2 TOPOGRAPHY

Missionary Bay is a shallow water body with extensive mud banks uncovered at low tides and separating shallow (1-2 m deep) channels at the mouth of the creeks. However, the creeks in the mangrove swamps are much deeper (4-6 m, with scour holes 20 m deep), with steep banks and relatively flat bottoms. The creeks themselves are clear of vegetation. Mangrove trees grow on both sides up to the banks of the creek. In the swamps, the vegetation density is high, but the surface of the substrate is smooth in the sense that it is relatively free of small channels and depressions, and has a gentle slope towards the open water of the creeks (Fig. 1, and slides). Coral Creek receives no freshwater save for direct rainfall over the creek and surrounding swamps.

3 MATHEMATICAL MODEL

The choice of a computer model required a novel approach. An implicit scheme was required to avoid the constraint of a too small time step of the order of seconds if an explicit scheme was used, compared to 15 min as used in this study. Because the swamps are completely drained of surface water at low tide, the boundaries are moving and a fully implicit model based on the full equations of motion and applied to both the creek and the swamps would have been too big for our PDP-11 computer with a 28K memory.

Since water currents through mangroves are small (< 10 cm (sec)), inertia effects can be neglected in the swamps for which a two-dimensional model was necessary because both lateral and longitudinal flow was considerable. A one-dimensional model allowing for branching was adequate for the creek where inertia effects could not be neglected.

To accommodate these constraints, a model was developed that links a one-dimensional finite-difference implicit model of open channel flow in Coral Creek, based on the full equations of motion, with a two-dimensional finite-difference implicit model of flow through a vegetated flood plain, based on the equations of motion where inertia terms are neglected. These models were linked by setting water levels in the mangroves and in the creek to be the same at their boundaries,

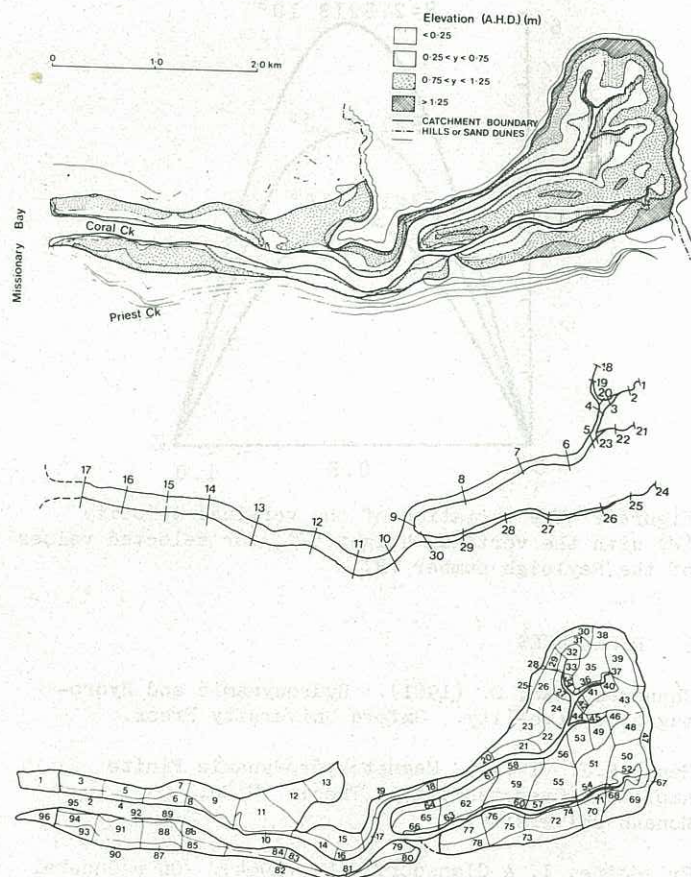


Figure 1. Topography of mangrove swamps around Coral Creek (Top); Division of Creek in sections (Middle); Division of swamps into cells (Bottom)

and by assuring the conservation of water volume in the system. A brief outline of these models is given below. More details can be found in Wolanski *et al.* (1980).

3.1 The One-Dimensional Model

The foundations of the model are the equations for unsteady flow in open channels,

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q \quad (1)$$

$$\frac{\partial Q}{\partial t} + \frac{\partial (Q^2/A)}{\partial x} + gA \frac{\partial (y+z)}{\partial x} + gAS_f + \Delta = 0 \quad (2)$$

where x is the distance along the river axis oriented downstream, t the time, Q the discharge, y the depth, A the cross-sectional area of the stream, g the acceleration due to gravity, z the elevation of the bottom of the stream cross-section, q the lateral exchange rate between the stream and the mangrove swamps or another branching channel. The frictional slope, S_f , was computed by Manning formula as a function of Q , of A , of the wetted perimeter and of the Manning roughness coefficient in the creek. The term Δ in eq. (2) was found necessary for numerical stability purposes and characterizes the momentum transfer due to branching and lateral exchange of water, q , which is dependent on whether the water level is rising or falling (Dronkers, 1964, p. 194).

The downstream boundary condition is the observed tide curve at the river mouth. The upstream boundary condition is a zero discharge at the upstream end of the channel (i.e. at sections 1, 18, 21 and 24, Fig. 1). Each of the terms in eqs. (1) and (2) was discretized around a lattice of grid points in the x - t plane according to Preissman (1960) implicit scheme. For n sections ($n = 30$ here), a system of $2n$ non-linear equations in $2n$ unknowns (y and Q at the new time at every section) was obtained and was solved by a Newton-Taylor iterative scheme (Amein and Chu, 1975).

3.2 The Two-Dimensional Model

Groundwater flow was neglected because salinity of groundwater, even very close to the surface, was found to be several parts per thousand larger than creek water, suggesting that water exchange through the sediments is 'small'.

The mangrove swamp was divided into a number of cells selected to fit the contour of the terrain (Fig. 1) and intersecting the creek at the location of the cross-sections used in the one-dimensional model. The movement of water between the cells was then determined from the conservation equations (Vicens *et al.*, 1975, Zanobetti *et al.*, 1975),

$$\frac{\partial V_i}{\partial t} = \sum_j Q_{ij} - q \, dx \quad (3)$$

$$Q_{ij} = A_{ij} R_{ij}^{2/3} S_{f,ij}^{1/2} / n_{ij} \quad (4)$$

where V_i is the volume of water in cell i , Q_{ij} the flow rate from cell i to cell j , q the lateral exchange rate of cell i with the stream along their common boundary of length dx (the same q as used in eq. (1)), A_{ij} and R_{ij} are the area and the hydraulic radius of the cross-section between cell i and cell j , $S_{f,ij}$ the free surface slope and n_{ij} the Manning coefficient.

Eqs. (3) and (4) were written in implicit finite-difference form for every cell not adjacent to the stream. For a cell adjacent to the stream, eq. (3) was temporarily bypassed and the water level was set equal to the one in the creek. A Newton-Taylor iterative scheme was used to solve the resulting system of equations. Eq. (3) was then solved for the cells adjacent to the creek.

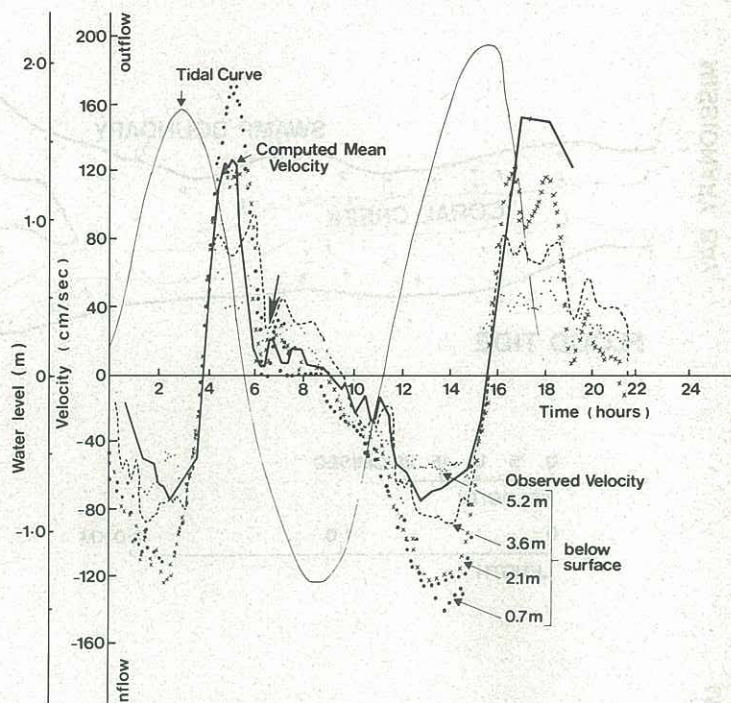


Figure 2. Tide curve and observed and computed water velocities during spring tides, at the mouth

4. VERIFICATION OF THE MODEL

As detailed in Wolanski *et al.* (1980), the value of the Manning roughness coefficient in the mangrove swamps was taken to be function of vegetation density following Petryk and Bosmajan (1975) technique.

Currents in the creek, at the mouth as well as at sections well away from the mouth, were reproduced satisfactorily by the model. Even for extreme forcing conditions of spring tides (Fig. 2), when vertical gradients of longitudinal velocity were considerable, the model was able to reproduce the large differences between mean velocities at flood and ebb tides, as well as the timing for the second rise in velocity at falling tide (see arrow in Fig. 2).

Because of low velocities often less than the threshold value for most current meters, and because the density of vegetation precluded the use of current meters with fins, currents in the swamps were measured by following floating polystyrene beads and, in clearings only, by self-recording current meters. It was found, and confirmed by the model, that at rising tides velocities were always low, usually less than 3 cm/sec, and directed roughly perpendicular to the banks of Coral Creek. At falling tides, however, velocities were characteristically twice as high and the flowpath was oriented downstream intersecting the banks of Coral Creek at an angle between 10 and 30 degrees.

The computed peak velocity field throughout the mangrove swamp is shown in Fig. 3. The asymmetry between ebb and flood currents is apparent, as well as the net longitudinal flow occurring during ebb tides.

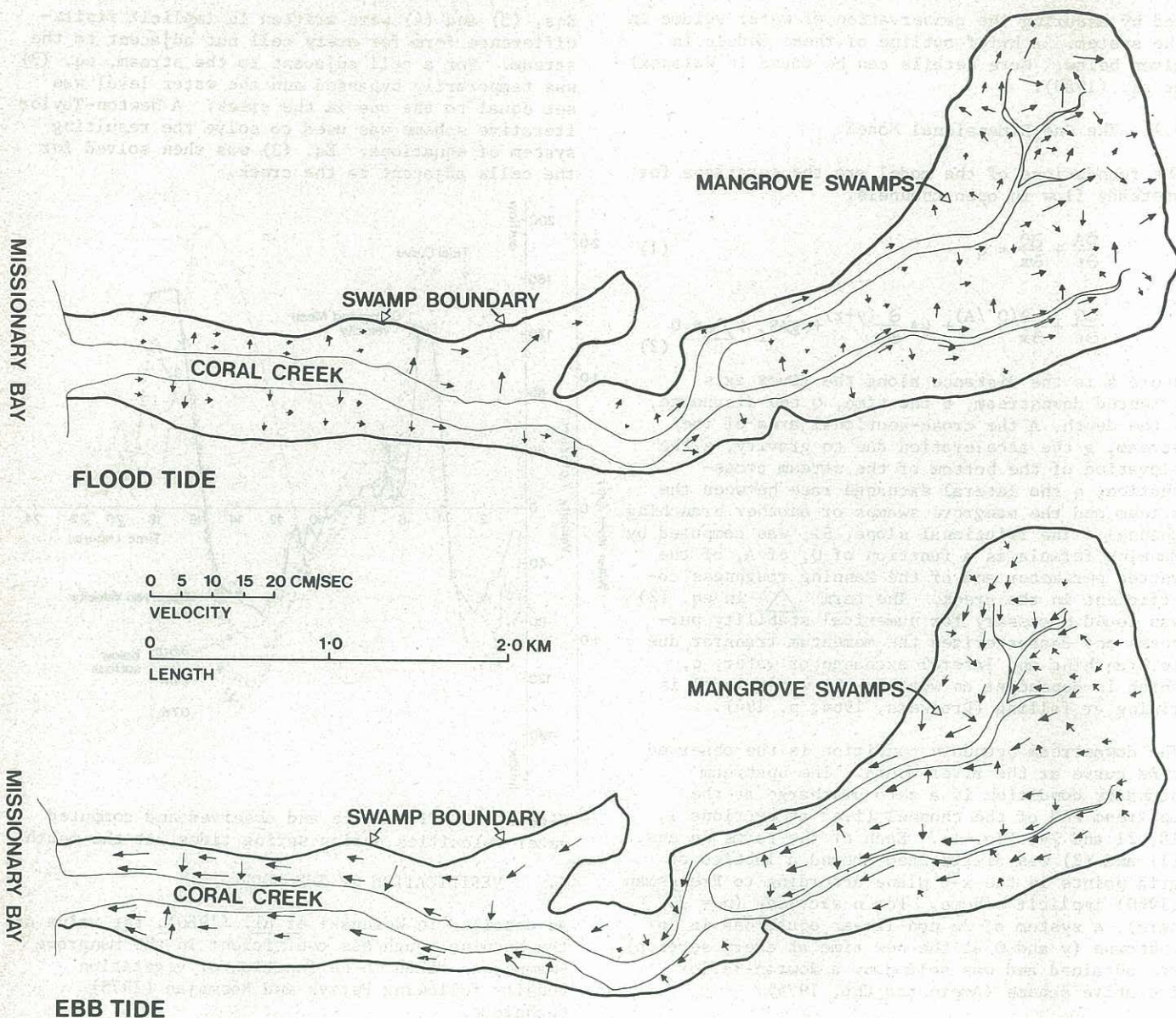


Figure 3. Computed peak velocity field in mangrove swamps

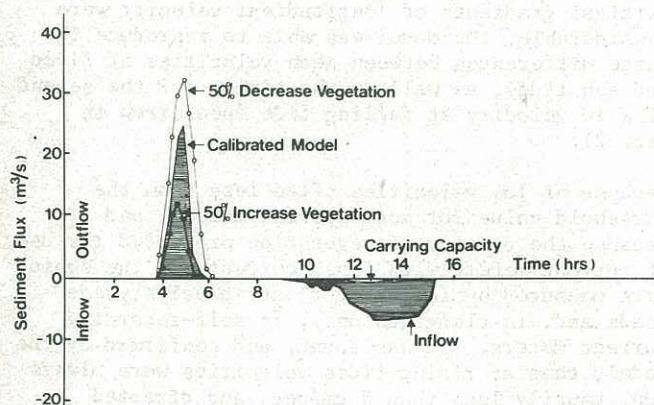


Figure 4. Time variation of sediment flux at the mouth

5 TRANSPORT OF PARTICULATES

The asymmetry of flood and ebb currents in the mangrove swamps is important in the transport of plant litter (e.g. fallen tree leaves) as visual observations revealed. At rising tides, fallen

tree leaves were trapped on the water surface by a surface film that inhibited their transport further inside the swamp. At falling tides however, the currents were strong enough to break this film and carry all leaves to the creek. The resulting net export of plant litter makes a significant contribution to the observed net export of nutrients from Coral Creek (Boto, 1979).

High sediment concentrations are common in surrounding coastal waters. Certainly, the latter have resulted in the extensive siltation of Missionary Bay which is well protected from ocean waves. Yet, Coral Creek is several meters deeper and shows no sign of siltation.

To simulate theoretically this phenomenon, the one-dimensional hydrodynamic model was linked with a sediment transport model based on the sediment conservation equation,

$$\frac{\partial Q_s}{\partial x} + B \frac{\partial z}{\partial t} = 0 \quad (5)$$

where B is the river width, Q_s the total bed load and suspended load volumetric sediment discharge excluding wash load. Q_s was calculated by the Engelund-Hansen formula.

For these conditions, the model revealed that the sediment carrying capacity during flood tides was only a fraction of the incoming suspended sediment load, so that the sediment would settle and the bottom rise (Fig. 4). Most of this material would however be flushed out at the next ebb tide.

Fig. 4 also shows the theoretical variation with time of the sediment flux at the mouth of Coral Creek for the model as calibrated, as well as for hypothetical 50% increase and decrease in vegetation density in the swamps. Clearly, an increase (decrease) in vegetation density would result in silting (scouring) of Coral Creek. Mangroves thus appear to be responsible for maintaining a drainage channel whose geometry (size and meanders) is related to vegetation density.

The presence of such a permanently deep body of water is probably important in the ecology of otherwise shallow coastal waters.

6 DISCUSSION

Coral Creek is a 6 km long tidal creek draining extensive and thickly vegetated tropical mangrove swamps in Missionary Bay, Hinchinbrook Island, North Queensland. Sediment load in coastal waters is large, especially in windy conditions or in the wet season, and has resulted in the extensive siltation of the surrounding sheltered coastline. Yet, the creek is several meters deep and shows no sign of siltation. A mathematical model was used to simulate the hydrodynamics of the system. A net downstream oriented longitudinal current was found in the mangroves and is responsible for the rapid export of plant detritus from the mangrove swamps. By further adding a sediment transport model, it was shown that the creek is self-scouring only because of the presence of surrounding mangrove swamps and that, indeed, mangrove vegetation density determines the physical characteristics of the creek.

7 REFERENCES

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