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Three-dimensional model of atoll hydrodynamics

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Abstract The objectives of this paper were three-fold: (a) Develop a three-dimensional method of modelling hydrodynamics in and around atolls. (b) Establish physical processes of benthic shear velocity and shear stress as significant for habitat suitability of coral reefs. (c) Enrich morphological modelling detail in case of Rongelap atoll, for example. The last objective is still a work-in progress, but the present paper has provided a good review of atoll modelling methods and established our benthic shear velocity as a habitat suitability indicator, measured by a new tool: the “under water weather balloon”, which can be used by resource assessment surveyors to quantify the hydrodynamic climate at dive sites.

Sound modelling methodology is a powerful tool that can answer many questions, such as what drives larval settlement in and around an isolated atoll and what would be the likely trajectories of sand, larvae, and anthropogenic pollutants. Hydrodynamic modelling may be useful to classify regions of an atoll’s sub-units on the basis of bathymetry and hydrodynamics to establish to direction and magnitude of bottom shear velocity, and to specifically empower resource managers to estimate the fate of effluent from aquaculture cages, for example.

Keywords atoll, habitat suitability, hydrodynamics

Introduction

Why are hydrodynamics important for coral atolls? The life history of most coral reef organisms involve a sedentary and a pelagic phase. The pelagic phase is important to dispersal of animals on small, regional and global scales. It is widely recognized that ocean currents transport pelagic larvae from their native populations to new settlement reefs. While currents between atolls facilitate the exchange of propagules between atolls, it is likely that a large proportion of recruitment is derived from native populations (Cowen, et al. 2000, Jones, et al. 1999, Swearer, et al. 2002). Shear stress at the substrate-water interface differentially influences the ability of inorganic and organic matter to settle (Peterson 1999b), and may be a substantial factor in the patchy precedence of events in the reef-building process.

What is an atoll? The word originated from “atolu” used in the Maldives. Our working definition is an isolated ring of shoals, enclosing a central lagoon, surrounded by deep ocean. Atoll morphology is believed to be the remnant of subsiding volcanic peaks, where coral reefs sustain accretion of substrate just below rising sea-level while an exposed peak may persist for some time, surrounded by expanding lagoon (Darwin 1842). Rising sea level or subsiding basement, with respect to isolated volcanic cones, appears to have formed many atolls.

Darwin’s theory was challenged in the 20th century by “glacial control theory”, evidenced by the stand of sea level 90 meters below present sea level during the last ice age. This partially explains why coral deposits are heightened on atoll rims, effected by relatively sudden sea level rise from melting of the glaciers (Daly 1915). The depths to the lagoon floors of most atolls are less than 70 m below present sea-level (Vecsei 2003), supporting the view that short term fluctuating sea levels have considerable influence on atoll morphology. Within the rim, atoll lagoon bathymetry is generally relatively flat, except where punctuated by near-surface pinnacles (Purdy, Winterer 2001). So we should model lagoons as relatively flat bottomed, between two alternative recent sea levels (warm level above and ice age level below). Atoll reef structures have recently been drilled in the Indian Ocean (Braithwaite, et al. 2000) to suggest other modifications to the Darwinian theory are required to suit the geological and hydrodynamic history of the equatorial Indian Ocean. Indeed, the Darwinian model of atoll morphology was founded in the Pacific. The hydrodynamic model we have developed is suitable for north and south Pacific locations in trade-winds with steep walled reefs which reflect surf. Research at Bikini found the morphology of grooves in the seaward face of the reef coupled with surge channels in the reef flat are perfectly tuned to dissipate the prevailing wave periods (Munk, Sargent 1948). Because we are interested in the transport and settlement of larvae, nutrients, and sediment, the present study concerns net flow through passes and over reef flats, rather than the oscillatory dynamics within the narrow fringing surf line at the windward face of an atoll. So we need a model to have a water level just inside the surf zone raised above the general sea level, so that water always

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flows downhill over the reef flat into the lagoon (Munk, Sargent 1948). Hydrographic observations were made from American military ships to estimate the probable drift of radioactive material from Bikini A-bomb tests (Barnes, et al. 1948). Field observations of circulation, exchange through passes, and flow over reef flats at Bikini and Rongelap atolls were confirmed with kinematically-similar laboratory models (von Arx 1948), finding that most of the motion of the lagoons is wind-driven. Before the advent of mainframe digital computers, field hydrodynamics and sampling studies were conducted at atomic test atolls (Noshkin, et al. 1974). Synoptic modelling of hydrodynamics through archipelagos have been used for tracking radioactive contaminants on a regional scale (Fujio, et al. 1992, Hazell, England 2003), but do not explain remobilisation from the steep slopes of the atolls and from lagoon sediment (Nakano, Povinec 2003). Computer modelling water exchange rates from French nuclear test lagoons was initially based on zero dimensional similitude (Deleersnijder, Tartinville 1997), and more recently three dimensional modelling using eddy viscosity and diffusivity (Mellor, Yamada 1982). These efforts were improved with a quasi-equilibrium stability model (Deleersnijder, Luyten 1994, Galperin, et al. 1988) in Moororoa, finding wind stress the dominant forcing (Deleersnijder, et al. 1996). Water exchange between Majuro Lagoon and the ocean was studied with a 3D Fourier transform of wave forcing in a finite volume grid was applied for Lagrangian particle transport diagnosis, finding water exchange rates were dominated by wave breaking on the reef flats (Kraines, et al. 2001, Kraines, et al. 1999). Recent detailed modelling of Moororoa Lagoon has resolve interactions between lagoon bathymetry and hydrodynamics, controlled by a balance between the bottom friction and wind stress (Burchard 1998, Mathieu, et al. 2002).

The Task Committee on Turbulence Models in Hydraulic Computations (ASCE 1989), reviewed the Reynolds-averaged Navier-Stokes equations resolved in three dimensional Cartesian space (x, y, z) as well as a forth state variable for pressure, p. This is a system of four equations, but alas there are more unknown turbulent velocity correlations. The concept of isotropic turbulent kinetic energy and dissipation (k-epsilon) provides two state variables to represent the total energy of the three turbulent deviations of velocity, and dissipation by applying the eddy-viscosity hypothesis (Boussinesq 1877) to assume turbulent stresses are similar to viscous stresses (proportional with the mean velocity gradient). Recent review publications find that the k-epsilon model is still among the best general purpose environmental turbulence models (Burcharda, Petersen 1999, Foti, Scandura 2004), while the competing closure model of Mellor–Yamada depends on a wall-proximity function that must be adjusted to suit the flow. (Warner, et al. 2005). The k-epsilon model has also proven suitable for calculating bottom shear stress effects of random waves plus current (Holmedal, et al. 2003). There are others advantages of the k-epsilon model of turbulent closure, especially when applied in a finite element domain with a Galerkin numerical method to solve combined propagation and diffusion (Umgiesser, et al. In-Press, Wilson, et al. 2002). The present authors have elected to employ the k-epsilon available in the finite element simulation package FIDAP (Engelman 1982, FDI 1993) developed especially to represent complex 3D geometries. Since "there is always going to be a better hydrodynamic model" (Bilgili, et al. 2003), we now leave arguments about the relative merits of alternative models, and explain the specific intention of the authors in understanding currents around atolls and associated characteristics of substrate condition.

Our discussion now moves to finding the patterns of shear stress acting tangentially to substrate surfaces: oceanic walls; lagoon bottoms; passes; and reef flats. The correlation between bulk water velocity and bottom shear stress may be expressed in terms of "shear velocity", U* defined as the square root of bottom shear stress divided by density of seawater (1024 kg/m³). The ratio of overlaying-speed to shear-velocity $U/U^* = 5.64 \times \log_{10} (12 \times R/k_s)$ (Peterson 1999a). R/k_s is the ratio of depth to roughness typically about 150, but may be dramatically less in branching coral.

Measurement of substrate quality was derived from the "Shield's Diagram" (Shields 1936) extended to lighter materials (Miller, et al. 1977) and readapted to compare organic and inorganic marine particles in Figure 1 (Peterson 1999b). It has been established that shear stress is critical in settlement of coral larvae (Koehl, Hadfield in-press), and attention to shear stress is generic in disciplines of Engineering.

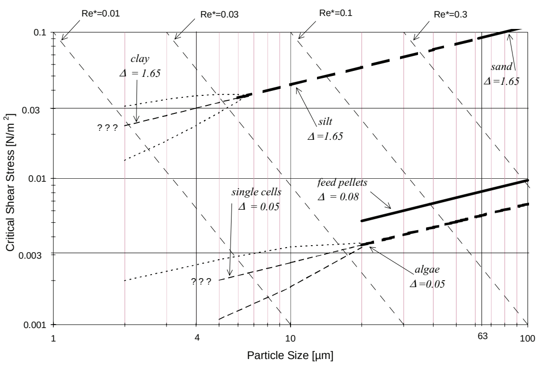

Fig. 1. Measure of substrate quality under tropical seawater. The relationship between hydrodynamics (expressed as benthic shear stress) and re-suspension of feed and plankton (as organic matter of various sizes), and also soil and sediment (classified as mineral particle sizes "sand", "silt", and "clay"). Various morphologies of coral colonies could be plotted on this sort of chart, albeit larger sizes & stresses.

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Methods

We have established the following steps to methodologically model atolls:

1) Establish morphology (bathymetry)
2) Define network of nodes (meshing)
3) Boundary Conditions (wind & tides)
4) Estimate initial conditions in the domain
   $k = {}^{3}/_{2} \cdot (\text{intensity} \cdot V)^2$ & $\varepsilon = 10 \cdot k^{3/2}$
5) Solve the flow-field (velocity, stress)
   search for convergence
6) Map zones of substrate quality (=> GIS)
7) Simulate trajectories (i.e larval transport)

Our model includes a layered dissection of hydrodynamic flow over substrates, illustrated in Figure 2, where the free surface is moving at bulk velocity u_∞, while the bottom is characterized by roughness k_s and experiences reaction shear stress τ, which is intuitively diagrammed by a black trapezoid distorted by the gradient of flow.

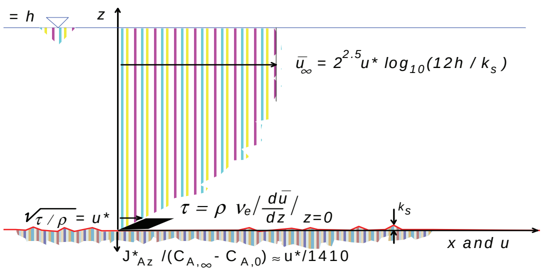

Fig. 2. One-dimensional view of flow over bottom substrates (from Peterson 1999)

Our model is partially driven by wind stress acting on the free surface, and by specification of regional ocean currents, acting on the outer boundaries of the computational domain. A two-dimensional slice through our model is illustrated in Figure 3, where a fixed number of computational layers of flow have been wrapped over the bathymetry. Our model is a "finite element" discretization of the domain, whereby the components of velocity, pressure and turbulence are computed at nodes located at the corner of each elemental brick. Finite elements appear as tetrahedrons (four corners) in two-dimensional projection. Special elements "pave" the layer of water in contact with the bottom, where there is a no-slip condition at the sediment/water interface, with a logarithmic representation of the fluid boundary layer formulated for turbulent shear of the specified roughness.

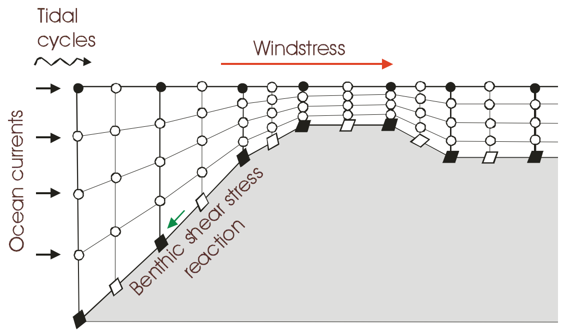

Fig. 3. Two-dimensional slice through finite elements adapted to atoll forms

The simulation tool we have used in the present research is FIDAP (FDI 1993), where the interested reader is directed for a detailed treatment of exactly how the flow-field is solved for a given set of boundary conditions. The key point of the present paper is that over 90% of the modeller's effort is concerned with defining an appropriately adapted mesh, concentrating nodes in bottlenecks where gradients of momentum are intense, and casting a wide net in quiescent areas. The paving algorithm employed by FIDAP was developed by Sandia National Laboratories to simulate the dynamics of nuclear explosions (rather than to continue bombing real atolls). We rotate our 2D slice model around a vertical cental axis, with the lagoon paved with the Sandia Algorithm, and with passes set equal to lagoon depth. A single southeast-pass atoll is outlined in plan figure 4, viewed isometrically from northeast in figure 7 is a simple 3D model, illustrating the external surfaces of finite elements with resulting simulation surface flow vector arrows due to east wind. Patterns of surface speed and bottom stress for the pseudo-atoll are plotted in Figures 5 and 6, with inflow into the southeast pass and out over the opposite reef flat.

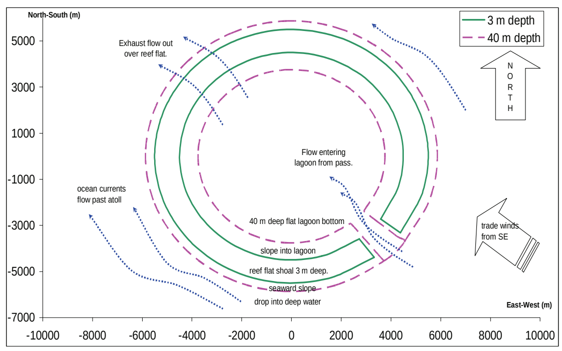

Fig. 4. Plan of pseudo atoll with single pass facing into southeast (same as tradewinds)

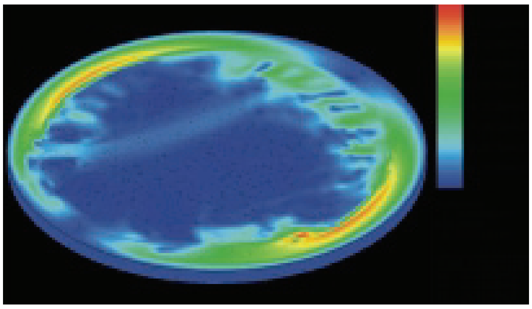

Fig. 5. View from northeast. Surface speed plotted on a colour scale (appear shades of grey).

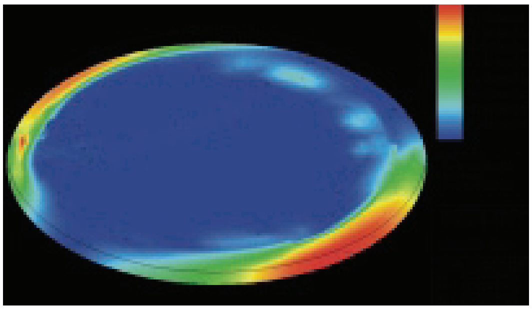

Fig. 6. Regions of bottom stress viewed from NE.

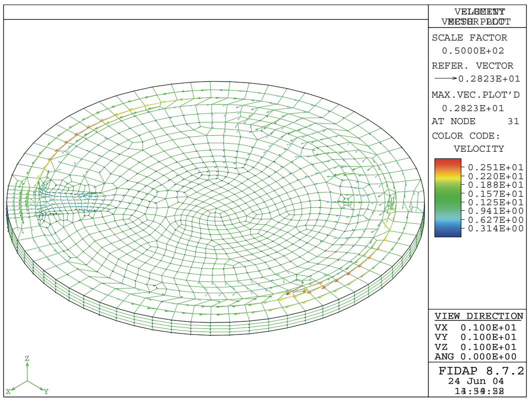

Fig. 7. Three-dimensional mesh overlayed with surface velocity vectors. Viewed from northeast.

Our computer predictions of atoll hydrodynamics must be independently checked with field observations before the results are applied to ecological studies and resource management. So we used a novel methodology we call the "underwater weather balloon" (Figure 8a). The "underwater weather balloon" is a balloon filled with fresh water (for subtle buoyancy) that is attached to four meters of tether-line from a trident-head spear impaled into substrate. There is a spirit level and a length of fibreglass tape at the top of the spear, which measures the displacement of the tether-line and balloon under the influence of the current. The compass bearing of flow direction is also noted, as well as depth gauge reading. The buoyancy, form drag, and lift of the balloon and finite differential segments of the tethering line are calculated to convert the measured displacement of the balloon down current to a measurement of current speed. Figure 8b shows the displacement of the balloon exposed various current speeds. The speed of the current at the balloon tends to be proportional to the tangent of the angle of the tether-line.

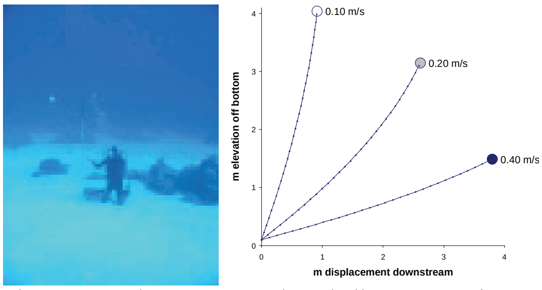

Fig. 8. "underwater weather balloon" reaction to varying current speeds (inflated 100mm).

Results of Fieldwork

Figure 9 presents the percentage coral cover versus benthic shear velocity measured at Rongelap Atoll. 6% of the variability of soft coral cover appeared to be explained by shear velocity.

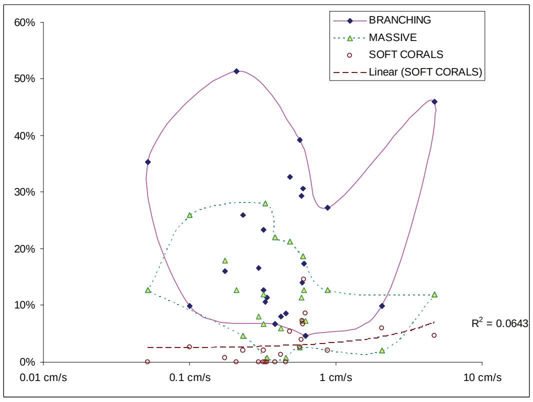

Fig. 9. Percent coral cover found at Rongelap dive sites vs shear velocity.

The strongest relationship was linear regression of percentage cover soft corals increasing with shear velocity, while there was a weaker inverse relationship between shear velocity and percentage cover of massive and encrusting corals.

We have constructed a three dimensional finite element mesh for solution on a main frame "super computer", illustrated in Figure 10. There are a few issues to resolve, as the convolutions of reef morphology which have collapsed a few finite elements, and will require some simplification to obtain a solution to the problem. We found Rongelap Atoll is a very complex structure like a fractal, and so we now believe it more pragmatic to calculate benthic shear velocity directly from hydrographic surveys to expedite conservation planning.

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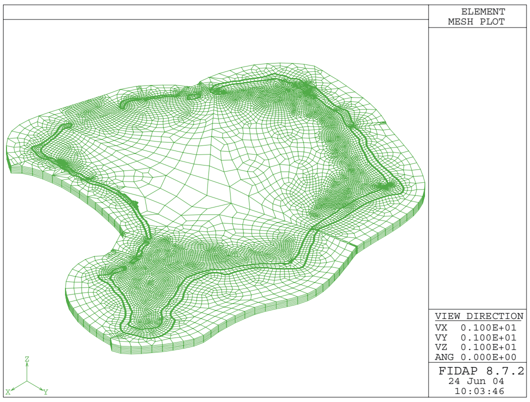

Fig. 10. Finite element mesh developed for Rongelap (isometric view from northeast)

Simulation results were not entirely successful. But we have established the importance of mapping benthic shear stress models of atoll substrates, and in the case of Rongelap Atoll in the Republic of the Marshall Islands we are building a habitat suitability zonation, based on facts of bathymetry and hydrodynamics surveys by von Arx. Published lagoon exchange rates summarised in Table 1 (von Arx 1948).

Table 1: Rongelap lagoon water exchange per tidal cycle (after von Arx 1948)

Segment	Flood	Ebb
Jaboan (S. Pass)	+630,000 m³	-374,000 m³
Enybarbar Pass	+200,000 m³	-100,000 m³
Gogan Pass	+20,000 m³	-20,000 m³
Northeast Pass	+94,000 m³	-60,000 m³
Northern Reefs	+180,000 m³	+140,000 m³
West Pass	-300,000 m³	-300,000 m³
Western Reefs	-40,000 m³	-65,000 m³
Kaeroga Pass	+200,000 m³	-200,000 m³
Enigan Pass	+35,000 m³	-30,000 m³
Pigen Pass	+44,000 m³	-35,000 m³
	=========	=========
Total exchange per tide	1,063,000 m³	-1,054,000 m³
47,000,000 m³ total volume of Rongelap lagoon		

Discussion

Our interest in building this modelling methodology was initially to study larval settlement in the established flow field of Rongelap atoll lagoon, but in the process we developed an interesting methodology. It appears from our literature review that we are the first to publish the application of a finite element grid adapted to an atoll lagoon, and also first to apply the k-epsilon turbulence closure to atoll lagoon hydrodynamics. Although we have not yet solved our model in application to Rongelap atoll, we have proven that our simulations rapidly converge in a simplified round "pseudo-atoll" with a single pass. Such may be directly useful in smaller atolls, such as Taiwan's marine reserve Dong-sha Atoll (Dai 2004).

The present paper has brought attention to the importance of physical factors which effect ecosystem function, and so should not be overlooked in the development of marine management plans for atoll reefs. In particular, we have developed a low cost flow measurement which can be readily employed by biologist surveyors to characterize the hydrodynamic climate at a dive site. Awareness of the flow field through a reef can be mapped along with regions of substrate such as sand, rubble, and coral to develop synoptic indications of the direction of pollutants. Such indicators are particularly important in developing countries, for example the local government of Rongelap Atoll could ensure that undesirable effluents are swept from below intensive aquaculture cages (splashaqua.com) and exhausted into deep water at West Pass, rather than recirculating in the lagoon.

Acknowledgements

Our analysis of Rongelap atoll lagoon hydrodynamics is a work in progress by the authors, so that we can interpret patterns of biodiversity and physical substrate at one of the most pristine reef systems left on earth. We will strive to provide our work as an assistance for a sustainable resettlement of the Rongelapese People.

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