PHILIPPINE ENVIRONMENTAL GOVERNANCE 2 PROJECT (EcoGov 2)

ESTIMATION OF MARICULTURE CARRYING CAPACITY IN DUMALINAO BAY USING HYDRODYNAMIC AND DISPERSAL MODELS

February 10, 2009

This publication was produced for review by the United States Agency for International Development. It was prepared by Development Alternatives, Inc.

The EcoGov 2 Project is an initiative of the Government of the Philippines, implemented in partnership with the Department of Environment and Natural Resources, Department of the Interior and Local Government, local government units and other stakeholders, funded by the United States Agency for International Development and managed by Development Alternatives, Inc. and its subcontractors:

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ESTIMATION OF MARICULTURE CARRYING CAPACITY IN DUMALINAO BAY USING HYDRODYNAMIC AND DISPERSAL MODELS

by: Cesar L Villanoy

February 10, 2009

The author's views expressed in this publication do not necessarily reflect the views of the United States Agency for International Development or the United States Government.

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INTRODUCTION

Mariculture development is fast becoming the most popular intervention to provide additional income for coastal communities in view of the declining capture fisheries production. Increasing demand for fish due to an ever increasing population is also making mariculture a very attractive investment option. Milkfish culture is perhaps the most common species cultured in brackish and marine fish ponds, pens and cages today. However, the high food conversion ratio (FCR) for milkfish culture in the Philippines is contributing to the euthrophication of coastal waters due to the high organic pollutant loading coming from this activity. The inefficient FCR is likely due to poor planning and site selection as well as overcrowding of fish farms. Such conditions have been experienced in some mariculture areas in the Philippines, particularly in Pangasinan. Excessive nutrient input due to feed waste and fish fecal material is the main source of these organic pollutants.

The objective of this study is to provide relevant information about the hydrodynamics and capacity of the waters in Dumalinao Bay to support mariculture activities, focusing on fish pen and cage culture. Dumalinao Bay is a small embayment within Pagadian Bay in the western side of Illana Bay in Mindanao (Figure 1). The depth of the bay is shallow with an average depth of <20m in the interior of the bay

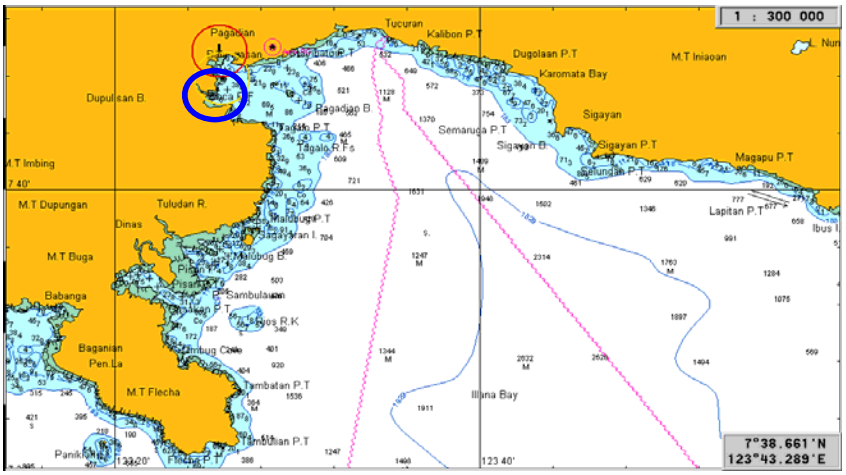

Figure 1. Map of Illana Bay showing location of Dumalinao Bay

(Figure 2). The 18m isobath which crosses the bay mouth lies parallel to the coast and more than half of the bay is less than 18m in depth. The southwest coast of the bay is lined with about 76 hectares of fishponds (Figure 3).

Seaweed farming is the most widespread mariculture activity in the coastal waters of Dumalinao. The Office of the City Agriculturist in Pagadian City reports about 85 hectares of seaweed farms operated by about 100 households in Dumalinao Bay.

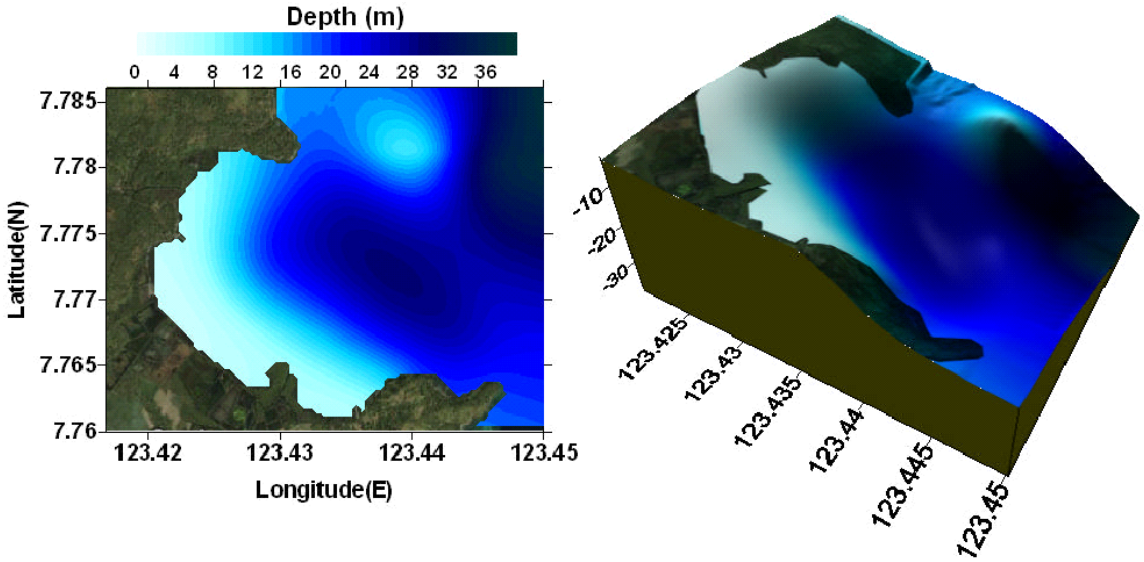

Figure 2. Bathymetry of Dumalinao Bay.

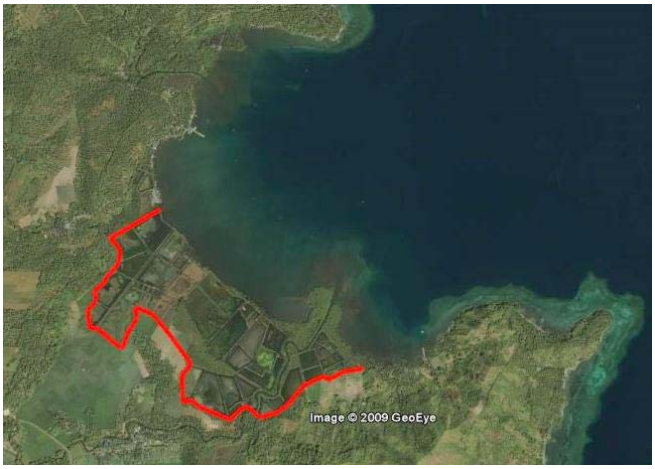

Figure 3. Map showing fishponds in Dumalinao Bay.

Fish cage farming is still in its infancy in Dumalinao, limited only to a few farms, most of which are pilot or experimental farms. Plans are underway to establish a mariculture park within the bay and information emanating from this study will be provided to the local government as inputs in the planning process.

METHODS

The model domain covers the shallow waters of Dumalinao, North Illana Bay, Zamboanga del Sur (Figure 2). Bathymetric data were digitized from electronic maps interpolated to a 100 m x 100 m resolution grid. A 3-dimensional hydrodynamic model was developed using the Delft3D modeling package where tides and wind were used as forcing to investigate different scenarios of current flow as influenced by tides and seasonal shifts in wind speeds and direction. The following scenarios were simulated: tidal forcing only, tidal and southwest wind forcing of 3 ms^{-1}, and tidal with northeast wind forcing of 3 ms^{-1}. Actual winds further offshore may reach average speeds of more than 3ms^{-1} (Figure 4) but a 3ms^{-1} wind speed was used in the simulations to account for possible sheltering effect by surrounding land masses.

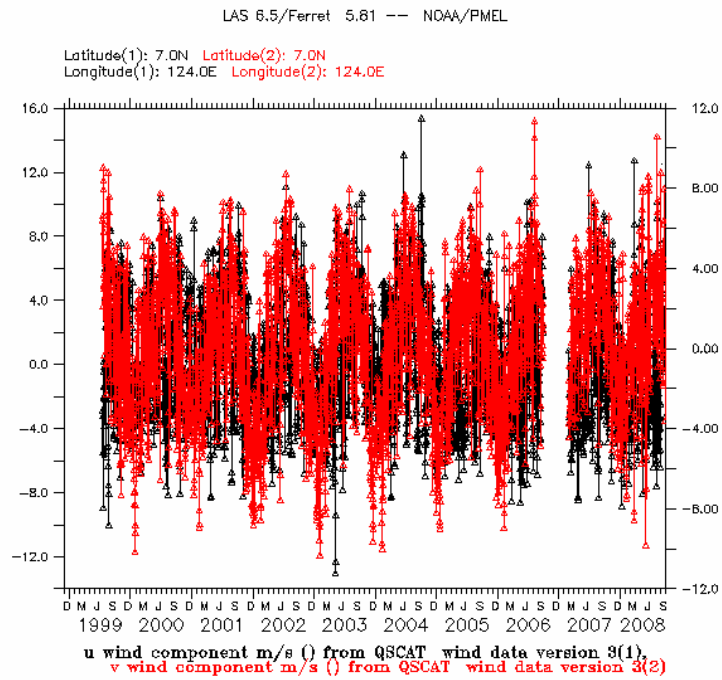

Figure 4. Time series of satellite-derived winds from QuickSCAT at 124°E, 7°N.

Variation of the sea surface elevation prescribed at the eastern open boundary was obtained from a Philippine-wide tide model implemented by Magno and Villanoy (2005) using the Oregon State University Tidal Inversion Software (OTIS). The amplitudes and phases of the 8 tidal constituents used in the model are listed in Table 1.

The velocities generated by the hydrodynamic model were used to simulate the transport of passive particles which form the basis for estimating residence time. Residence times were simulated using both surface and depth averaged velocities to assess the influence of wind speeds and direction in estimating the flushing condition of the site. Passive particles were initially placed at the center of each model grid. The location of each particle over time was then calculated using the equation of Tartinville et al. (1997) modified for 2D model:

$$r(t+\Delta t) = r(t) + \Delta t\{u + (6k_h/\Delta t)^{1/2} d_h\} \qquad (9)$$

where, r is the location of the particle at time t, Δt is increment time, d_h is a randomly generated dimensionless number between -1 and 1, k_h is the eddy diffusivity, and u is the advective velocity provided by hydrodynamic model. These particles can move freely between grid cells and once a particle exits the open boundary, it is completely removed in the calculation and never returns. The time from its release in a grid to its exit through the open boundaries is the residence time estimated for that grid. In a tidally dominated flow, the residence of a particle released close to the open boundaries will vary greatly with the phase of the tide. To compensate for the stochastic estimation of the position and location of the particles, the residence time was based on the average of 25 different simulations with the start time delayed by 1 hour each time the simulation is repeated. The integration time for each simulation is 30 days.

After determining the allowable zones for cage culture based on the residence time, sedimentation footprint and bottom sediment flux was estimated using a Lagrangian particle dispersal model. This is a modification of the model used in the residence time estimation by adding a vertical component to the horizontally moving particles. Particles can also move vertically based on a prescribed vertical sinking rate until it settles to the bottom. This simulates the dispersion of particulate wastes consisting of excess fish feed and fish excreta with periodic release times. The model tracked the passive particles for 15 days until they settled. The distance dispersed (d) is expressed by Gowen et al., 1989 (as cited by Panchang et al., 1997) as:

$$d = \frac{D \bullet C_v}{S} \qquad (1)$$

where: D is water depth , S is sinking velocity and C_v is the horizontal velocity.

In order to determine the different patterns of waste dispersal at different locations within the bay, hypothetical cages were introduced into the model. The locations of these cages are shown in Figure 5. Waste from both feeds and fecal material were allowed to be dispersed by the currents and at the same time sinking to the bottom using the prescribed sinking velocities. The total area where the particles settle is what is known as the sediment footprint of a cage.

The vertical sediment flux is the amount of organic matter deposited at the bottom expressed as carbon concentration in gC $m^{-2}d^{-1}$. Each particle released represents a fixed amount of organic matter and the number of particles deposited in a 5 m × 5 m area over the duration of the model simulation is used to calculate the waste flux. The amount discharged is a fraction of the total amount per feeding estimated for one crop production of 6 months. Milkfish is a daytime feeder and waste discharge was scheduled at 6 am, 9 am, 12 pm and 3 pm daily, similar to the practice observed in fish farm. Fish egestion was set simultaneously with feeding time. The model did not account for resuspension, remineralization and assimilation of nutrients. Moreover, organic decomposition of feces and fecal matter was not considered because the decay rate is beyond the simulation time of 15 days (Doglioli et al., 2004). Effluent discharge is held at a fixed point source thus fish pen size was not also accounted for. This approach was developed by Magdaong (2008).

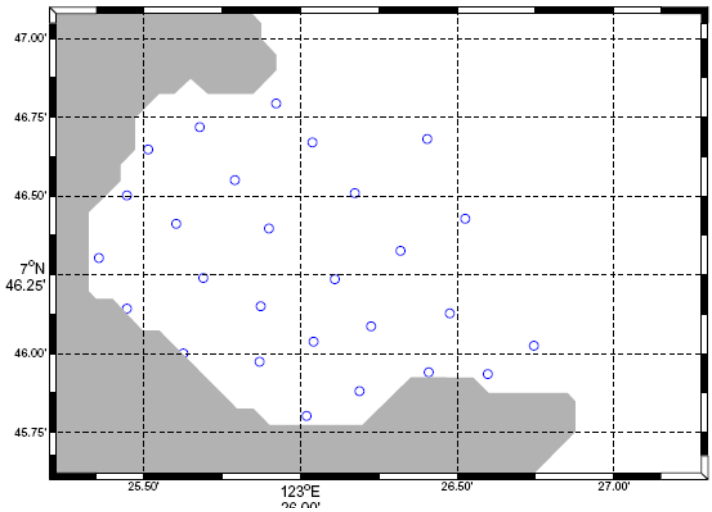

Figure 5. Map showing location of hypothetical fish cages.

The following information was used in the model: fish stock of 50,000 individuals, harvestable size of 500 g, Feed Conversion Ratio (FCR) of 2.5 and culture period of 6 months. Feed wastage is assumed to be 20% and directly falls on the bottom unconsumed. Feed input is estimated to be 62,500 kg while the amount of Carbon is evaluated as 20% of 372.3 g feces per kg of food fed per day. Feed sinking velocities used were: 5% at 6 cm s^{-1}, 20% at 3 cm s^{-1} and 75% at 1.5 cm s^{-1} while for fecal pellets were: 40% at 0.04 cm s^{-1}, 35% at 0.08 cm s^{-1} and 25% at 1.5 cm s^{-1}.

Nutrients such as total ammonia-nitrogen (TAN) and phosphate are released virtually in the model in particulate and dissolved forms. Ammonia bound nitrogen is excreted through the gills and orthophosphate is discharged via urine (Doglioli et al., 2004). Dissolved nutrient (TAN) was released once and tracked for 15 days to assess the fate of pollutants. The concentration was also averaged for 25 simulation times similar to the residence time model. Figure 6 shows the nutrient mass budget for a milkfish culture.

Table 1. Tidal amplitudes and phases applied at the model open boundaries

	M_2	S_2	O_1	K_1	N_2	P_1	K_2	Q_1
Amplitude(m)	0.642	0.374	0.127	0.161	0.104	0.051	0.105	0.03
Phase(°)	-142.6	-63.9	-113.2	-78	-169.7	-78.4	-73.7	-116.8

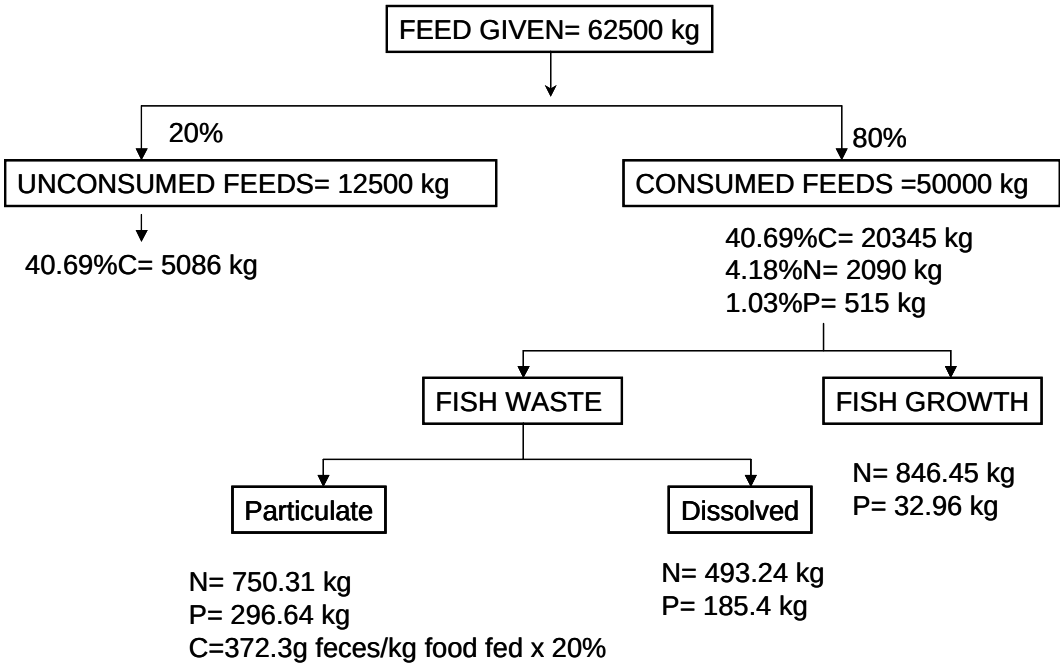

Figure 6. Nutrient mass budget of a fish cage in one culture period (from Magdaong, 2007)

RESULTS

Dumalinao Bay is located at the head of Illana Bay and as a consequence, the tidal current magnitudes are weak. Example snapshots of the velocity field are shown in Figure 7. Most of the strong flow occurs at the bay mouth and beyond, leaving the interior of Dumalinao Bay relatively sheltered by the flow. Thus, currents are relatively weak. Animations of the flow covering 15 days for all simulation cases are included in the attached electronic animation files.

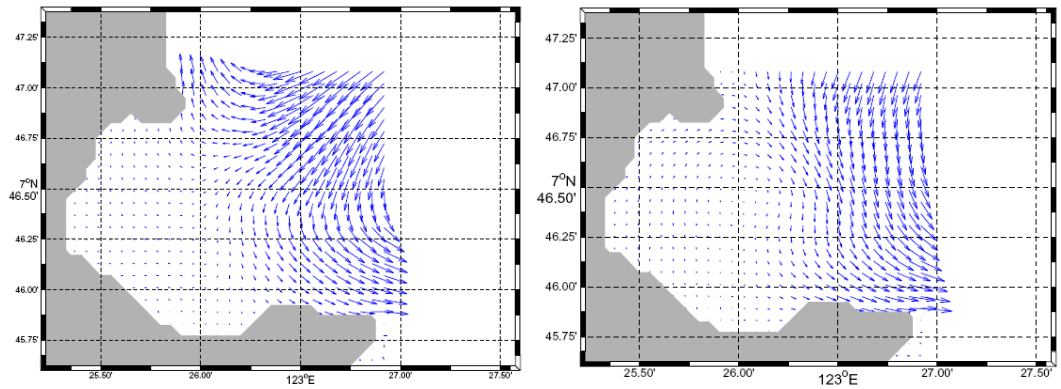

Figure 7. Vector plots for tidal forcing only simulation for hour 354 (left) and 360 (right).

Residence time here is used as a measure of flushing rate. Lower residence times indicate faster flushing with water from outside the bay, hence for mariculture waste, areas with lower residence times are better suited as polluted waters are carried out of the bay. On the other hand, transport of polluted waters outside the bay may mean that other habitats outside the bay may also be impacted by the transport of the pollutants. Hence, the residence time may provide information on potential sites for mariculture zone but should not be taken as the only basis for site selection or for determining the density or stocking rate of the cultured species as other considerations such as presence of neighboring critical habitats or condition of the sediment communities must also be taken into account.

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In addition, the residence time also gives indicative timescales of pollutant flushing. For instance, in shallow embayments such as Dumalinao Bay, the circulation is dominated by the tides. Variability of the tidal flow is at daily and fortnightly (spring-neap) cycles thus areas with residence times of not more than 14 days suggest that the waters from this area will be completely flushed at least once every 14 days. This value appears to be a reasonable upper limit for residence times of mariculture areas.

The calculated residence times of Dumalinao Bay for the three modeled cases are shown in Figure 8. Residence time estimates calculated using surface currents and vertically-averaged currents are also shown. In general, residence times in Dumalinao Bay are short with residence times of less than a few days for most of the bay. The longest residence times (>25 days) are in the interior of Dumalinao Bay during the northeast monsoon when the winds force currents to flow onshore. Conversely, the shortest are during the southwest monsoon when wind directions are reversed.

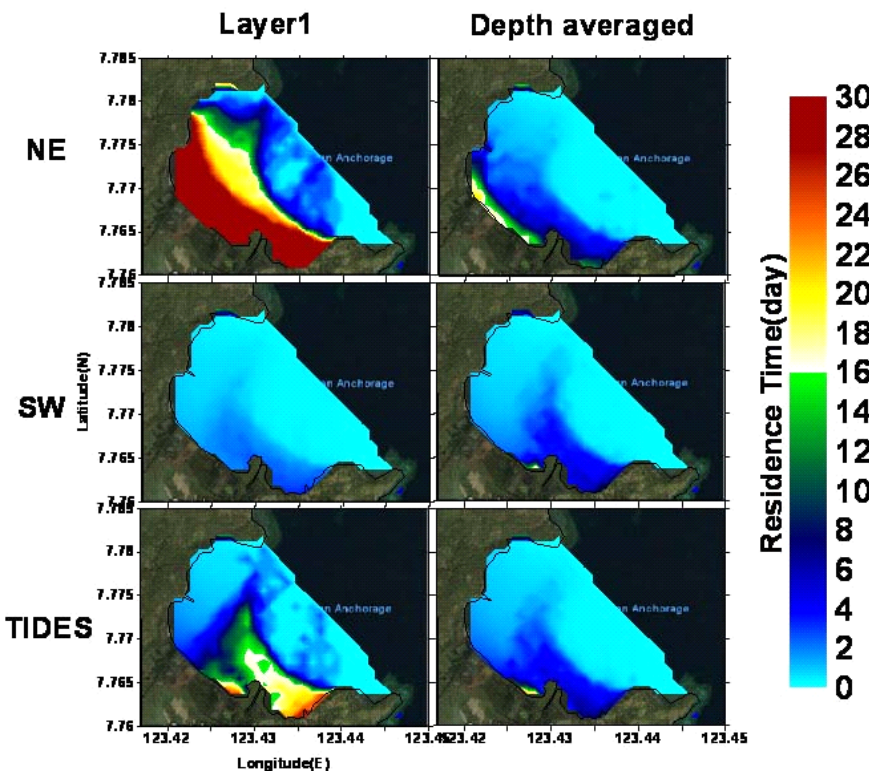

Figure 8. Residence time maps of Dumalinao. Plots on the left are residence times calculated using the top layer of a three layer water column while the plots in the right are residence times computed using vertically-averaged velocities.

In any simulation case, the southern part of Dumalinao Bay always has a relatively higher residence time. The difference in residence time between this area and the rest of the Bay can range from 3 to 24 days. This area appears to be the least flushed among the waters in Dumalinao Bay. Although located near the mouth, the strong flow across the mouth appears to limit exchange of water between this area and the rest of the bay.

If the 14 day residence time upper limit is applied, it seems that the southern coast of Dumalinao Bay may not be well suited for caged or pen culture of fish requiring heavy input of feeds. Although residence times exceed 14 days in the interior of the bay during the northeast monsoon, strong waves in areas exposed to the northeast monsoon may be too rough for cage culture. On the other hand, conditions during the southwest monsoon may be more favorable for mariculture as residence times are low and the bay is sheltered from the monsoon winds by land.

The waste dispersal model was used to simulate the dispersal from each of the hypothetical cages shown in Figure 5. The results of the simulations are shown in Figure 9. Cages with

large sediment footprints are areas where horizontal currents are strong and/or water depths are deep such that particles remain in the water long enough to be carried by currents horizontally away from the source. Clearly, the relationship between depth and sediment footprint is not straight-forward as current variability also plays an important role. For instance, near the coast, depths are fairly uniform but sediment footprint sizes vary with the largest footprints found in the southern end. The very small footprint size in the head of the bay is most likely a function of the shallow depth and weak currents.

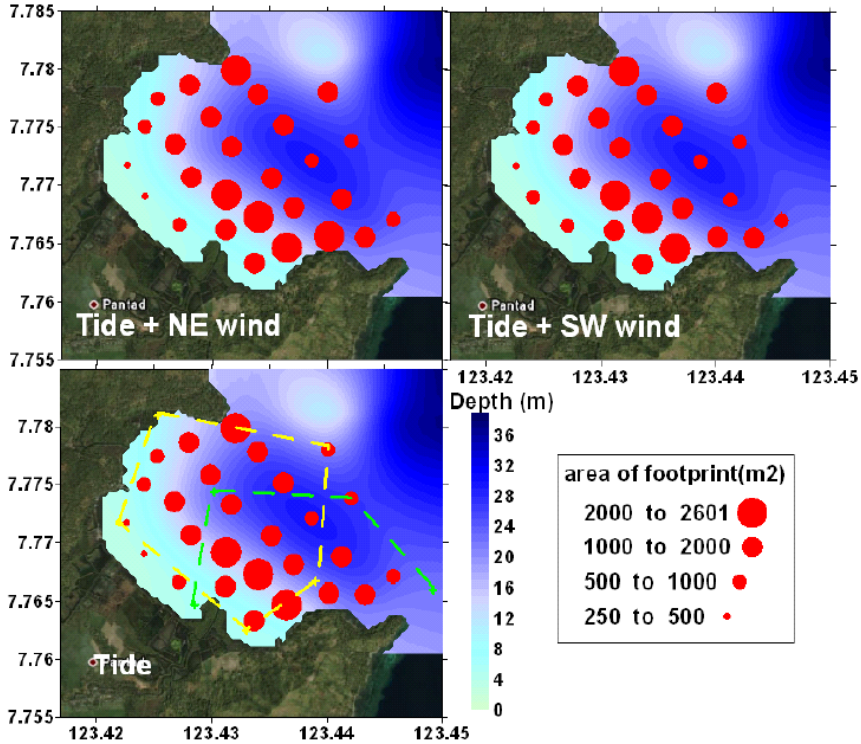

Figure 9. Sediment footprint areas from hypothetical cages overlain with bathymetry.

No such clear relationship is also seen with residence time and footprint size (Figure 10). However, the area identified previously in the southern part of the bay as having a high residence time also has a larger sediment footprint. To prevent serious impacts on the bottom sediments, it should be ideal that the footprints of adjacent cages should not overlap.

Other than the sediment footprint size, it is also important to consider the sediment flux rates. A sediment footprint from a particular cage may be small but if it exceeds a given rate, bottom sediment communities may be unable to cope up with the flux rates. Findlay and Watling (1997) suggests a

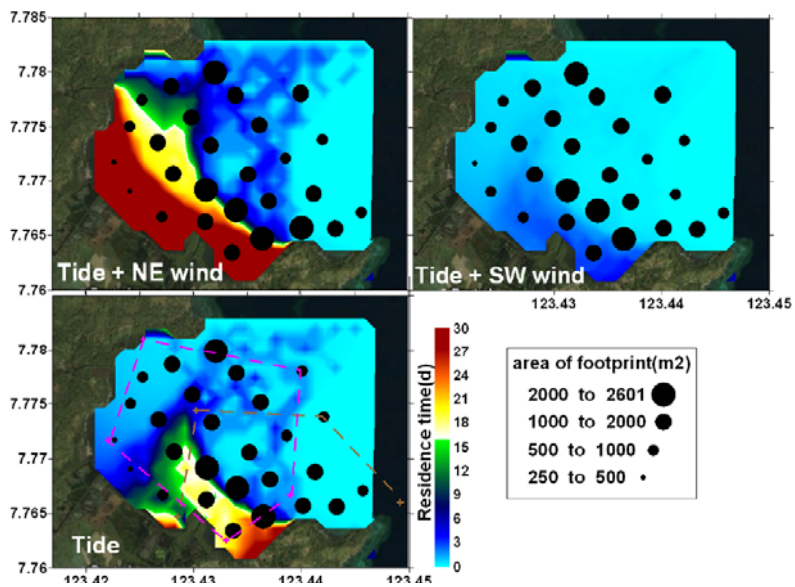

Figure 10. Residence time and footprint for surface ve3locities

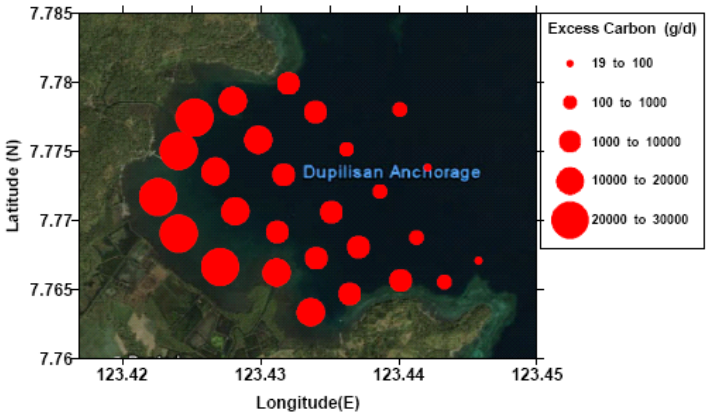

Figure 11. Amount of excess carbon above critical sediment flux

rate of about 5gC m^{-2} day^{-1}. For example, Figure 11 shows the excess carbon above the critical sediment flux for each of the hypothetical cages. The excess is much larger in areas where the sediment footprint is smaller. Reduction of the sediment flux rates may be necessary by adopting measures to optimize feeding and reduce wastage. For instance, a reduction in the Feed Conversion Ratio (FCR) of 2.5 to a more ideal 1.5 results in a reduction of the areas exceeding the critical sediment flux threshold from less than 25% to almost 100% (Figure 12).

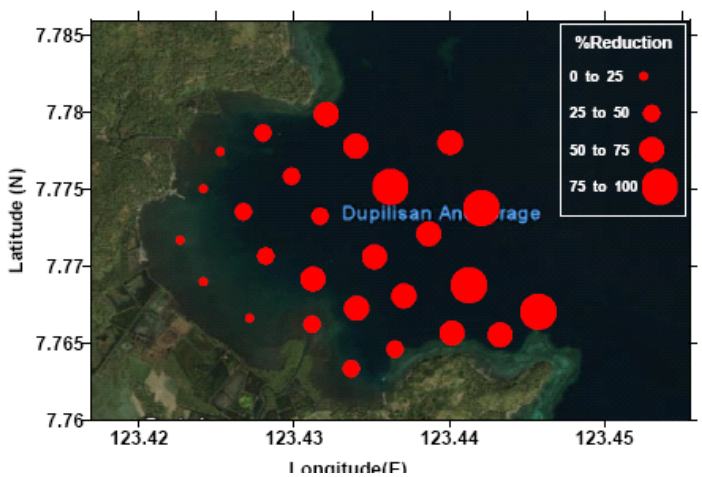

Figure 12. Percent reduction in area exceeding critical sediment flux by reducing FCR from 2.5 to 1.5..

The nutrient mass balance shown in Figure 6 also indicate that about 23% of N and 35% of P in the feeds are also released into the water in dissolved form. It is significantly more difficult to predict the fate of the dissolved component as it is highly non-conservative with highly complex chemical interactions with the other components of the ecosystem. Nevertheless, it is possible to do a qualitative estimate of potential impact areas by just simply simulating passive dispersal patterns. The results presented in Figure 13 to Figure 15 show potential destination of nutrients released from hypothetical cages representing the dissolved component of the waste load from fish farms. The results from all the simulations all clearly show particles accumulating on the southern coast of Dumalinao Bay. The spread along the southern coast and relative concentrations vary with the type of forcing. A purely tidal forcing shows the highest concentrations in the area west of 124.43°E. The SW wind and tide-forced run shows a higher scatter along the southern coast and lower overall concentrations while the run with NW wind forcing shows the highest concentration between 123.43°E and 123.44°E. Other simulations where the cages releasing the dissolved components are located on the western or eastern half of the bay show similar results where the area affected is the southern coast of Dumalinao Bay.

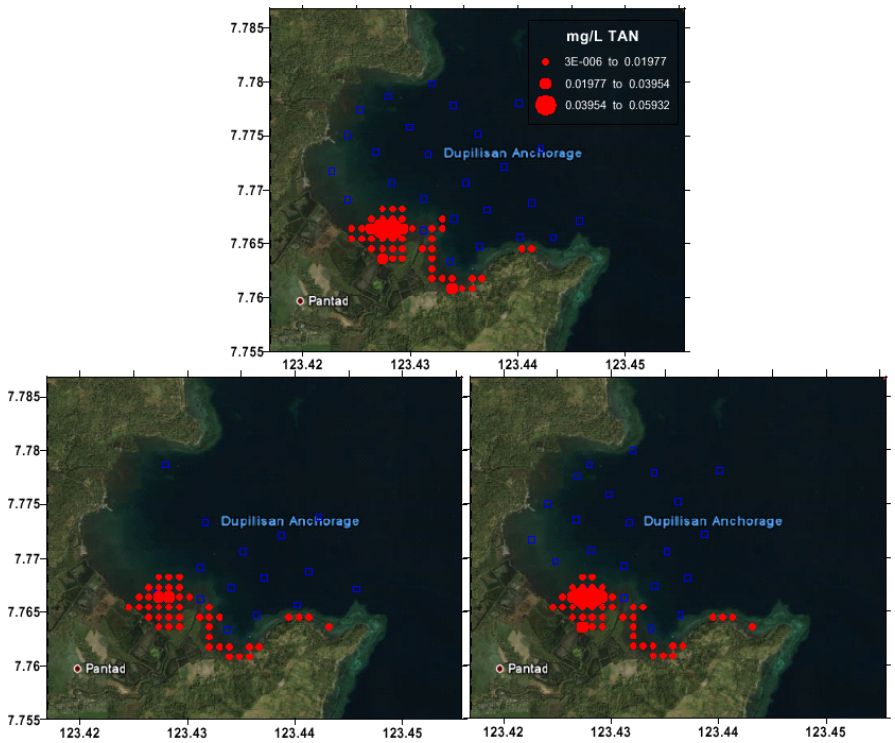

Figure 13. Destination of passive dispersal of lagrangian particles released from hypothetical cages (blue squares). Red circles denote relative concentrations. Model forced by tides only.

Tide with SW wind

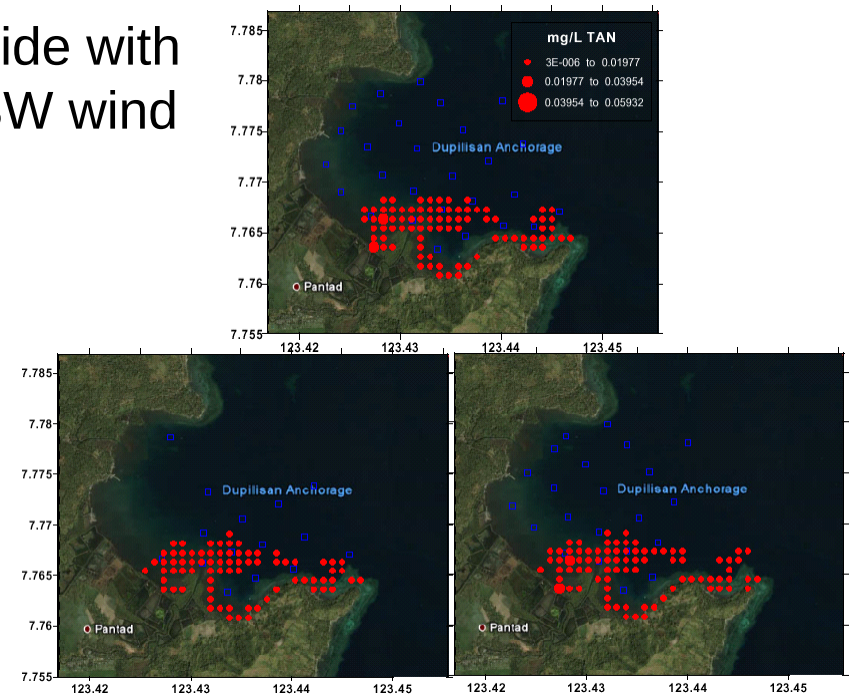

Figure 14. Destination of passive dispersal of lagrangian particles released from hypothetical cages (blue squares). Red circles denote relative concentrations. Model forced by tides and SW winds.

Tide with
NE wind

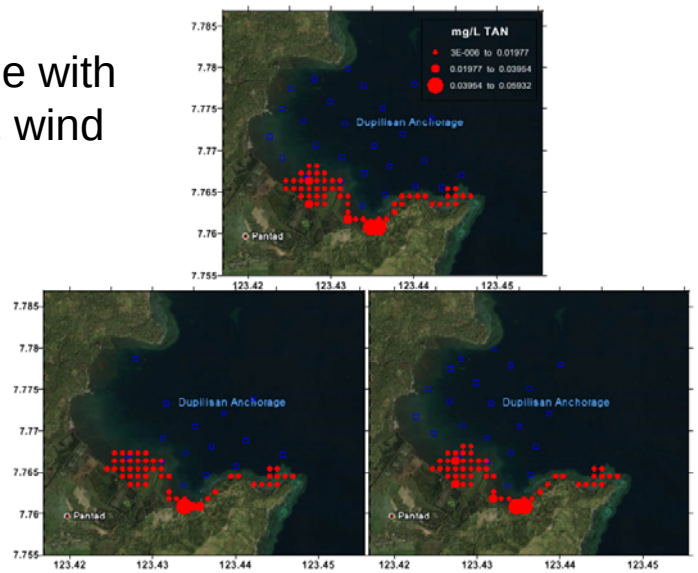

Figure 15. Destination of passive dispersal of lagrangian particles released from hypothetical cages (blue squares). Red circles denote relative concentrations. Model forced by tides and NW winds.

DISCUSSION

The Provincial Fishery Office in Pagadian City proposed two options in delineating mariculture zones in Dumalinao Bay. The first option (blue polygon in Figure 16) with an area of 248 hectares, covers almost the entire bay while the second option (yellow polygon in Figure 16) with an area of 116 hectares covers the southeastern part of the bay. The results of the study indicate that neither of these two options may be suitable. For instance, residence time estimates show that regardless of season, the residence time on the south-eastern part of the bay is relatively higher than the rest. Although a large area adjacent to the coast has a high residence time during the northeast monsoon months, exposure to the monsoon waves may limit the setting up of cages. Nevertheless, it appears that the western part of the bay may be more suitable for fin fish mariculture based on residence times alone. Experiments with the dispersal of the dissolved components of the mari-culture waste also show the southern coast as the most affected. This affected area extends from the central part of the bay, where most of the fishponds are found, east-ward up to the southern tip of the bay mouth. Habitat maps from the IBRA 9 Aquaculture study show most of the reefs found along this part of the bay (Figure 17).

Figure 16. Proposed mariculture zones. Option 1 is marked blue and option 2 is marked yellow.

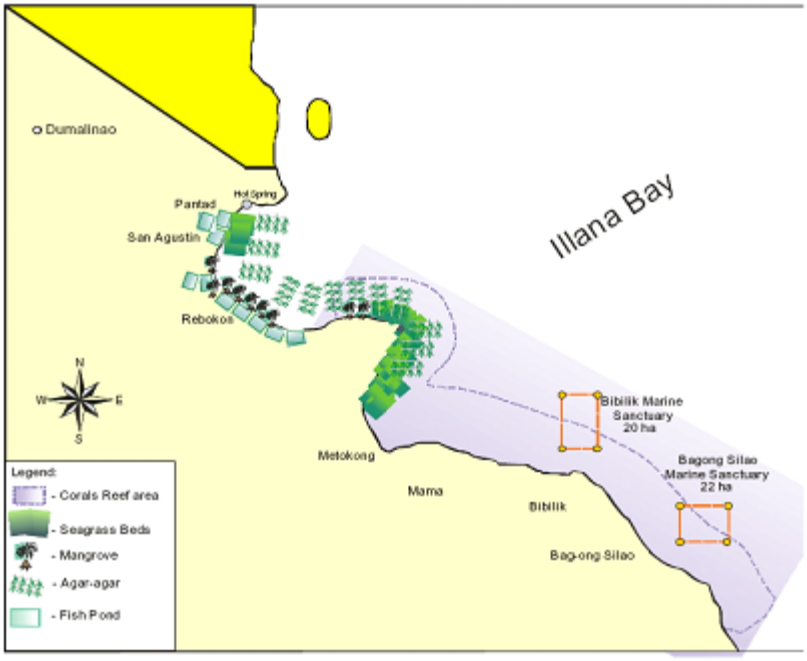

Figure 17. Map showing location of aquaculture farms and major habitats in Dumalinao.

These modeling exercises also highlights that the

southern part of the bay where most of the critical habitats are found is also the most vulnerable to organic pollution. If plans to develop mariculture in Dumalinao push through, it is important to consider these results in designing zones. It seems more reasonable to limit aquaculture activities with high organic loading on the western side where flushing appears to be better and the less pollutive seaweed farming in the southern part where they can also serve as biofilters, consuming excess nutrient introduced into the water.

The question of how many cages a mariculture zone can contain may be partly addressed by examining the results of the sediment footprint and sediment flux rate calculations. Figure 18 the scatterplots between footprint size, excess carbon and depth. The largest footprint size encountered in the simulations is about 2,500m^2 thus in order for the sediment footprints of neighboring cages not to overlap, there must be only at most 4 cages per hectare of mariculture area.

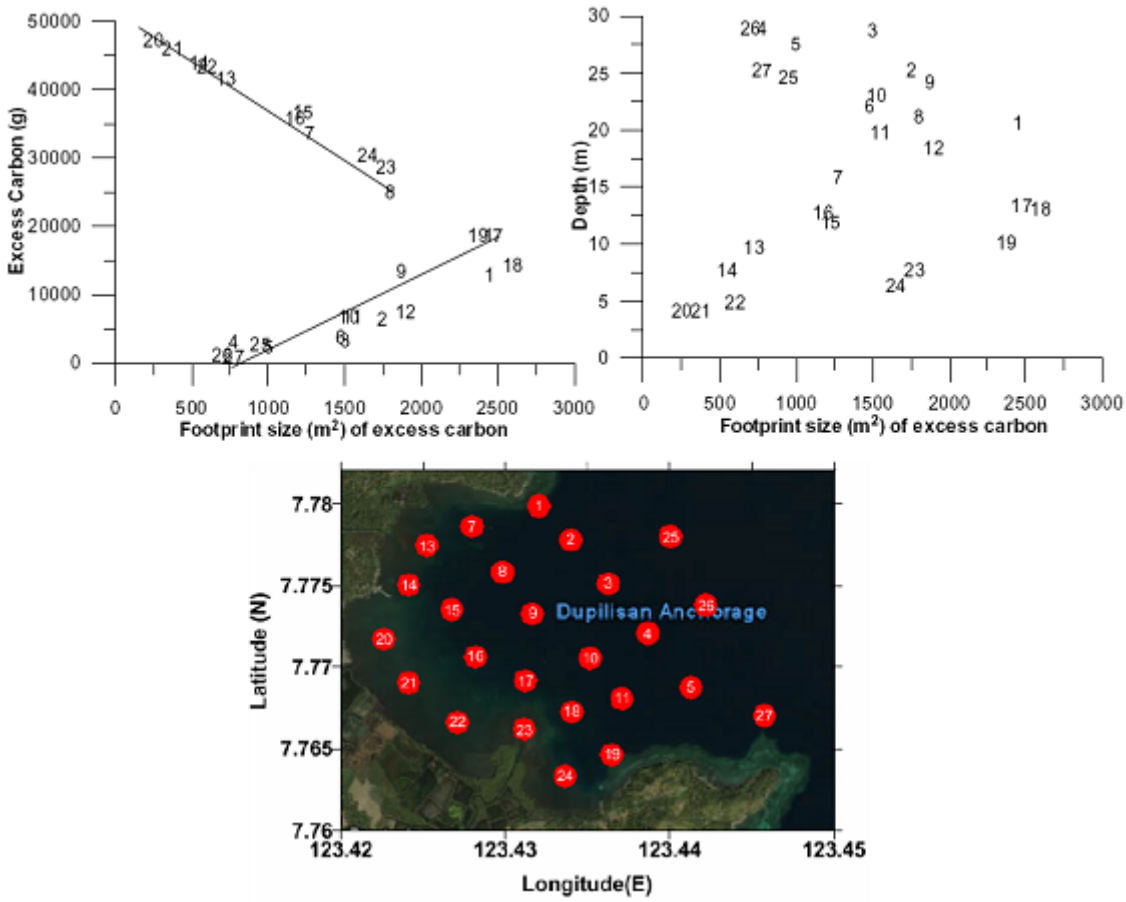

Figure 18. Scatterplots of sediment footprint size with excess carbon (top left) and depth (top right). Point labels represent location number indicated in themap (bottom).

The western part of the basin is also unique in the sense that sediment footprints are generally small but excess carbon is high. This relationship shows up clearly in Figure 18 where we find the smallest footprints and the largest excess carbon in shallow waters in the western side of the basin. Avoiding the placement of cages in depths shallower than 10m is one approach of reducing the total excess carbon to the bottom by avoiding the placement of cages in shallow depths (<10m in this study). These results also highlight the fact that areas with excessive carbon fluxes in small footprints will have a better chance of soft bottom communities to rework the sediments if a fallowing period after each cropping is observed.

SUMMARY AND CONCLUSIONS

A series of models were used to simulate hydrodynamics and waste dispersal patterns from potential mariculture sources in Dumalinao Bay. A hydrodynamic model was used to drive a lagrangian particle tracking model to estimate spatially explicit residence time of the bay waters, sedimentation footprints and sediment flux rates at the bottom and passive dispersal of the dissolved component of nutrients from feeds released into the water. The results highlight the vulnerability of the southern coast of Dumalinao Bay for organic pollution, probably due to the relatively higher residence times in the area. On the other hand, the western side is relatively well flushed and is more sheltered from the monsoon winds. Taking these results into account, fish cage culture may be more appropriate in the western side and the non-pollutive seaweed cuture on the south coast. Once the zones are identified, the sediment footprint results can be used to provide information of the density of cages and separation distances between cages. It is also important to note that these conclusions are based on hydrodynamic considerations alone and it is clear that other factors should also be considered when finalizing plans for mariculture development.

RECOMMENDATIONS

The models indicate the pollution impacts of finfish mariculture may be more significant if the sources are located in Zone 2 (yellow box in Figure 16). Dissolved nutrient dispersal also show accumulation in the southern coast of the Bay where most of the coral reef areas are located (Figure 17). These results suggest that the southeastern side of the bay may be more sensitive to organic waste associated with fin fish culture such as milkfish.

The proposed Zone 1 in Figure 16 can be where higher density of fish cages can be established. The low residence time and strong flushing may minimize impact within the area. However since footprints are small and excess carbon is high, fallowing is important. Fish cage areas in one area may be moved to a different area for the next season to allow the bottom communities to recover. The higher residence time and accumulation of dissolved nutrients from the model results also suggests that Zone 2 be limited to low organic waster loading mariculture (e.g. much wider separation between cages) or promote seaweed farming instead where is can also act as biofilters for nutrients in the water.

In the low density zone, maximum cage density should be at most 4 cages per hectare while in the high density zone, cage density can be as much as 6 cages per hectare.

Integrating the culture of seaweeds and selecting the right locations can also help reduce excess nutrients in the water from fish cages. Suitable areas include the southeastern coast of the bay as well as along the western coasts at depths of less than 10m.

It must be noted that these results are generated by models which have not been sufficiently validated in the field hence it makes good sense to be on the conservative side when using information from these models. Monitoring both production of the fish farms and environmental conditions will provide the needed data to show whether things need to be adjusted. Comparison of models with monitoring over time will help increase the reliability of models and keep mariculture at a sustainable level.

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