Proposal of a practical method to estimate the ecological carrying capacity for finfish mariculture with respect to particulate carbon deposition to the sea floor

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gez. Prof. Dr. Natascha Oppelt

to my beloved sister

Christine Jasmin

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SYMBOLS AND ABBREVIATIONS

(s-1) .... relative density [-], relative density [-]
APMFAN .... Asia-Pacific Marine Finfish Aquaculture Network
BM .... standing stock or biomass [kg]
BM_g .... gained biomass per production period [kg]
c .... mass concenration [gCl^{-1}]
C_{3D} .... Chézy coefficient for 3D-flow [$m^{1/2}s^{-1}$]
c_b .... sediment concentration near the bed [gCl^{-1}]
CD .... drag coefficient [-]
C_{EX} .... proportion of the consumed carbon excreted as faeces [-]
C_F .... carbon content of feed [-]
c_p .... prescribed max. dissolved nutrient concentration (Middelton and Doubell, 2014)
d .... transport distance [m]
D .... deposition flux [gCm^{-2}]
D_A .... transport distance [m]
Dia .... diameter of particle [m]
DSS .... Decision Support System
E .... erosion flux [gCm^{-2}]
EAA .... Ecosystem Approach for Aquaculture
F .... body forces arising from gravitational and Coriolis accelerations [N]
F_1 .... emissions from net pens (Stigebrandt and Aure, 1995)]
F_2 .... sedimentation rate at distance r (Stigebrandt and Aure, 1995)]
FCR .... feed conversion ratio [-]
Feed .... feed fed per day [kgd^{-1}]
f_n .... max. allowed nutrient flux (Middelton and Doubell, 2014)
Fr .... Froude number [-]
$f_R(C,t)$ .... reaction term
g .... gravitational acceleration [ms^{-2}]
GRIM .... Gondol Institute for Mariculture
h .... characteristic water depth [m]
H .... total water depth [m]
HDPE .... High Density Polyethylene
ISL .... Index of Suitable Location (Yokoyama, 2004)
ITI .... Infaunal Trophic Index
K .... constant diffusivity (Middelton and Doubell, 2014)
M .... first order erosion flux [gCm^{-2}]
Mb .... POC deposition rate to the seafloor [$gCm^{-2}d^{-1}$]
Ms .... POC emission rate from the farm [$gCm^{-2}d^{-1}$]
Ms_{max} .... maximum allowable POC emission [$gCm^{-2}d^{-1}$]
n .... Manning's roughness coefficient [$sm^{-1/3}$]
NCAR .... National Centers for Atmospheric Research, USA]
NCEP .... National Centers of Environmental Prediction, USA]
P .... pressure [Nm^{-2}]
POC .... Particulate Organic Carbon]
POC_{FAE} .... POC emitted via fish faeces [kgd^{-1}]
POC_{FF} .... total POC emitted from fish farm [kgd^{-1}]
POC_{WF} .... POC emitted via waste feed [$kgCd^{-1}$]
PON .... Particulate Organic Nitrogen

Re .... *Reynolds number [-]*
Ri .... *Richardson number [-]*
S .... *sources*
SD_{av} .... *average stocking density [kgm^{-3}]*
std_f .... *standard deviation of flow (Stigebrandt and Aure, 1995)*
S_{WF} .... *share of feed wasted [-]*
T^* .... *flushing time scale (Middelton and Doubell, 2014)*
T_a .... *advective time scale (Middelton and Doubell, 2014)*
T_d .... *diffusive time scale (Middelton and Doubell, 2014)*
T_{gro} .... *grow-out period [d]*
u, v, w .... *fluid velocities in x, y, z direction [ms^{-1}]*
u_b .... *flow velocity at bed layer [ms^{-1}]*
V .... *characteristic flow velocity [ms^{-1}]*
V_{max} .... *maximum flow velocity [ms^{-1}]*
Vol_c .... *total cage volume [m³]*
W .... *length scale of cage lease (Middelton and Doubell, 2014)*
Ws .... *settling velocity [ms^{-1}]*
*Ws** .... *non-dimensional settling velocity [-]*
Δ_{zb} .... *thickness of bed layer [m]*
ε .... *diffusion coefficients [-]*
κ .... *van Kármán constant [-]*
μ .... *normalised loading function (Stigebrandt and Aure, 1995)]*
ν .... *kinematic viscosity of water [m²s^{-1}]*
ρ .... *density of water [kgm^{-3}]*
ρ_s .... *density of particle [kgm^{-3}]*
σ .... *terms denoting turbulent pressure [Nm^{-2}]*
σ_T .... *dispersion length (Stigebrandt and Aure, 1995)*
τ .... *shear stress [Nm^{-2}]*
τ_b .... *bottom shear stress [Nm^{-2}]*
τ_d .... *critical shear stress for deposition [Nm^{-2}]*
τ_e .... *critical shear stress for erosion [Nm^{-2}]*
τ_{flow} .... *bottom shear stress due to flow [Nm^{-2}]*
φ .... *functional dependence*
π .... *dimensionless group [-]*

ABSTRACT

In the last years, aquaculture has become continuously more important for the supply of fish for human consumption. Finfish mariculture in floating net cages causes considerable amounts of dissolved and particulate bound nutrient emissions which may cause deterioration of ecological conditions. Its global expansion and intensification has therefore been of growing concern and development of mariculture activities should be guided by considerations with respect to the ecological carrying capacity of the coastal area of interest.

This study proposes a practical method to estimate the ecological carrying capacity for marine cage fish farming with respect to the fluxes of particulate organic carbon (POC) to the sea floor. The method was developed as a screening tool to support decision making at feasibility stage when a coastal area is assessed for its potential for finfish mariculture.

Dimensional analysis was used to simplify complex physical interdependencies by identifying meaningful and general relations between the most relevant parameters for POC transport and deposition. For a given bed roughness coefficient (*n*), the ratio of settled to emitted particulate organic wastes (*Mb/Ms*) was found to be a function of the local Reynolds number of the flow (*Re*) and the non-dimensional characteristic settling velocity of the particulates (*Ws**). Numerical flow and particle transport models from the Delft3D modelling suite were employed to empirically confirm the found relationship which forms the basis of the developed method.

The method was applied to Pegametan Bay in Bali, Indonesia to define the holding capacity of existing cage fish farms. The validity of the method was verified with *in-situ* investigations on sediment quality underneath the fish farms and at unaffected reference sites. The assimilative capacity of the bay in terms of maximum allowable POC deposition rates was estimated to be around 4 $gCm^{-2}d^{-1}$. It was exemplarily shown how the method can be applied to propose a fish farm set-up adjusted to the ecological carrying capacity of the bay.

Its universal and easy applicability is regarded as the strength of the method. Only few input data is needed which is especially useful in remote regions with limited availability of environmental data. Further potentiality of the method lies in the possible combination with hydrodynamic model results. The method allows the evaluation of the potential for mariculture production on different levels, ranging from coastal regions to a single farm.

KURZFASSUNG

In den letzten Jahren hat die Bedeutung von Aquakultur für die Bereitstellung von Speisefisch beständig zugenommen. Marikultur von Fischen in Netzkäfigen verursacht Emission gelöster und partikulär gebundener Nährstoffe, welche zu einer Beeinträchtigung des Ökosystems führen können. Aus diesem Grund wird die globale Ausweitung und Intensivierung von Marikultur kritisch betrachtet und bei der Entwicklung von Marikultur sollte die ökologische Tragfähigkeit der betroffenen Gebiete berücksichtigt werden.

Diese Studie präsentiert eine praktikable Methode zur Abschätzung der ökologischen Tragfähigkeit für Marikultur in Netzkäfigen im Bezug auf die Sedimentation von partikulären organischen Abfallstoffen (POC) aus Marikultur. Die Methode wurde entwickelt, um in der Phase der Machbarkeitsanalyse Entscheidungshilfen beizutragen, wenn Küstengebiete auf ihr Potential für Fisch Marikultur bewertet werden.

Mittels Dimensionsanalyse wurden die komplexen physikalischen Zusammenhänge vereinfacht und generelle und aussagekräftige Zusammenhänge zwischen den wichtigsten Variablen für POC-Transport und -Sedimentation identifiziert. Für einen festgelegten Rauheitskoeffizienten (*n*), ist das Verhältnis zwischen abgelagertem und emittiertem organischen Material (*Mb/Ms*) eine Funktion der lokalen Reynoldszahl (*Re*) und der dimensionslosen charakteristischen Sinkgeschwindigkeit der Partikel (*Ws**). Numerische Strömungs- und Transportmodelle aus der Delft3D Modellfamilie wurden verwendet, um die funktionale Beziehung zu bestätigen, welche die Grundlage für die entwickelte Methode darstellt.

Die Methode wurde in der Pegametan Bucht in Bali, Indonesien angewendet, um die Tragfähigkeit bestehender Fischfarmen zu definieren. Die Aussagekraft der Methode wurde anhand von *in-situ* Untersuchungen zur Sedimentqualität unter den Fischfarmen und an unbeeinflussten Referenzpunkten bestätigt. Die assimilative Kapazität in der Bucht hinsichtlich maximaler POC-Depositionsraten wurde auf 4 $gCm^{-2}d^{-1}$ geschätzt. Beispielhaft wurde gezeigt, wie mit Hilfe der Methode Vorschläge für die Platzierungen von Fischfarmen generiert und eine Abschätzung der ökologischen Tragfähigkeit vorgenommen werden kann.

Die Stärke der vorgeschlagenen Methode liegt in ihrer einfachen und universellen Anwendbarkeit. Es sind nur wenige Eingangsgrößen erforderlich, was insbesondere in abgelegenen Gebieten mit geringer Datenverfügbarkeit von Vorteil ist. Ein weiteres Potential der

Methode liegt in der Kombination mit hydrodynamischen Modellergebnissen. Die Methode ermöglicht eine schnelle Beurteilung der Entwicklungspotentiale für Fisch Marikultur auf unterschiedlichen Ebenen, von Küstengebieten bis hin zur einzelnen Farm.

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1 INTRODUCTION

The role of finfish mariculture with respect to global fish supply has become more important over the last decades (FAO, 2014). Today many high-value fish species are produced in marine farms and marine cage culture has become increasingly important for the fisheries sector in terms of both, production and value (FAO, 2014). While wild fish stocks decline, mariculture seems to be a save and profitable source for food fish. However, with the rise and expansion of finfish mariculture, pressure on marine ecosystems has increased. More coastal area is required and mariculture is competing with other coastal usages. The intensification of the farming techniques has increased the need for external inputs as well as the impact on the environment. One of the most obvious and well recognized effects is the deterioration of sediment quality and benthic biodiversity caused by nutrient enrichment via farm wastes (Alongi et al., 2009; Findlay et al., 1995; Gowen and Bradbury, 1987; Hall et al., 1990; Hargrave et al., 1997; Holmer et al., 2008; Kalantzi and Karakassis, 2006; Leopardas et al., 2016; Mazzola et al., 2000; Vezzulli et al., 2008; Wildish et al., 2003)

1.1 FISH FARM PARTICULATE WASTES AND ASSOCIATED ENVIRONMENTAL ISSUES

Intensive mariculture is characterized by the fact that many fish are held in a confined area. This leads to considerable amounts of organic waste which is released to the environment. In the context of this study the term "waste" refers to particulate organic wastes including fish faeces and "waste feed". Latter describes the amount of feed which was not or only partly devoured by the fish and therefore is directly lost to the environment.

The amount and characteristics of particulate organic wastes differ between cultured species, culture practices and feed type. In general, fish are fed with formulated (pelleted) feed or fresh fish feed. The latter feed type consists of small fish of low (commercial) value also called "trash fish". As it is relatively cheap and easy to obtain, trash fish forms an important dietary component in Asian finfish mariculture production (De Silva and Turchini, 2009; Huntington and Hasan, 2009). With respect to environmental effects, trash fish is considered to be more problematic than formulated feed as it has a higher feed conversion ratio (FCR) and causes larger amounts of wasted feed (De Silva and Turchini, 2009; Gao et al., 2005; Wu, 1995). The FCR describes the ratio of given feed mass to the increase in body mass and is a simple measure how well the feed is taken up by the fish. A low ratio indicates a more efficient use of feed and hence less particulate organic waste emission than a higher ratio.

Once released to the environment, the fish farm wastes are dispersed by currents, may be ingested by marine organisms and eventually settle to the sea floor. The environmental effects associated with fish farm organic wastes have been depicted in numerous studies (Fernandes et al., 2001; Fisheries and Oceans Canada, 2003; Forrest et al., 2007; Kalantzi and Karakassis, 2006; Ministry for Primary Industries New Zealand, 2013; Pearson and Black, 2001; Sanz-Lázaro and Marín, 2008; Wu, 1995). The following description gives an overview of the related processes and effects.

Accumulation of organic farm wastes below the farms is usually detectable by elevated levels of organic matter and pore water nutrients in the sediments. Bacterial decomposition of organic matter requires oxygen. Hence, additional organic matter input may alter sedimentary oxygen demand and redox chemistry. At high deposition rates the oxygen demand in the sediment may exceed the oxygen supply from the water column and the sediment pore water. As a result, anaerobic processes start to dominate biological degradation. Reduced redox potential and elevated sulphide concentrations caused by sulphate-reducing bacteria are indicative for such conditions.

Moderate increases in organic matter supply may stimulate macro fauna production and increase infaunal abundance. However, with increasing organic matter input and concurrent anoxic conditions only few organisms, tolerant to resist such extreme conditions, remain and biodiversity of benthic macrofauna is significantly reduced (Angel et al., 2000; Gao et al., 2005; Holmer et al., 2008; Leopardas et al., 2016; Tomassetti et al., 2016; Tsutsumi, 1995).

The most pronounced impact by organic matter from fish farms is generally found below the cages. According to the dispersion of the emitted waste, organic loads and related effects decrease with distance from the farm. The area being affected depends on several factors such as mariculture practice, hydrological conditions and type of the impacted coastal ecosystem. Field studies on benthic community response in the Mediterranean showed evidence that wastes from marine fish farms have impact on the benthic fauna to distances of few tens to about 300 meters away from the cages (Karakassis et al., 2001; Neofitou et al., 2010; Tomassetti et al., 2016, 2009).

1.2 ECOLOGICAL CARRYING CAPACITY, HOLDING CAPACITY AND ASSIMILATIVE CAPACITY

To control and facilitate the development of finfish mariculture in a coastal region, decision support systems (DSS) have been introduced. Within such systems, the ecosystem approach to aquaculture (EAA) has been adopted to avoid negative effects and to ensure sustainable operation (FAO, 1995). Its key components are site selection and carrying capacity assessment which need to be carried out in accordance with sustainability, resilience and best practice guidelines (Ross et al., 2013).

Site selection refers to the identification of areas within a coastal environment, which are suitable for the installation of floating net fish cages. Site selection criteria include physical aspects, socio-economic aspects as well as physio-chemical and biological environmental conditions addressing the requirements of the culture system and reared species. Besides these issues which aim to maximise production, factors controlling the impact on the marine environment should also be considered (e.g. dispersion of wastes by strong currents).

Once an area has been investigated for its suitability for mariculture, carrying capacity with respect to different categories has to be addressed. The concept of carrying capacity comprises the possibilities of aquaculture development within certain limitations regarding production, environmental and social aspects. Four categories of carrying capacity can be defined after Inglis et al. (2000) and McKindsey et al. (2006).

The *physical carrying capacity* is the available area suitable for a certain type of aquaculture with respect to its physical and biological requirements. This category does not offer limitations on stocking density or produced biomass.

The *production carrying capacity* as originally defined for bivalve aquaculture, is the maximum stocking density at which harvests are maximised in a farm. In this definition production carrying capacity is limited by it natural resources and therefore greatly depends on the physical carrying capacity. In the context of finfish aquaculture production, the term production carrying capacity has been used by Gečck and Legović (2010), where it is the "maximal number of aquaculture units with stocking rates that could be achieved before there is a deterioration in water quality harmful to production stock". The production carrying capacity is hence defined by the properties and tolerances of the cultured species.

The *ecological carrying capacity* is defined as the magnitude of aquaculture production which can be supported without causing unacceptable ecological impacts (Inglis et al., 2000; McKindsey et al., 2006). Byron and Costa-Pierce (2013) offer a more precise idea on what is found to be unacceptable when they define ecological carrying capacity to be "the magnitude of aquaculture production that can be supported without leading to significant changes to ecological processes, species, populations, or communities in the environment." On farm level the ecological carrying capacity can also be referred to as *holding capacity* (Stigebrandt et al., 2004).

The *social carrying* capacity is determined by the level of farm operation which does not cause unacceptable social impacts. It is concerned with interests of all stakeholders as well as environmental demands and therefore includes the before mentioned categories of carrying capacity.

In this study, ecological carrying capacity or holding capacity are of special interest as they give the basis for finding a sustainable level of aquaculture production with respect to environmental effects. A key factor for the ecological carrying capacity or holding capacity with respect to organic wastes resulting from fish farms, is the hydrodynamic character of a fish farm site, represented by the bathymetry and current magnitude (Borja et al., 2009; Giles, 2008). Hydrodynamics control the dispersion of organic emissions from mariculture, the loading of particulate organic wastes on the seabed as well as the oxygen supply to the benthic environment. Areas with larger depths below the cages and higher flow velocities were found to represent more dispersive and resilient environments than shallow systems with low current velocities (Keeley et al., 2013; Molina Domínguez et al., 2001; Pearson and Black, 2001; Urbina, 2016).

Closely related to the environmental carrying capacity is the assimilative capacity which is the ability of an ecosystem to maintain a "healthy" environment and to accommodate wastes (Fernandes et al., 2001). With respect to particulate organic waste deposition the assimilative capacity is the ability of benthic organisms to decompose organic matter without altering the natural oxic state of the sediment. The assimilative capacity can in this context be expressed as enrichment threshold before negative effects can be observed in the benthic environment. It is not a given property but is related to the abovementioned factors and depends on site specific conditions.

1.3 TOOLS ESTIMATING ECOLOGICAL CARRYING CAPACITY FOR FINFISH FARMING

Several tools were developed to estimate ecological carrying capacity or holding capacity for cage fish mariculture to facilitate spatial planning and ecosystem-based management. This section introduces selected methods to exemplify the status of the available tools.

Roughly, two groups can be distinguished. The first group includes tools which are used to predict environmental changes associated to various siting options and fish production levels and to estimate the holding capacity of specific locations and arrangements. With respect to the fate and effect of particulate wastes from fish farms, most of the tools use particle tracking models which utilize algorithms to determine the distribution and amount of carbon loading.

One of the first particle tracking models was developed by Gowen et al. (1989). It simulates the transport distance (*d*) of emitted particulate wastes before they settle to the seabed and considers water depth (*h*), current velocity (*V*) and settling speed of the particles (*Ws*).

$$d = \frac{Vh}{Ws} \qquad \text{............} \quad \textit{Equation 1}$$

The model was further refined to account for the effect of varying depths, variations in vertical current velocity and diffusion (Gillibrand et al., 2002; Gowen et al., 1994; Hevia et al., 1996). Over the years, predictive approaches on the deposition of particulate organic wastes from fish farms were developed using Geographic Information Systems (e.g. Pérez et al., 2002) and flow fields resulting from hydrodynamic models (e.g. AWATS (Dudley et al., 2000) and LAMP 3D (Doglioli et al., 2004)).

To estimate maximum holding capacities, particle tracking models were expanded by benthic modules considering benthic impact to define maximum allowable emission rates. DEPOMOD is a validated particle tracking model which predicts the deposition of waste feed and faeces and associated benthic impacts from specific farm settings (Cromey et al., 2002). It requires local hydrodynamic data as well as specific production data as input. The holding capacity with respect to the benthic impact is determined through an empirical relationship between depositional flux and the Infaunal Trophic Index (ITI). Latter characterises benthic communities with respect to the amount of particulate organic material present in the benthic environment by considering different feeding strategies of benthic fauna (Word, 1979). The DEPOMOD model considers resuspension and has been validated using sediment trap experiments. AUTODEPOMOD simulations are part of the regulatory licensing process in Scotland (SEPA, 2005). Within the DEPOMOD framework, the following models have been adapted for different species and regions: MERAMOD, CODMOD and DEPOMOD for shellfish (Cromey et al., 2012, 2009; Weise et al., 2009). A similar particle tracking model to predict the impact of particulate waste from fish farms and to estimate holding capacities considering hypoxia on the sea floor is the KK3D model developed by Jusup et al. (2007).

The MOM system (Modelling On growing fish farms Monitoring) developed by Stigebrandt et al. (2004) uses a dispersion model which expresses the dispersion capacity of a specific site by the dispersion length (σ_T). Latter is calculated using the standard deviation of a time series of flow (std_f), a characteristic water depth and the settling velocity of the particles.

$$\sigma_T = \frac{\mathrm{std_f} h}{Ws} \qquad \text{Equation 2}$$

For various σ_T, normalised loading (sedimentation) functions (μ) have been defined (Stigebrandt and Aure, 1995). The respective function can be used to relate the sedimentation rate (F_2) at a distance (r) to the emission from the net pens (F_1).

$$F_2(r) = \mu(r)F_1 \qquad \text{Equation 3}$$

The MOM model works on the level of a net pen (cage), allowing investigating varying pen configurations and overlapping accumulation. The model consists of four sub-models: a fish model, a cage water quality model, a dispersion model and a benthic model. The sub-models require specific input data and are interlinked. The dispersion sub-model uses input data from the fish model and local hydrodynamic information to calculate holding capacity. The maximum acceptable sedimentation of organic matter to the sea floor is determined in the benthic sub-model through the limiting oxygen supply to the sediment which maintains benthic infauna. Furthermore, the holding capacity is defined in the water quality model based on oxygen and ammonium concentrations in the cages. In Norway, the MOM system is applied for calculating the ecological carrying capacity of an area in the regulatory licensing process for mariculture (The Norwegian Ministry of Fisheries and Coastal Affairs, 2009).

The second group of tools offers more simple and universal approaches for site selection and evaluation of the potential for fish farm production, which are based on general relationships and physical interdependencies. Such models need a limited set of input data and, although less accurate, they are valuable at the feasibility stage when a coastal area is investigated for its potential for finfish mariculture. Of this kind, only few tools have been developed to the stage that they give orientation on maximum holding capacities and even less consider the deposition and impact of particulate wastes.

Halide et al. (2008a) used stepwise discriminant analysis to extract 6 out of 28 input variables in the MOM model (Stigebrandt et al., 2004). The six variables are deemed adequate for predicting maximum production rates within three groups of production capacity (low, medium, high). The variables are current magnitude and variability, ammonium concentration, critical oxygen concentrations, water depth and the ratio of cage depth to water depth. Maximum holding capacity was calculated from the variables in 100 simulations using a simplified version of the MOM model. Classification into production level is done by two resulting discriminant functions of the abovementioned variables. The analysis implies that high surface currents, low ammonium levels and low critical oxygen concentrations in the cages as well as deep cages and high ratio of cage depth to water depth are favouring high production levels. The method was used to give production maps showing potential production capacities in a bay in South Sulawesi, Indonesia.

Middelton and Doubell and Middelton et al. (2014; 2014) derived an parameter based on hydrodynamic variables describing the flushing time scale (*T**) of the cage or lease region including advective (T_a) and diffusive (T_d) time scales.

$$T^* = \frac{T_a}{1+p}$$ .... Equation *4*

Where

$$p = \frac{T_a}{T_d}\ ,\ T_a = \frac{W}{V}\ ,\ T_d = \frac{W^2}{2K}$$

with *W* being a length scale of the cage or lease, *V* being the mean vectoral velocity and *K* being a constant diffusivity. *T** is used to estimate the maximum allowed dissolved nutrient flux (f_n) for a prescribed maximum dissolved nutrient concentration (c_p).

$$f_n = \frac{c_p}{T^*}$$ .... *Equation 5*

The method was applied to estimate feed rates and holding capacities at new lease sites in Spencer Gulf, South Australia where a 3D hydrodynamic model was employed to provide the parameters needed to calculate *T** (Middleton et al., 2014).

While the method of Middelton and Doubell (2014) and Middelton et al. (2014) is focused on dissolved nutrients in the water column, Yokoyama et al. (2004) correlated sediment quality parameters to hydrodynamic conditions and proposed the Index of Suitable Location (*ISL*) as an simple indicator for site selection. The ISL is expressed in terms of local flow velocity (*V*) and water depth (*h*) and is considered to represent the potential to disperse fish farm wastes and to supply oxygen to the seabed. The index is defined as shown in *Equation 6*.

$$ISL = hV^2 \qquad \text{Equation 6}$$

The ISL was correlated with fish production and abiotic and biotic sediment properties (Yokoyama, 2003; Yokoyama et al., 2007, 2004). Higher ISL represent locations with better dispersion and oxygen supply, allowing a higher production before negative effects to the benthic environment could be expected. This relation is presented by the authors in a general diagram to estimate maximum production levels for different ISL. By means of correlating production rates to ISL, this approach is determined to the production type present in the area where the investigations were made (red sea bream and yellowtail cage culture in Japan).

1.4 AIM AND OUTLINE OF THE STUDY

One of the main restrictions in the applicability of methods estimating the carrying capacity for finfish mariculture is the availability of environmental data. Most of the existing approaches rely on extensive data sets. Collecting representative spatial information on variables, such as oxygen and ammonium concentration is mostly costly and time consuming. In many regions, such as South East Asia, this type of data is rarely available. Nevertheless, in South East Asia mariculture is rapidly expanding and forms an important component in coastal management plans and there is a need for systematic procedures for sustainable coastal development, to avoid adverse environmental impact. In this context, practical screening tools, which are not restricted to a specific scenario and based on few input data, are useful to give an early-on estimation at feasibility stage when a coastal area is evaluated for its potentials for finfish mariculture.

The aim of this study is to develop and show the adequacy of a practical method to estimate the potential for finfish farming with respect to the dynamics of emitted particulate organic wastes. The study proposes a generally applicable method to support the planning process at a feasibility stage in areas where little spatial environmental data is available.

The presented method is based on the physical interdependencies in particulate waste transport and deposition. Information on hydrodynamic conditions such as water depth and flow velocities can be obtained relatively faster from charts, measurements and numerical modelling, than data on biogeochemical parameters. Furthermore, hydrodynamic factors define the dispersive character of a site and therefore strongly influence the ecological carrying capacity with respect to nutrient loads to the environment (see Section 1.2).

Dimensional analysis is applied, to find meaningful and general relations between the most relevant parameters for particulate waste transport and deposition. Numerical modelling is employed, to generate data to empirically confirm these relationships. Combining the results of dimensional considerations and numerical modelling leads to a functional description of the relation between the ratio of emitted to deposited particulate organic matter, the hydrodynamic character of an area and the characteristic settling velocity of the particulates.

The method is exemplarily applied to a bay in Bali, Indonesia to assess the holding capacity of existing farms. Sediment analysis of samples taken below the fish farms and at unaffected reference locations is used, to define the assimilative capacity of the area and to verify the adequacy of the developed method. To give an example for further application of the method, a new farm arrangement, adjusted to the ecological carrying capacity of the area, is proposed.

2 METHODOLOGY AND REQUIRED DATA

The proposed method was developed in two steps. First, dimensional analysis was performed to define the relevant variables influencing the transport and deposition of particulate organic matter from fish farms and to derive some general relationships. Secondly, numerical modelling was applied to simulate the fate of particulate carbon being emitted from fish farms. The model results provided data, necessary to confirm and consolidate the general relationship found by means dimensional analysis.

The method was developed, applied and validated using data from Pegametan Bay, Indonesia. The area serves as model domain for the numerical model. Furthermore, operational data of existing fish farms in Pegametan Bay and sediment quality measurements below the farms and at unaffected reference sites were applied in this study.

Model simulations in combination with sediment quality measurements were used to estimate the assimilative capacity of the area. Holding capacities calculated by the presented method were compared to the standing stock of existing cage farms. To verify the method, the comparison was checked against sediment quality measurements. To present the possible applications of the developed method, an applied example was conducted, proposing a new farm arrangement adjusted to the carrying capacity in Pegametan Bay.

2.1 STUDY AREA

The method presented in this study was developed and applied using environmental and fish farming data of Pegametan Bay in North Bali, Indonesia (8.13 °S 114.6 °E). The area of interest covers about 35 km² along a coastal stretch of around 10 km. The most prominent characteristics are a reef and channel system situated at the centre of Pegametan Bay. The picture in *Fig. 2-1* gives an overview of the study site. Water depth is less than 1 m in the coral reef area and greater than 50 m at the reef slope. The reefs divide the inner Bay into two main channels with depths from 10 to 20 m. The flow in the bay is tide-dominated with a mean tidal range of about 1.8 m.

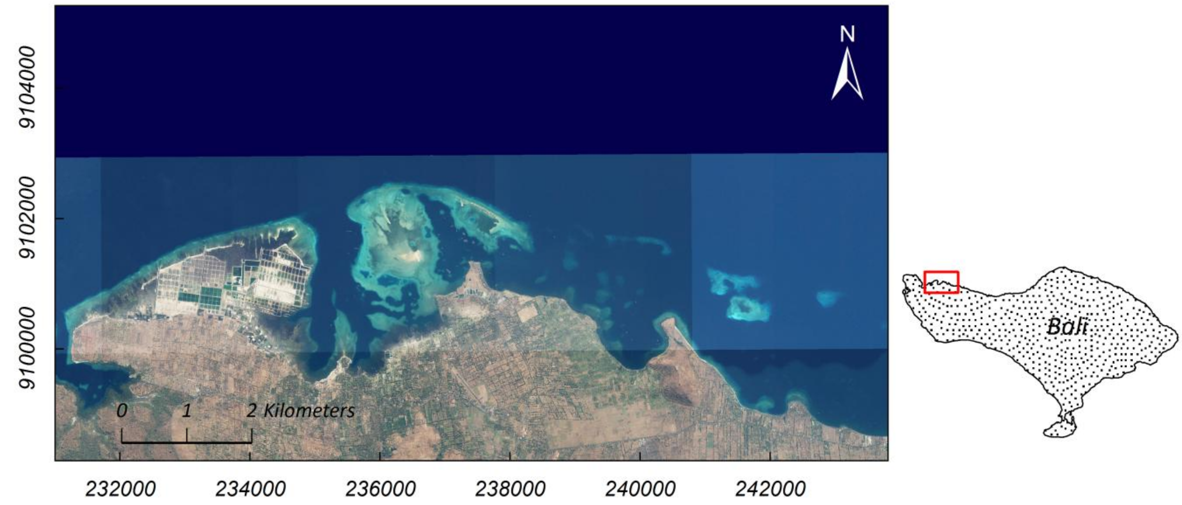

Fig. 2-1 Pegametan Bay at the north coast of Bali, Indonesia (Satellite imagery: Yahoo maps)

The sediments in the channels display fine to clayey sands, containing varying amounts of shells and coral debris. Sea water temperatures are in the range of 25 to 35 ^{0}C and salinity varies between 32 and 36 psu. Fresh water enters the bay mainly through diffuse runoff and small streams, which appear seasonally during rainy season (December-February). North-west and south-east monsoon winds can reach maximum speeds of about 12 and 6 ms^{-1}, respectively (Kalnay et al., 1996). During inter-monsoon periods, winds are variable and generally weak. The coastline is structured by beaches and patches of mangrove forest. A large shrimp farm is located in the western part of the study area.

Finfish mariculture using floating net cages has been practised in Pegametan Bay since 2001. The first cage farms were located in the eastern channel. Between 2011 and 2013 the number of farms increased significantly and cage farming was extended into the western channel. The Gondol Research Institute for Mariculture (GRIM) is located nearby and has an experimental grow-out farm in the bay. The institute is part of the Asia-Pacific Marine Finfish Aquaculture Network (APMFAN) and internationally acknowledged for its research on tropical finfish culture and hatchery techniques. Its suitability for mariculture and the on-site experience with marine finfish culture, makes Pegametan Bay a well suited location for the investigations conducted in this study.

At the time of this study, there were 30 operating cage farms in Pegametan Bay (*Fig. 2-2*). The farms existed at least since 2 to 5 years; however exact information on farm development was not available. In this study the duration of the farm operation was therefore not taken into account.

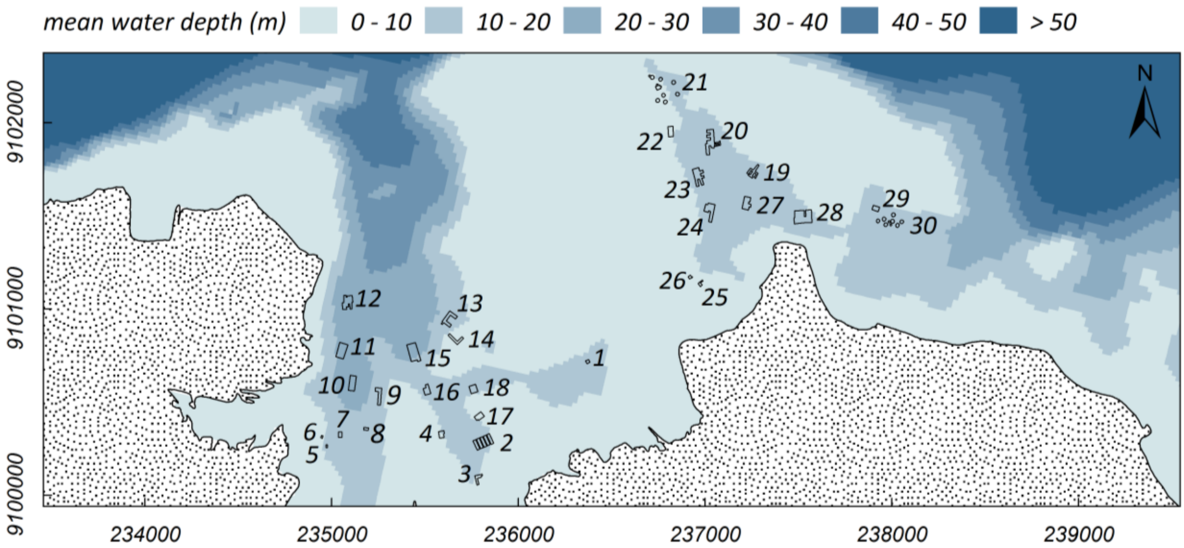

Fig. 2-2 Operating cage fish farms in Pegametan Bay (2014)

Most of the farms are made of wooden rectangular cages with common dimensions of 3x3x3 meters. The floating net cages consist of a buoyant collar or frame, supporting the submerged net bag. Typically, cages are combined to form cage clusters of 20 cages, which are moored to the sea floor by ropes and anchors to keep them in a particular location. Several clusters are linked to form a farm. *Fig. 2-3* and *Fig. 2-4* show a picture of a cage farm situated in Pegametan Bay and a sketch of the basic design of a floating net cage, respectively.

Fig. 2-3 Floating net cage farm in Pegametan Bay (Photo: van der Wulp 2008)

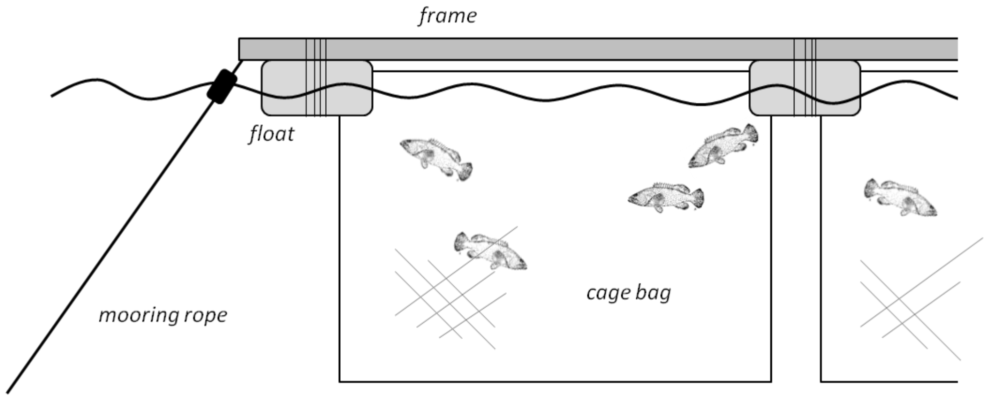

Fig. 2-4 Basic design of a net cage

Two farms (21 and 30) were additionally using circular cages with high density polyethylene (*HDPE*) framing of 5 and 10 meters radius. Cage numbers were recorded during field studies and approximated from Google Earth. For each farm, the cage volume was calculated assuming a cage depth of 3 m (rectangular cages), 6 m (circular cages in farm 21) and 8 m (circular cages in farm 30) based on appraisal by Radiarta (2015).

Finfish species, cultured in Pegametan Bay, include Asian Sea Bass (*Lates calcarifer*), Humpback Grouper (*Epinephelus altivelis*) and some species of ornamental fish. The bulk of the standing stock consists of Brown Marbled Grouper (*Epinephelus fuscoguttatus*).

Production data is scarce and had to be reasonably assumed based on the information available. Operating fish farms are usually not fully stocked, but some cages are left empty. Within the remaining cages, fish are re-distributed and stocked at different stocking densities over the production cycle (Radiarta, 2015). For Humpback grouper, with a body weight larger than 10 g, the recommended maximum stocking density is 7 kgm^{-3} for optimal growth and good health of the fish (DKDP, 2007). Young fish are usually held at lower stocking densities of about 2-3 kgm^{-3} (Radiarta, 2015). A common farm utilization uses about 50 % of the cages, of which half are stocked with fish at marketable size (at assumed stocking density of 7 kgm^{-3}) and half are stocked with younger fish (at assumed average stocking density of 2.5 kgm^{-3}) (Radiarta, 2015). To consider the empty cages and the varying stocking densities in the stocked cages, an average stocking density of 2 kgm^{-3} was assumed for the whole cage volume, to estimate the average standing stock of the farms in Pegametan Bay. For fish farms 21 and 30, an average stocking density of 4 kgm^{-3} was defined, as fish production is practiced more intensely and farm volume is used more efficiently in these farms (Radiarta, 2015). From the average stocking density (SD_{av})

and the total cage volume (Vol_c), the standing stock or biomass (*BM*) in each farm can be estimated as follows:

$$BM = Vol_c \cdot SD_{av} \quad \text{............ Equation 7}$$

Fry is collected in coastal waters or bred in hatcheries. The young fish are held in nurseries before they are transferred to the cage farms at a total body length of around 8 - 15 cm at a weight of about 10 - 60 g (Baliao et al., 2000; DKDP and JICA, 2005). At 10 cm total body length, tiger grouper weight about 25 g (Ismi et al., 2012). The marketable size of 400 - 500 g is reached after a 5 to 10 month grow-out period in the cages (Baliao et al., 2000; DKDP, 2007; DKDP and JICA, 2005). In this study, an initial weight of 25 g (10 cm) and an aspired market weight of 500 g, which is reached after a grow-out period of 10 month (300 days), were assumed. The corresponding biomass gained in the cages is 475 g per fish or 95 % of the total body weight. Accordingly, taking into account the initial body weight of the stocked fish, the gained biomass (BM_g) during the grow-out period is 95 % of the total biomass in the cages and can be calculated as shown in *Equation 8*.

$$BM_g = BM \cdot 0.95 \quad \text{............ Equation 8}$$

The amount of feed fed per day (*Feed*) can be derived using the feed conversion ratio (*FCR*), which is the number of units of feed required to increase the biomass by one unit within the grow-out period (T_{gro}).

$$Feed = \frac{BM_g \cdot FCR}{T_{gro}} \quad \text{............ Equation 9}$$

In Pegametan Bay, grouper feed on a mixture of trash fish and formulated feed (pellets), the ratio of which mostly depends on the availability of formulated feed (Radiarta, 2015). The FCR for trash fish lies between 4 to 5.8, while for formulated feed it lies between 1.3 and 1.5 (DKDP, 2007; DKDP and JICA, 2005). This study applies an average FCR value of 3.15.

Particulate organic carbon (POC) is mostly released from the farm in the form of wasted fish feed and fish faeces. The amount of POC being emitted through waste feed (POC_{WF}) can be calculated considering the carbon content of the feed (C_F) and the share of feed being wasted (S_{WF}) as shown in *Equation 10*.

$$POC_{WF} = Feed \cdot C_F \cdot S_{WF} \quad \text{............ Equation 10}$$

The fraction of feed wasted by fish being fed with trash fish is around 50 %, while for dry feed it is about 10 % (Wu, 1995). This study assumes an average of 30 % loss of feed. After measurements done by Alongi et al. (2009), the carbon content of trash fish and formulated feed was found to be approximately 13.1 % and 19.6 % wet weight, corresponding to 39.6 % and 47.9 % dry weight respectively assuming a wet weight to dry weight conversion factor of 33 % (Alongi et al., 2003). An average value of 16.4 % wet weight (43.8 % dry weight) is assumed in the study at hand.

The amount of POC being emitted via fish faeces (*POC_{FAE}*) is based on the amount and carbon content of the feed ingested by the fish and the assumed proportion of the consumed carbon, which is excreted as faeces (*C_{EX}*) and can be calculated as shown below:

$POC_{FAE} = Feed \cdot C_F \cdot (1 - S_{WF}) \cdot C_{EX}$ .... *Equation 11*

The fraction of ingested carbon excreted as faeces was simplifying estimated to be around 20 % after Hevia (1996). The sum of the wasted and the excreted POC forms the total amount of POC being emitted from a farm (*POC_{FF}*).

$POC_{FF} = POC_{WF} + POC_{FAE}$ .... *Equation 12*

Tab. 2-1 gives an overview of the farm dimensions and particulate carbon emissions in Pegametan Bay. The total standing stock was estimated to be 346 tonnes being distributed over a cage area of about 40 ha and a cage volume of 139,190 m³.

Tab. 2-1 Estimated farm dimensions, standing stock and POC emissions of the farms in Pegametan Bay

Farm No.	Cages	Cage area (m^2)	cage volume (m^3)	av. stocking density (kgm^{-3})	Est. standing stock (t)	POC emissions ($kgCd^{-1}$)
1	16	64	192	2	0.4	0.3
2	250	3,125	9,375	2	18.8	13.6
3	60	540	1,620	2	3.2	2.3
4	63	567	1,701	2	3.4	2.5
5	8	72	216	2	0.4	0.3
6	6	54	162	2	0.3	0.2
7	40	360	1,080	2	2.2	1.6
8	32	288	864	2	1.7	1.3
9	120	1,080	3,240	2	6.5	4.7
10	166	1,494	4,482	2	9.0	6.5
11	380	3,420	10,260	2	20.5	14.9
12	290	2,610	7,830	2	15.7	11.3
13	166	1,494	4,482	2	9.0	6.5
14	90	810	2,430	2	4.9	3.5
15	320	2,880	8,640	2	17.3	12.5
16	100	900	2,700	2	5.4	3.9
17	84	776	2,328	2	4.7	3.4
18	168	1,512	4,536	2	9.1	6.6
19	84	756	2,268	2	4.5	3.3
20	319	2,671	8,013	2	16.0	11.6
21	28	2,528	14,707	4	58.8	42.6
22	50	450	1,350	2	2.7	2.0
23	212	1,908	5,724	2	11.4	8.3
24	212	1,908	5,724	2	11.4	8.3
25	30	270	810	2	1.6	1.2
26	15	135	405	2	0.8	0.6
27	182	1,638	4,914	2	9.8	7.1
28	321	2,889	8,667	2	17.3	12.6
29	60	540	1,620	2	3.2	2.3
30	9	2,356	18,850	4	75.4	54.6
		40,113	139,190		346	

Particulate farm wastes display a wide range of settling speeds due to their different shape and mass. Settling rates for trash fish feed can vary between 0.014 to 0.027 ms^{-1}, while for grouper feed pellets they can be up to 0.12 ms^{-1} (Chu, 2002). At the time of this study, public data on settling velocities of grouper faeces was not available. Settling velocities of faeces of Atlantic Salmon fed by different commercial diets ranged between 0.037 to 0.092 ms^{-1} (Chen et al., 2003). Another study on Atlantic salmon by Cromey et al. (2002) found an average settling velocity of 0.032 ms^{-1} with a standard deviation of 0.011 ms^{-1}. Magill et al. (2006) determined mean settling rates of 0.0048 and 0.007 ms^{-1} for faeces from cultured gilthead sea bream and sea bass, respectively. This study does not distinguish between waste feed and faeces, but considers a single waste fraction. Based on the abovementioned information a constant average settling rate of 0.04 ms^{-1} was defined.

Tab. 2-2 gives a summary on the considered values for the parameters used to estimate the emission rates from grouper culture in Pegametan Bay using "mixed feed", consisting of trash fish and pellets.

Tab. 2-2 Assumed values for estimating emission rates from grouper culture with "mixed feed"

Parameter	*Value*	*Unit*
Initial body weight of groupers	*25*	*g*
Marked weight of groupers	*500*	*g*
Production period	*300*	*days*
Feed conversion rate	*3.15*	*-*
Fraction of ingested carbon excreted as faeces	*0.2*	*-*
Fraction of feed wasted	*0.3*	*-*
C content of fresh weight feed	*0.164*	*-*
Average settling rate fish farm waste	*0.04*	*ms^{-1}*
Max. stocking density with respect to fish health	*7*	*kg^{-3}*

2.2 DIMENSIONAL ANALYSIS

The dispersion and deposition of particulate organic material from a fish farm is a complex process involving many variables. Dimensionless analysis is a method to reduce this complexity by decreasing the number of variables specifying the process, through finding meaningful and general relations between them. A prerequisite for dimensional analysis is the identification of the relevant variables (independent variables) describing the physical process under consideration (dependent variable).

The dependent and independent variables are expressed in units of the SI system (Système Internationale d'unités) which quantify the properties of the physical parameters. For dimensional analysis however, the nature of the dimension and not its quantity is of interest. The basic idea of dimensional analysis is that a physical law must be independent from the units of the physical variables involved, i.e., the relationship between the physical variables remains valid, independent of their units. As a consequence in a dimensionally homogenous relationship both sides of an equation have the same dimensions.

Dimensions are certain properties a physical situation has, e.g. length, velocity, volume. All dimensions can be derived from some base quantities. In the SI system of units, seven basic quantities are defined: length, time, mass, thermodynamic temperature, electric current, amount of substance and luminous intensity. *Tab. 2-3* shows the three base quantities used in this study and some derived quantities. It can be seen from those examples that any derived quantity is a product of powers of numerical values of the base quantities.

Tab. 2-3 Some base quantities and derived quantities of the SI system of units and their dimensions

Base quantities

Name	*Symbol*	*Unit name*	*Unit symbol*	*Dimension*
Length	*l*	*meter*	*m*	*L*
Time	*t*	*second*	*s*	*T*
Mass	*m*	*kilogram*	*kg*	*M*

Derived quantities

Name	*Symbol*	*Unit name*	*Unit symbol*	*Dimension*
Area	*A*	*square meter*	m^2	L^2
Speed	*v*	*meter per second*	$m\ s^{-1}$	$L\ T^{-1}$
density, mass density	*ρ*	*kilogram per cubic meter*	$kg\ m^{-3}$	$M\ L^{-3}$

One strategy to solve a dimensional analysis is the Buckingham's π-theorems. The first theorem states that the relationship between the variables can be expressed by a defined number of non-dimensional π groups. The number of groups can be found by calculating the difference between the number of dimensional groups and the number of independent variables.

The second theorem states that each group is a function of a defined number of governing or repeating variables plus one of the remaining variables. The number of repeating variables is the same as the number of base dimensions. The repeating variables are the variables which reoccur in all or most of the dimensionless groups. Furthermore they have to fulfil some conditions:

- When combined, the repeating variables must contain all base dimensions (M, L, T)
- A combination of the repeating variables must not form a dimensionless group
- The repeating variables should be well measurable

As the π groups are dimensionless they have the form $M^0L^0T^0$. To be dimensionally homogenous, for each dimension the powers must be equal on both sides of the equation. In the dimensional analysis the non-dimensional groups are formed by equalizing the powers.

In the study at hand the interest lies on the flux of particulate organic wastes to the sea floor (dependent variable) which should be described by a complete set of independent variables. The analysis integrates physical variables only. Biogeochemical processes influencing the mass balance of organic material from the fish farm, such as potential mineralisation of carbon in the water column and feeding of wild organisms on fish farm wastes, are not taken into account. A schematic overview over the physical processes determining the transport and deposition of particulate fish farm wastes is given in *Fig. 2-5*.

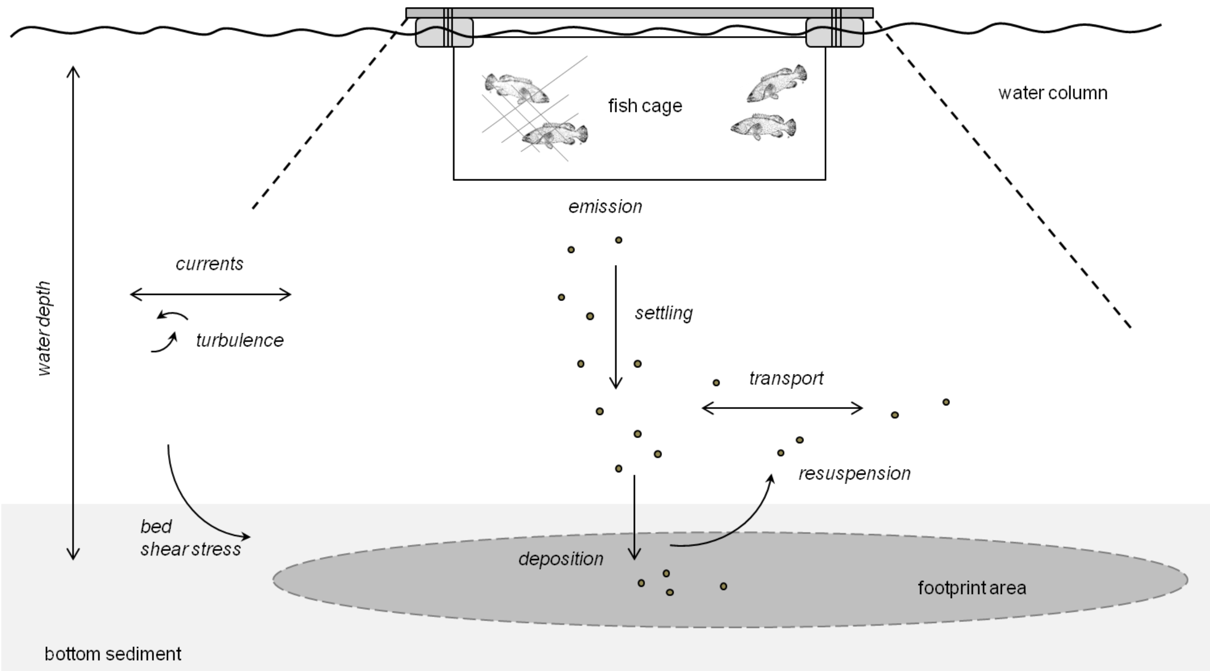

Fig. 2-5 Transport scheme of particulate fish farm wastes

The variable having the most direct effect on the magnitude of particulate organic flux to the sea floor is the amount of ***particulate organic waste being emitted from the farm***. Once released from the net cages, the wastes are exposed to complex physical processes simultaneously influencing their transport. They are carried by advection in the main flow direction and diffusion and dispersion processes lead to mixing and equalization of spatial concentration gradients. Waste dispersion and diffusion processes result from velocity gradients and fluctuations in the flow and are thus no independent variables by themselves. ***Current magnitude***, ***water depth*** and ***kinematic viscosity*** of the water represent site specific hydrodynamic variables of the water body. The kinematic viscosity depends on the density of water influenced by salinity, temperature and suspended sediment concentration in the water column. In this approach it is assumed, that variations in density can be neglected.

Due to their own mass, the particles eventually settle to the sea floor. Particulate wastes are of different shape and density which may change while they sink to the sea floor and influence the settling rate. The settling velocity of the particles is a function of ***gravity***, the ***density of water*** and particle properties, mainly the ***density of the particle*** and the shape of the particle. Latter is hard to determine and is often being described by a shape factor as a ratio of some axes across the particle (Vanoni 2006). Being defined this way, the shape of a particle is a function of its ***diameter***. Due to mutual interference of particles, sediment concentration in the water column may also have an effect on the falling velocity. After deposition, the particles may be entrained in the water column by strong currents exerting sufficient shear stress on the sediment to trigger resuspension. The concentration of the sediment in the water column is not independent but does depend on the waste load from the farm and the hydrodynamic variables at the location. The influence of the *sea* bed roughness on the flow velocities and shear stress at the sea floor is expressed here by the ***Manning's roughness coefficient***.

Regarding the above mentioned processes and interrelations the deposition flux of particulate waste (*Mb*) is a function of the set of independent variables show in *Equation 13*.

$$Mb = \phi(Ms, V, h, \nu, g, \rho, \rho_s, Dia, n) \quad \text{...................} \quad \textit{Equation 13}$$

where ϕ shows the functional dependence and has to be determined experimentally

Mb deposition rate to the sea floor [$gCm^{-2}d^{-1}$]

Ms emission rate from the farm [$gCm^{-2}d^{-1}$]

V characteristic flow velocity [ms^{-1}]

h characteristic water depth [m]

ν kinematic viscosity of water [m^2s^{-1}]

g gravitational acceleration [ms^{-2}]

ρ density of water [kgm^{-3}]

ρ_s density of particle [kgm^{-3}]

Dia diameter of particle [m]

n Manning's roughness coefficient [s $m^{-1/3}$]

The ratio between the particulate matter deposited on the bed and the emitted material (*Mb/Ms*) is expected to be independent of the amount of material being emitted from the farm. However, it is expected to be depending on the variables determining the dispersion and deposition of the material. The ratio *Mb/Ms* can be expressed in a functional form as shown in *Equation 14*.

$$\frac{Mb}{Ms} = \phi(V, h, \nu, g, \rho, \rho_S, Dia, n\,) \quad \text{Equation 14}$$

In this study, roughness (*n*) was excluded from the dimensional analysis and was considered in the experimental analysis by varying the Manning's roughness coefficient in the numerical models (see Section 2.3.3). Hence *Mb/Ms* is a function of the variables shown in *Equation 15*.

$$\frac{Mb}{Ms} = \phi(V, h, \nu, g, \rho, \rho_S, Dia\,) \quad \text{Equation 15}$$

Similar to the examples shown in *Tab. 2-3*, the seven independent variables shown in *Equation 15* can be expressed using the three base quantities, mass M, length L and time T.

$[V] = L\,T^{-1}$

$[h] = L$

$[\nu] = L^2\,T^{-1}$

$[g] = L\,T^{-2}$

$[\rho] = M\,L^{-3}$

$[\rho_s] = M\,L^{-3}$

$[Dia] = L$

Seven independent variables are described by three base dimensions (M, L, T). According to the Buckingham's theorem, four dimensionless groups can be formed (*Equation 16*).

$$\phi(\pi_1, \pi_2, \pi_3, \pi_4) = 0 \quad \text{Equation 16}$$

With respect to the second Buckingham's theorem, the variables *V* and *g* and *ρ* were chosen to be the repeating variables.

The first group includes the particle's density. The densities are combined to form the relative density (*s-1*) which is the ratio of the submerged density of the sediment (*ρs-ρ*) and the density of water as shown in *Equation 17*.

$\pi_1 = V^a g^b \rho^c \rho_s$

$M^0 L^0 T^0 = (LT^{-1})^a (LT^{-2})^b (ML^{-3})^c (ML^{-3})$

$For\ M \quad 0 = c + 1$

$For\ L \quad 0 = a + b - 3c - 3$

$For\ T \quad 0 = -a - 2b$

$a = 0$

$b = 0$

$c = -1$

$\pi_1 = \frac{\rho_s}{\rho} = \frac{\rho_s - \rho}{\rho} = relative\ density\ (s-1)$ .... *Equation 17*

The second group includes the kinematic viscosity of water resulting in the term shown in *Equation 18*.

$\pi_2 = V^a g^b \rho^c \nu$

$M^0 L^0 T^0 = (LT^{-1})^a (LT^{-2})^b (ML^{-3})^c (L^2 T^{-1})$

$For\ M \quad 0 = c$

$For\ L \quad 0 = a + b - 3c + 2$

$For\ T \quad 0 = -a - 2b - 1$

$a = -3$

$b = 1$

$c = 0$

$\pi_2 = \frac{V^3}{gv}$ .... *Equation 18*

The third group includes the water depth and forms the Richardson number (*Ri*), as shown in *Equation 19.*

$\pi_3 = \mathrm{V^a g^b \rho^c h}$

$M^0L^0T^0 = (LT^{-1})^a(LT^{-2})^b(ML^{-3})^c(L)$

$For\ M \quad 0 = c$

$For\ L \quad 0 = a + b - 3c + 1$

$For\ T \quad 0 = -a - 2b$

$a = -2$

$b = 1$

$c = 0$

$\pi_3 = \frac{gh}{V^2} = Richardson\ number, Ri$ .... *Equation 19*

The Richardson number describes the ratio of potential to kinetic energy is used to describe the stability of stratification or the damping of turbulence by stratification. In the tide dominated flow considered here, the effect of stratification is assumed to be less important. The group can be rearranged to form the Froude number (*Fr*) as shown in *Equation 20.* Fr gives the ratio of a characteristic flow velocity (inertia force) to the gravitational wave velocity (gravitational force).

$\pi_3 = \frac{V}{\sqrt{\mathrm{gh}}} = Frounde\ number, Fr$ .... *Equation 20*

The fourth group includes the diameter of the particles resulting in the term shown in *Equation 21*.

$\pi_4 = \mathrm{V^a g^b \rho^c Dia}$

$M^0L^0T^0 = (LT^{-1})^a(LT^{-2})^b(ML^{-3})^c(L)$

$For\ M \quad 0 = c$

$For\ L \quad 0 = a + b - 3c + 1$

$For\ T \quad 0 = -a - 2b$

$a = -2$

$b = 1$

$c = 0$

$\pi_4 = \frac{gDia}{V^2}$ .... *Equation 21*

After the first dimensional considerations, the *Mb/Ms* ratio may be described by the following function of four non-dimensional π groups as shown in *Equation 22.*

$\frac{Mb}{Ms} = \phi\left((s-1), \frac{V^3}{gv}, \frac{V}{\sqrt{\mathrm{gh}}}, \frac{gDia}{V^2}\right)$ for a given value of n .... *Equation 22*

To further refine the functional relationship of the dependent variable and to reduce the number of variables, the groups can be combined and manipulated (e.g. inverted, squared).

For the tidal flow considered here *Fr* is very small. The setting of the waste material in the turbulent flow towards the bed is not affected by the free surface effects. Therefore the effect of *Fr* is only of second order importance. Combining group π_2 with group π_3 results in the Reynolds number (*Re*) which is denoted as group π_5 and presented in *Equation 23*.

$\pi_5 = \pi_2\pi_3 = \frac{V^3}{gv}\frac{gh}{V^2} = \frac{Vh}{v} = Reynolds\ number, Re$ .... *Equation 23*

To consider the particle diameter and settling velocity, groups π_2 and π_4 are combined to form a new group π_6 as shown in *Equation 24.*

$\pi_6 = (\pi_2)^2(\pi_4)^3 = \left(\frac{V^3}{gv}\right)^2\left(\frac{gDia}{V^2}\right)^3 = \frac{gDia^3}{v^2}$ .... *Equation 24*

After performing the next step in dimensional analysis the problem may be described by the following function of three non-dimensional π groups given in *Equation 25*.

$\frac{Mb}{Ms} = \phi\left((s-1), \frac{Vh}{v}, \frac{gDia^3}{v^2}\right)$ for a given value of n .... *Equation 25*

In general, the diameter of fish farm waste is hard to determine because it is very variable and difficult to measure. Following Cheng (1997) settling velocity of a sphere is related to its diameter and the drag coefficient (C_D) as shown in *Equation 26.* This is a simplification because particulate wastes from a fish farm are never spherical but display a large variety of sizes and shapes.

$$Ws = \sqrt{\frac{4(s-1)gDia}{3C_D}}$$ .... *Equation 26*

The C_D depends on the particle Reynolds number ($Re = \frac{Ws \cdot Dia}{v}$). If C_D is assumed to be nearly constant, *Dia* will take the form shown in *Equation 27*.

$$Dia \approx \frac{Ws^2}{g(s-1)}$$ .... *Equation 27*

When the diameter is substituted into group π_6 it turns into

$$\pi_6 = \frac{\mathrm{g}\left(\frac{Ws^2}{g(s-1)}\right)^3}{v^2} = \frac{\mathrm{Ws}^6}{(s-1)^3\mathrm{g}^2v^2}$$ .... *Equation 28*

Combining group π_6 with group π_1 the term becomes

$$\pi_7 = \pi_6\pi_1 = \frac{\mathrm{Ws}^6}{(s-1)^3\mathrm{g}^2v^2}(s-1) = \frac{\mathrm{Ws}^6}{(s-1)^2\mathrm{g}^2v^2}$$

Taking the root of the new group finally gives the non-dimensional settling velocity (*Ws**) proposed by Dietrich (1982) as presented in *Equation 29*.

$$\sqrt{\pi_7} = \frac{\mathrm{Ws}^6}{(s-1)^2\mathrm{g}^2v^2} = \sqrt{\frac{\mathrm{Ws}^6}{(s-1)^2\mathrm{g}^2v^2}} = \frac{\mathrm{Ws}^3}{(s-1)\mathrm{g}v} = dimensionless\ settling\ velocity, Ws^*$$

Equation 29

After substituting the diameter into group π_6 and combining it with group π_1, the functional relationship is described by the groups π_5 and π_7 and becomes

$$\frac{Mb}{Ms} = \phi\ (Re, Ws^*)$$ .... *Equation 30*

Note that groups π_2, π_3 and π_4 were absorbed into the newly derived groups π_5 and π_6 and that groups π_1 and π_6 were included into group π_7.

2.3 NUMERICAL MODELLING

To empirically confirm the relationship found by means of dimensional analysis, a set of values on Reynolds number (*Re*), dimensionless settling velocity (*Ws**) as well as emission and deposition rates of organic carbon (*Mb/Ms*) was needed. Collecting this information as field data is time consuming and costly. In this study, a combination of a validated numerical hydrodynamic flow model (FLOW model) and a particle transport model (WAQ model) from the Delft3D modelling suite were used, to give results on hydrodynamics and deposition rates for pre-defined values for farm emission rates and settling velocities. The model results depend on the underlying assumptions and model settings as demonstrated in sensitivity studies as will be presented in the following sections. *Fig. 2-6* shows the model domain (Pegametan model).

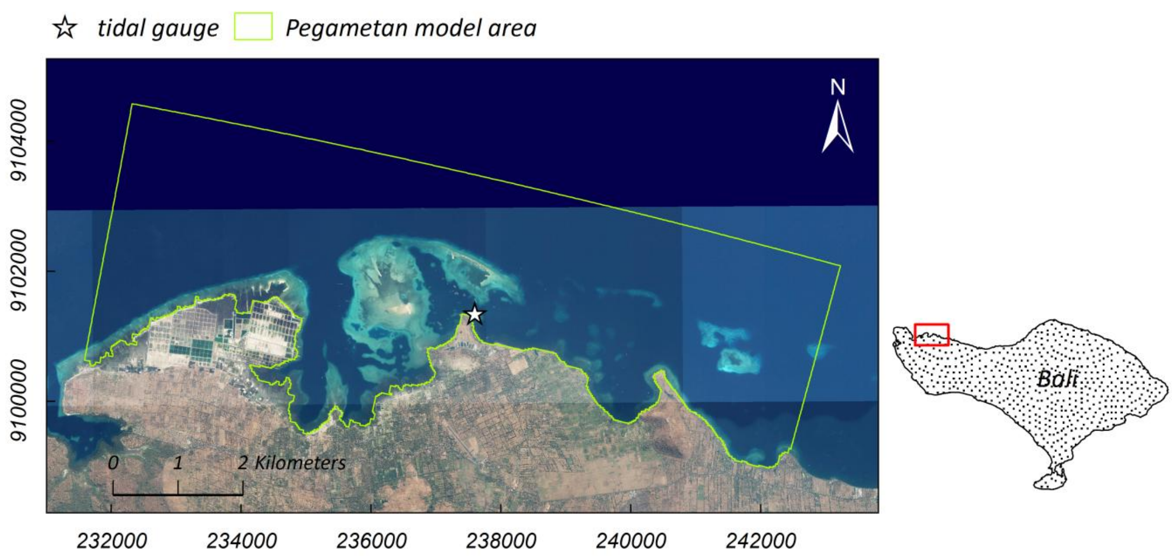

Fig. 2-6 Model domain of the Pegametan model (Satellite imagery: Yahoo maps)

2.3.1 HYDRODYNAMIC FLOW MODEL

The FLOW model solves unsteady momentum equations for incompressible fluid and the continuity equation on a computational grid. Vertically induced acceleration of fluid is neglected; hence the shallow water approximation is imposed on the equations of motion. The variations of water density are not taken into account. The FLOW model solves tide-driven flow including baroclinic and barotropic effects.

The equations describing the flow are the continuity and the momentum equations. The three-dimensional continuity equation for a constant fluid density reads:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \quad \text{Equation 31}$$

where u, v, w are respectively fluid velocities in the x, y and z directions.

The momentum equations in the x, y and z directions are:

$$\frac{\partial}{\partial t}(\rho u)+\frac{\partial}{\partial x}(\rho uu)+\frac{\partial}{\partial y}(\rho uv)+\frac{\partial}{\partial z}(\rho uw)+\frac{\partial p}{\partial x}-\frac{\partial \sigma_{xx}}{\partial x}-\frac{\partial \tau_{xy}}{\partial y}-\frac{\partial \tau_{xz}}{\partial z}-\sum\frac{Fx}{dxdydz}=0 \quad \text{Equation 32}$$

$$\frac{\partial}{\partial t}(\rho v)+\frac{\partial}{\partial x}(\rho vu)+\frac{\partial}{\partial y}(\rho vv)+\frac{\partial}{\partial z}(\rho vw)+\frac{\partial p}{\partial y}-\frac{\partial \tau_{yx}}{\partial x}-\frac{\partial \sigma_{yy}}{\partial y}-\frac{\partial \tau_{yz}}{\partial z}-\sum\frac{Fy}{dxdydz}=0 \quad \text{Equation 33}$$

$$\frac{\partial}{\partial t}(\rho w)+\frac{\partial}{\partial x}(\rho wu)+\frac{\partial}{\partial y}(\rho wv)+\frac{\partial}{\partial z}(\rho ww)+\frac{\partial p}{\partial z}-\frac{\partial \tau_{zx}}{\partial x}-\frac{\partial \tau_{zy}}{\partial y}-\frac{\partial \sigma_{zz}}{\partial z}-\sum\frac{Fz}{dxdydz}=0$$

Equation 34

where

P pressure [Nm^{-2}]

σ terms denote the turbulent pressure [Nm^{-2}]

τ denotes shear stresses [Nm^{-2}]

F body forces arising from gravitational and Coriolis accelerations [N]

Turbulent shear stresses are computed using eddy viscosity determined through the k-Є turbulence model (Deltares, 2014a).

Bed roughness is specified by Manning's roughness coefficient *n*. In the flow model Manning's *n* is converted into local Chezy's coefficient to find the shear stresses acting on the sea bed of the model domain. The bottom shear stress due to flow (τ_{flow}) and the Chezy coefficient for three-dimensional flows (C_{3D}) can be written as:

$$\tau_{flow}=\frac{\rho\cdot g}{C_{3D}^{2}}|u_b|^2 \quad \text{Equation 35}$$

$$C_{3D}=\frac{\sqrt[6]{H}}{n}+\frac{\sqrt{g}}{\kappa}\left(1+ln\left(\frac{0.5\Delta_{zb}}{H}\right)\right) \quad \text{Equation 36}$$

where

τ_{flow} bottom shear stress due to flow [Nm^{-2}]

C_{3D} Chezy coefficient for 3D-flow [$m^{1/2}s^{-1}$]

u_b velocity at the bed layer [ms^{-1}]

H total water depth [m]

κ van Kármán constant [-]

Δ_{zb} thickness of bed layer [m]

The FLOW model of Pegametan Bay is driven by tidal forcing at three open boundaries. Sub-domain decomposition was adopted to permit grid refinements as shown in *Fig. 2-7*. The largest model is driven by astronomic forcing using tidal constituents extracted from the Global Tidal Model (Egbert and Erofeeva, 2002).

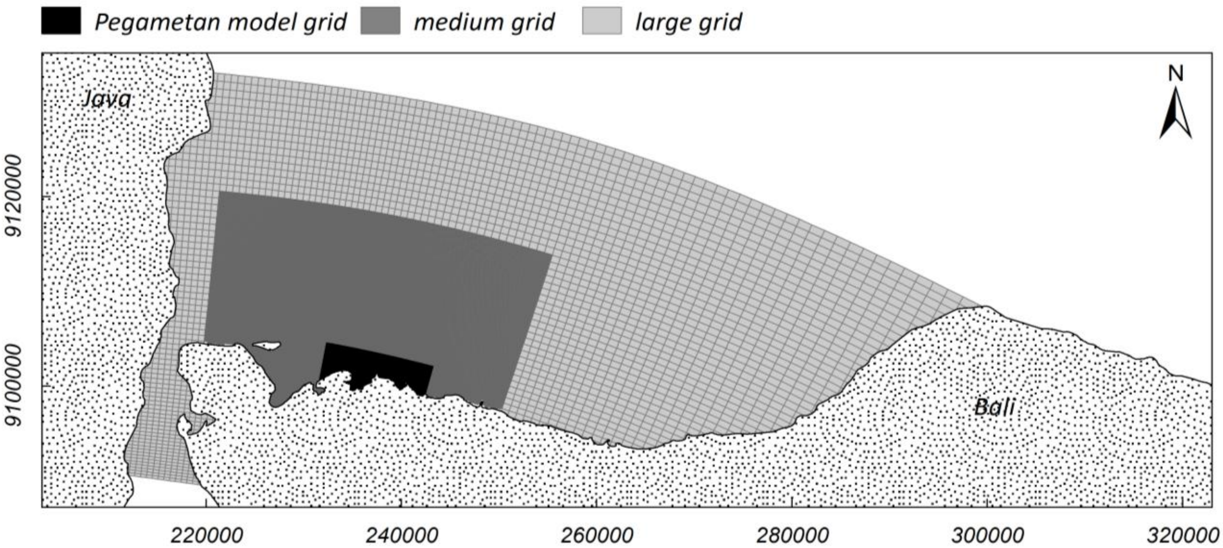

Fig. 2-7 Domain decomposition model sequence for Pegametan model

The 3D grid of the Pegametan model has a horizontal resolution of about 25 m in the vicinity of the fish farms and is vertically divided into 5 sigma-layers, each covering 20 % of the water depth (Deltares, 2014a).

Water depths in the bay were compiled from the General Bathymetric Chart of the Oceans (IOC et al., 2003) and coastal measurements taken by the Indonesian National Survey Authorities (Barkosurtanal, 2008). Near shore data was complemented by field measurements using echo sounder. Space and time varying wind and pressure fields, extracted from the NCEP/NCAR reanalysis database (Kalnay et al., 1996), were imposed.

SENSITIVITY STUDY

Sensitivity studies were performed to estimate the effect of changes in the following model parameters:

Bottom roughness

Bottom roughness was varied using various Manning's roughness coefficients. The velocity is affected by Manning's *n*. Generally, the effect of changes in bottom roughness on the flow is more pronounced at locations with smaller water depth and/or higher flow velocities with larger bed roughness causing smaller flow velocities. Changes in bed roughness have comparably little effect on current directions and no significant effect on water levels.

Wind

The FLOW model was also run with and without the presence of wind. The effect of wind from north-northeast direction with speeds of 4 ms^{-1} and 8 ms^{-1} on water depth and flow velocity has been exemplarily studied. The simulations showed that wind affected current magnitude and direction only in the shallower regions of the study area. Water depth was not significantly affected by wind.

MODEL VALIDATION

FLOW model performance was assessed by comparing computed with the measured water level time series registered at a tidal gauge station located in the model area (*Fig. 2-6*). Water levels were recorded using Cera-Diver® data loggers manufactured by Schlumberger Water Services.

The model used for validation was run with a Manning's roughness coefficient of n = 0.03 $sm^{-1/3}$. This value corresponds typically to a sandy, slightly vegetated bottom and approximately represents the reef environment with coral sands and moderate coral occurrence present in Pegametan Bay. A runtime period of 31 days was considered for validation of the hydrodynamic model. *Fig. 2-8* gives a comparison of measured and computed water level time series.

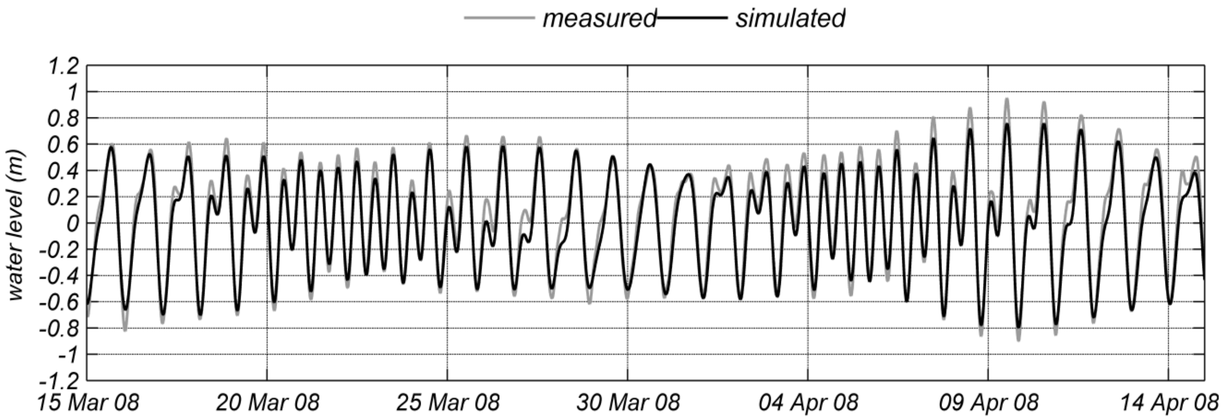

Fig. 2-8 Comparison of modelled to measured water level in Pegametan Bay

Mean deviations (*Bias*) and standard deviations (*Stdev*) of the computed to the measured water levels is given in *Tab. 2-4* for time series and for high and low water levels.

Tab. 2-4 Statistical evaluation of the differences model-measurements for water levels

Time series		*High water*		*Low water*	
Bias (m)	*Stdev (m)*	*Bias (m)*	*Stdev (m)*	*Bias (m)*	*Stdev (m)*
-0.05	*0.07*	*-0.10*	*0.05*	*0.02*	*0.06*

The mean position of the high and low water levels is well captured by the model. The mean low water is slightly overestimated, the mean high water is slightly underestimated. The comparison of the time series shows the correct representation of the tidal curve by the model. Bias and standard deviation lie at or below +/- 0.1 m. Phase shift is 3 minutes for high water and less than one minute for low water.

2.3.2 PARTICLE TRANSPORT MODEL

The particle transport model is based on the water quality model (WAQ model) of the Deft3D modelling suite and solves the advection-diffusion-reaction equation on a computational grid for a wide range of scalar quantities (Deltares, 2014b). In the present work the particulate fish farm wastes are essentially constituted by particulate carbon (POC). The scalar quantity is the carbon content of the waste material in the form of particulates leaving the fish cages.

For the mass transport of a scalar quantity, the following three-dimensional transport equation is solved:

$$\frac{\partial c}{\partial t}+\frac{\partial uc}{\partial x}+\frac{\partial vc}{\partial y}+\frac{\partial (w-w_s)c}{\partial z}-\frac{\partial}{\partial x}\left(\varepsilon_x\frac{\partial c}{\partial x}\right)-\frac{\partial}{\partial y}\left(\varepsilon_y\frac{\partial c}{\partial y}\right)-\frac{\partial}{\partial z}\left(\varepsilon_z\frac{\partial c}{\partial z}\right)=S+f_R(C,t) \quad \text{.... } \textit{Equation 37}$$

where

c mass concentration [gl^{-1}]

ε diffusion coefficients

S sources

$f_R(C,t)$ reaction term

The diffusion coefficient is assumed to be the same as the eddy viscosity which is imported from the FLOW model. In the transport equation the settling velocity of the particles is user-defined. Transport of particulates between the grid cells by flow and diffusion is computed by the WAQ model in combination with the FLOW model.

The WAQ model determines the deposition flux according to Krone (1962) as shown in *Equation 38*.

$$D=w_s c_b\left(1-\frac{\tau_b}{\tau_d}\right) \quad \text{.. } \textit{Equation 38}$$

where

D deposition flux [gCm^{-2}]

c_b suspended sediment concentration near the bed [gCl^{-1}]

τ_b bottom shear stress [Nm^{-2}]

τ_d critical shear stress for deposition [Nm^{-2}]

According to *Equation 38*, the settling of particles on the bed occurs when the bottom shear stress is less than the user-defined critical shear stress for sedimentation. In the 3D model, settling of particulates is important not only in the process of deposition on the sea bed but also in the transport of particulate matter from one computational cell to the one below.

Similarly to the deposition process, particulate matter can be resuspended in the model if the actual bottom shear stress exceeds the user-defined critical shear stress for resuspension. The formula for erosion of bed material is based on Partheniades (1962) and reads as shown in *Equation 39*.

$$E = M\left(\frac{\tau_b}{\tau_d} - 1\right) \qquad \text{Equation 39}$$

where

(*s-1*)

E	erosion flux [gCm^{-2}]

M	first order erosion flux [gCm^{-2}]

τ_e	critical shear stress for erosion [Nm^{-2}]

The eroded material is added to the mass in the water column. The erosion flux is limited by the available amount of sediment on the sea bed.

SENSITIVITY STUDY

In a sensitivity study, the WAQ model was run with different values assigned to model input parameters to get a better understanding of their influence on model results. Discharge points at different locations were separately simulated. The following parameters were considered in the sensitivity analysis:

Emission rate

Emission rates from the discharge points were varied. Deposition increased linearly with increasing emission from the point. The results indicated that the ratio between deposited and emitted material (*Mb/Ms*) stays the same at each location, irrespectively of the value of the emission rate.

Settling velocity

In the model, the settling velocity is necessary to calculate the settling of material through the water column and the sedimentation flux to the sea floor. In this study, the carbon emissions through faeces and waste feed were combined to be considered as single waste fraction with a mean settling velocity. As the material is less dispersed when it's settling speed increases, higher settling velocities lead to higher mean deposition rates below the fish farm points. Correspondingly, the *Mb/Ms* ratio increased with higher settling rates. Depositional area increased with low settling velocities.

Dispersion coefficient

The dispersion coefficient is required to solve the advection-dispersion-equation. It can be defined in the model and is generally used as a calibration factor. Higher horizontal dispersion coefficients increased particle dispersion from the source and reduced the deposition rates below the farm point. Therefore, at each point higher coefficients lead to a reduction of the *Mb/Ms* ratio.

Critical shear stress for sedimentation

The critical shear stress for sedimentation is a user-defined model input and used in the calculation of the deposition flux to the sea bed. Higher values of critical shear for deposition lead to higher deposition rates and higher *Mb/Ms* ratios. Considering *Equation 38*, deposition occurs when the actual bottom shear stress falls below the critical shear stress for sedimentation. With higher critical shear stresses, this is more often the case and hence deposition increases. At locations where flow velocities are very small, the critical shear stresses applied in the sensitivity study were mostly higher than the computed bed shear stress. Therefore deposition was always possible and no difference was seen between the investigated cases.

Resuspension

The effect of resuspension on the deposition rate was checked by comparing simulations with and without resuspension considered in the calculations. The effect of resuspension on the mean net-deposition became noticeable only at few stations where flow velocities are relatively high, causing shear stresses, which exceed the critical shear stress for resuspension. At these locations, inclusion of the resuspension process leads to slightly lower mean net-deposition rates and hence lowers *Mb/Ms* ratios. Lower critical shear stresses for resuspension increase the resuspension flux as the probability increases that critical shear stress is exceeded by the actual bottom shear stress. This way, low critical shear stresses support higher resuspension and lower net-sedimentation rates. Hence, *Mb/Ms* ratios were reduced with decreasing critical shear stresses for resuspension.

MODEL VALIDATION

The model simulates the deposition of POC to the sea floor. No measurements of carbon deposition were available to directly compare calculated and measured deposition rates to validate the model performance of the WAQ model.

2.3.3 EXPERIMENTAL MODEL SET UP

To generate data for confirmation of the derived relationships, deposition rates of POC (*Mb*) were simulated at thirty locations of different hydrodynamic character, defined by the average Reynolds number (*Re*), as shown in *Fig. 2-9*.

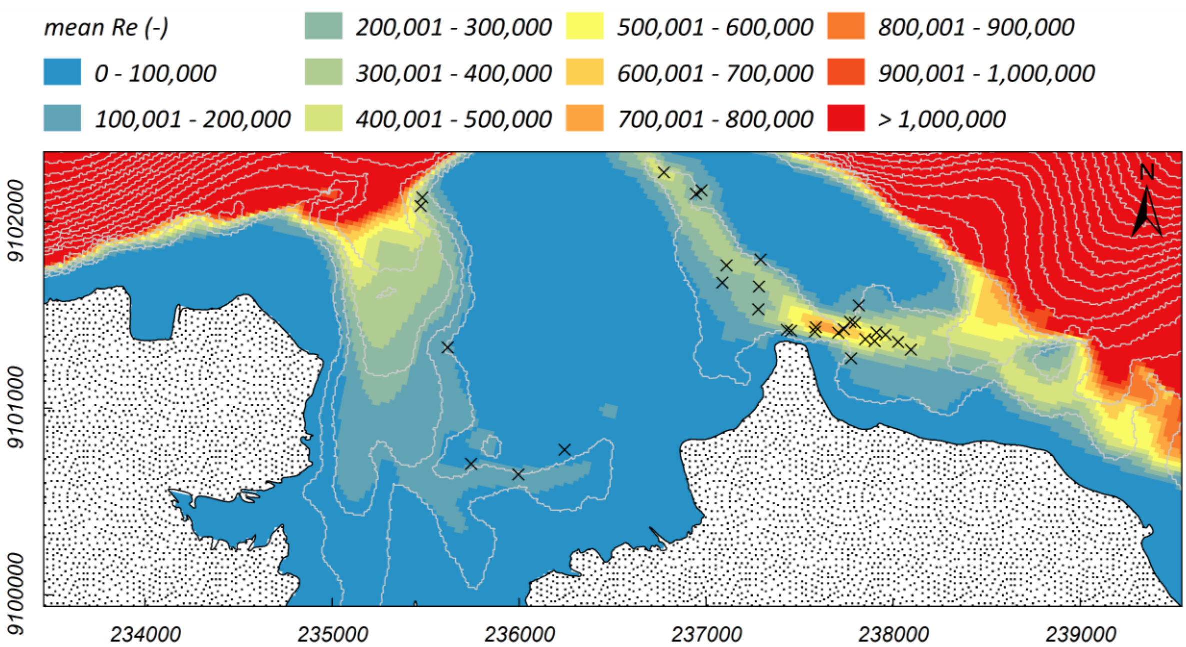

Fig. 2-9 Thirty discharge points (x) at locations with different average Reynolds number (Re at n = 0.03 sm$^{-1/3}$)

Mean simulated water depths at the 30 points vary between 6.2 and 18.7 m, and mean depth-averaged velocities range between 0.009 and 0.06 ms^{-1}. Average Re values at the points lay between 70,000 and 770,000 for n = 0.02 sm$^{-1/3}$ and 63,000 and 690,000 for n = 0.03 sm$^{-1/3}$.

Tab. 2-5 summarizes the settings of the FLOW model used to calculate the water levels and the flow field in Pegametan Bay. Simulations with different Manning's roughness coefficients were carried out. Cage effects upon water flow were ignored.

Tab. 2-5 Parameters and settings used in the Pegametan Bay FLOW model

Parameter	*Value*	*Unit*
Vertical layers	*5*	*-*
Layer thickness	*20*	*% of total water depth*
Time step	*0.05*	*min*
Water density	*1024*	*kgm^{-3}*
Manning roughness coefficient	*0.02, 0.03*	*$sm^{-1/3}$*
Horizontal eddy viscosity	*1*	*m^2s^{-1}*
Model for 3D turbulence	*k-Epsilon*	*-*

In the Pegametan WAQ model, the particulate organic fish farm waste is represented by its carbon fraction (POC) with a specific average constant settling velocity (*Ws*). Separate WAQ models were run considering different *Ws*, corresponding to different values of *Ws**. The waste is released from the surface at discharge points covering one grid cell. The discharge from a fish farm is considered as POC concentration at a constant rate (*Ms*). In this study, mineralisation of carbon and reduction of POC by wild feeding in the water column was not considered. Critical shear stress for deposition was assumed to be 0.004 Nm^{-2} after Cromey et al. (2002). This study exclusively considers the sedimentation process; flocculation and hindered settling were not taken into account. Processes in the deposited sediment layer such as consolidation, burial or bioturbation were also not considered. As the prevailing flow velocities at the points chosen in Pegametan Bay are low, the effect of resuspension is considered to be small. Therefore, in a first step, the method is developed without considering sediment motion due to resuspension.

Interaction between releases from different locations was avoided; the model was run with discharge of waste from one location at a time. Computation was carried out using FLOW model results with different Manning's roughness coefficients. To consider the effect of different average settling velocities, a range between 0.01 and 0.10 ms^{-1} was investigated in this study. *Tab. 2-6* summarises the settings of the WAQ model.

Tab. 2-6 Parameters and settings used in the Pegametan Bay WAQ model

Parameter	*Value*	*Unit*
Vertical layers	*5*	*-*
Layer thickness	*20*	*% of total water depth*
Time step	*15*	*min*
Horizontal dispersion coefficient	*0.1*	*m^2s^{-1}*
Range of average settling velocities	*0.01 - 0.1*	*ms^{-1}*
Critical shear stress for deposition	*0.004*	*Nm^{-2}*

The models were run over a period of about 15 days, covering one neap to neap tidal cycle. All averaged values are based on this period.

2.4 CONSOLIDATION OF RESULTS FROM DIMENSIONAL ANALYSIS AND NUMERICAL MODELLING

The results of dimensional analysis and numerical modelling were combined, by presenting the model results in the relationship found by dimensional analysis. Multiple regression was performed considering simulated *Mb/Ms* ratios and corresponding values of *Re* and *Ws**. The resulting equations describe the functional relationship between *Re, Ws** and *Mb/Ms* ratio and form the basis of the developed method.

The functional relationship found by combination of results of dimensional analysis and numerical modelling was used to calculate *Mb/Ms* ratios within the Pegametan Bay model area. A spatial representation of the *Mb/Ms* ratios in Pegametan Bay was created by considering average *Re* values, based on simulated hydrodynamic information.

2.5 ESTIMATION OF THE ASSIMILATIVE CAPACITY IN PEGAMETAN BAY

To ensure sustainable operation of a fish farm, the deposition rate of organic carbon (*Mb*) must not exceed the bacterial decomposition rate of carbon. Otherwise accumulation of organic waste leads to deterioration of sediment quality. A crucial part of the developed method is therefore the definition of a threshold value for POC deposition. The capability of the environment to assimilate wastes is probably not a constant, but may vary with space and time. Site specific estimates on bacterial decomposition over the seasons are necessary to make predictions based on the presented method effective.

At the time of this study, no information on the assimilative capacity of the benthic environment in Pegametan Bay was available. To define an appropriate threshold value for POC deposition for Pegametan Bay, simulated deposition rates were compared to measurements of sulphide concentration and redox potential as indices for the degree of organic matter sedimentation. For this purpose, a particle transport model (WAQ model) was set up to simulate POC deposition rates resulting from the existing farm arrangement in Pegametan Bay (see *Fig. 2-2*). Model settings were set according to the settings described in *Tab. 2-5* (with n = 0.03 $sm^{-1/3}$) and *Tab. 2-*

6 (with Ws = 0.04 ms^{-1}) in Section 2.3.3. Farm dimensions and emission rates were defined according to *Tab. 2-1* and based on information given in *Tab. 2-2* in Section 2.1.

For the methods applied to sediment sampling and analysis, please refer to Section 2.8 in this chapter.

2.6 ESTIMATING HOLDING CAPACITIES FOR EXISTING FISH FARMS IN PEGAMETAN BAY

The maximum allowable POC emission rates from the fish farm (Ms_{max}) were estimated using Mb/Ms ratio as shown in *Equations 40* and *41,* where Mb represents the threshold value for POC deposition.

$$X = \frac{Mb}{Ms} \qquad \text{Equation 40}$$

$$Ms_{max} = \frac{Mb}{X} \qquad \text{Equation 41}$$

Including production data such as cage dimensions, feed type and fish metabolism, Ms_{max} was translated into maximum holding capacity in terms of stocking density. As stocking densities encountered in a farm may be variable over time and farm area, the resulting stocking densities were defined to represent average values.

For grouper, reared in net cages with production characteristics according to *Tab. 2-2* in Section 2.1, the spatial distribution of maximum allowable average stocking densities in Pegametan Bay were produced considering *Equations 7* to *12* in Section 2.1. To derive the maximum average stocking density, stocking density (*SD*) was raised until carbon emissions from the farm (C_{FF}) exceeded the maximum emission rate (Ms_{max}). Maximum average stocking densities were restricted by the highest stocking density with respect to fish health (7 kgm^{-3}, see Section 2.1 and *Tab. 2-2*).

Maximum average stocking densities found at a location were used in combination with farm dimensions to estimate the holding capacity of the farm. Farm dimensions of the existing cage farms were taken according to *Tab. 2-1* in Section 2.1. The holding capacity of a farm was estimated considering the average of the maximum average stocking densities within the farm area. To assess if existing farms in Pegametan Bay operate within the ecological carrying capacity of their location, assumed existing standing stocks, as given in *Tab. 2-1*, were compared to calculated holding capacities.

2.7 PROPOSAL OF A FISH FARM ARRANGEMENT AND ESTIMATION OF THE ECOLOGICAL CARRYING CAPACITY IN PEGAMETAN BAY

In this application example it was assumed that there were no farms existing in the bay and the method was used to propose an optimal farm arrangement. In a first step, a suitability analysis was performed to define physically suited areas. Then fish farms were arranged with respect to the highest maximum average stocking density and for each farm location the holding capacity was defined.

The projected type of mariculture was assumed to be cage mariculture for the grow-out of grouper species, as defined in Section 2.1. It was assumed that the planned farm type is the common type, using square net cages of approximately 3x3x3 meters. The anticipated farm size was set to a farm with 100 net cages, which is close to the average cage number of the existing farms in Pegametan Bay (137 cages).

Typically, the farms are composed of units containing 20 cages, where five units are tied together to form a 100 cages combination (*Fig. 2-10*).

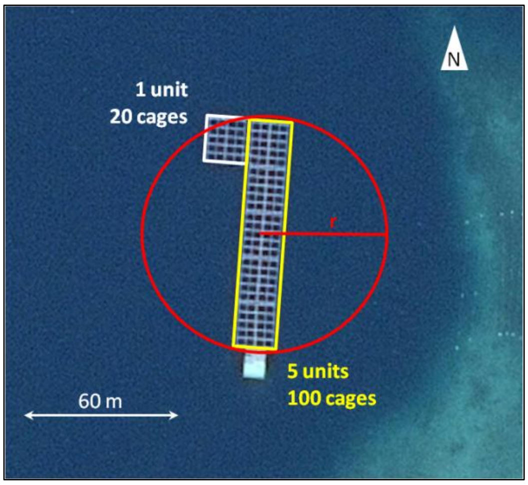

Fig. 2-10 Cage farm of 120 cages and corresponding circular potential farm area for a farm with 100 cages (5 units) (Google Earth Image ©2016 CNES / Astrium)

To avoid fluid interference between the cage cluster, cages should be placed normal to the main current direction (Løland, 1993). This implies that, to provide best possible flushing, the cage combination should face the main current direction with its longest side. However, other factors such as mooring conditions and accessibility can influence the orientation of the farm set-up. In this study the exact positions of the potential farms were not determined as this accuracy is taken to be inappropriate, considering the possible variations of the farm set-up. Instead, the study applied a circular potential farm area with the radius (*r*) of half the length of the longest side of the cage combination.

2.7.1 SUITABILITY ANALYSIS

The identification of suitable locations is an essential task for a successful mariculture operation. Site selection should be carried out in accordance with sustainability, resilience and best practice guidelines where environmental, social and economic aspects need to be considered (Ross et al., 2013). The following parameters were included in the suitability study for Pegametan Bay:

WATER DEPTH

Cages should be sited in sufficient depth to keep the cage volume constant and to facilitate water exchange. On the other hand, siting in very deep water should be avoided to prevent high mooring costs.

CURRENT VELOCITY

Good water exchange by currents is essential for oxygen supply and to minimize waste accumulation below the cages. On the other hand, excessive currents cause strain on the farm structures and can adversely affect fish health due to stress.

WAVE HEIGHT

Waves should be considered in mariculture siting because high waves can cause unfavourable operating conditions or even damage the cage structures.

WATER QUALITY

Good water quality is essential for a successful culture of the farmed fish as insufficient water quality adversely affects the growth and health of the fish. Each cultured species has an optimal temperature and salinity range and suffer of stress under sub-optimal conditions or during strong fluctuations. Fish need oxygen for energy production and hence require a certain concentration of dissolved oxygen. The necessary concentration depends on the farmed species and on environmental conditions such as temperature and salinity. High concentrations of

Ammonium, Nitrite and Nitrate can be toxic for the fish and should be avoided. The toxicity of pollutants can be affected by pH and extreme values of pH can negatively affect stocked fish. Phosphate concentrations have to be considered to prevent the excessive growth of phytoplankton which causes oxygen depletion. High concentrations of suspended sediments should be avoided as they can reduce the efficiency of fish gills and impede feeding on sight.

COASTAL USE AND SERVICES

Placement of fish farms in a coastal area needs to consider the dedication of coastal waters to other uses such as fishing, tourism or nature conservation. For practicable mariculture operation, the accessibility to broodstock and feed, the proximity to markets as well as the existence of harbours and shore facilities should be considered.

Suitability criteria were applied according to *Tab. 2-7* on the basis of values found in literature .

Tab. 2-7 Suitability criteria for grouper mariculture

Indicator	*Parameter*	*Unit*	*Allowable*	*Optimum*	*Source*
Physical	*Minimum water depth*	*m*	*> 10*		*1*
	Maximum water depth	*m*	*< 30*		*1*
	Minimum (mean) current	*m/s*	*> 0.01*	*> 0.05*	*1*
	Maximum (mean) currents	*m/s*	*< 0.5*	*< 0.2*	*1*
	Exposure to maximum waves	*m*	*< 1*	*< 0.5*	*1*
Water quality	*Water temperature*	*°C*	*27 – 31*		*2*
	Salinity	*PSU*	*10 – 33*	*15*	*2*
	Dissolved oxygen	*mg/l*	*> 4*	*> 5*	*2*
	pH	*log H+*	*7-8.5*		*2*
	Secchi depth	*m*	*1-5*		*1*
	NH_4-Ammonium	*mg/l*	*< 1*	*< 0.5*	*1*
	NO_2-Nitrite	*mg/l*	*< 4*		*2*
	NO_3-Nitrate	*mg/l*	*< 200*		*2*
	PO_4-Phosphate	*mg /l*	*< 70*		*2*
	Suspended sediment	*mg/l*	*< 10*		*2*
Coastal use & risk	*Distance to harbours*	*km*	*> 0.5 , < 8*		*3*
	Distance to navigation lines	*km*	*> 0.5*		*4*
	Distance to touristic areas	*km*	*> 0.3*	*> 2.5*	*5*

1 (Halide et al., 2008b), 2 (UNDP/FAO, 1989), 3 (Perez et al., 2005), 4 (MARITIME New Zealand, 2005), 5 (Pérez et al., 2003).

According to the criteria in *Tab. 2-7,* information on the parameters is classified into 'Suitable' (2), 'Allowable' (1) or 'Unsuited' (0) to give suitability grids for each parameter. To define the overall suitability, a grid overlay was performed with all parameter grids by averaging the suitability scores. Once a grid cell was found unsuited with respect to one of the parameters, the overall score was declared unsuited.

Physical information including the hydrodynamic parameters water depth, current velocity was drawn from results of the numerical FLOW model introduced in Section 2.3.1. Maximum significant wave heights were simulated using the Delft3D WAVE module. The WAVE module simulates wind-generated waves in coastal waters by computing wave propagation and wave generation by wind, non-linear wave-wave interactions and dissipation of waves (Deltares, 2014c). The module by default uses the third-generation SWAN model (Simulating WAves Nearshore,) to simulate the evolution of random, short-crested wind-generated waves (Booij et al., 1999; Ris et al., 1999). The results are presented as significant wave height which is defined as the average of the highest one-third of the waves.

To retrieve maximum significant wave heights in Pegametan Bay, a wind event was simulated which occurred at the north coast of Bali in March 2012. The event can be defined as a strong breeze with over 11 ms^{-1} during its peak on 15. March 2012. For wave simulation, online wave coupling was applied. In this case, a FLOW and WAVE model are run in parallel and information is exchanged during the simulation. This way, flow-wave interaction was taken into account. The WAVE model ran on one grid covering the whole domain decomposition area (see *Fig. 2-7*) with a resolution of 60 meters. The temporal resolution was 15 minutes. Topography of the WAVE model was generated using GEBCO (resolution 0.9 km, (IOC et al., 2003)). At the open model boundaries, astronomical tidal constituents based on TPXO (Egbert and Erofeeva, 2002) and wind data from the global GME model (Majewski and Ritter, 2002) were defined. No swell was considered, hence only wind generated waves were simulated.

2.7.2 FARM PLACEMENT AND ECOLOGICAL CARRYING CAPACITY

Farm placement within the suitable area was done by finding the best locations with respect to the maximum stocking density, determined by means of the developed method under the consideration of specific values for *Ws* and *Mb*. The found coordinates were taken as the centre points of the farms off which the potential farm area was defined using the radius *r* (see *Fig. 2-10*). The holding capacity of each farm area was defined by the mean of the maximum stocking densities within the potential farm area and the assumed farm dimensions (100 cages). The sum of the according standing stocks results in the overall ecological carrying capacity of the bay with respect to the deposition of POC to the sea floor.

To prevent mutual effects of waste deposition from different farms, buffer distances between the farms were defined. Being dependent on the complex interrelation of temporally and spatially variable parameters such as velocity and bed topography, the spatial extend of the impacted area (footprint area) by fish farm wastes is difficult to be accurately determined. To get an approximation of the appropriate buffer distances in Pegametan Bay, the advective transport distance (D_A) of mariculture wastes was estimated using water depth (h), maximum flow velocity (V_{max}) and settling velocities (Ws) ranging from 0.02 ms^{-1} to 0.1 ms^{-1}.

$$D_A = \frac{hV_{max}}{Ws} \quad \text{Equation 42}$$

Maximum advective transport distances in the suitable area are below 250 m. Taking a conservative approach, buffer distances were set to 300 m.

2.8 SEDIMENT SAMPLING AND ANALYSIS

Sediment samples were taken below the farms in Pegametan Bay to identify a threshold value for POC deposition at which the values of measured indices start to deviate from values found at unaffected reference sites (see Section 2.5). Furthermore, results of the sediment analysis were used to investigate, if compliance or exceedance of calculated holding capacities (see Section 2.6) can be detected in the sediment quality, and hence if the assessment can be verified.

The impact of organic matter deposition from fish farms on the underlying sediment can be estimated from geochemical sediment parameters. Redox potential and sulphide concentration in sediments are directly related to microbial activity and are suitable parameters to detect changes from aerobic to anaerobic conditions. Increasing sulphide concentrations and decreasing redox potential were found to identify organic matter enrichment and hence these parameters were defined to be appropriate indicators to anticipate changes in sediment quality due to fish farm organic deposits (Brooks and Mahnken, 2003; Hargrave, 2005; Hargrave et al., 2008; Wildish et al., 1999). The concentration of particulate organic nitrogen (PON) and POC additionally give information on particulate organic matter content and availability in the sediment.

Sediment samples were collected in Pegametan Bay in November 2015 and January 2016 below 12 fish farms and at reference stations at distances of > 100 meters away from the farms. Additionally, underwater video recordings were taken of selected locations.

Samples were taken as sediment cores by divers, using 20 cm long PVC tubes with a diameter of 8 cm. The samples were closed with lids to be undisturbed when brought vertically to the surface (*Fig. 2-11*). Two to eight samples were taken below each farm. Probes were employed to measure sulphide concentrations and redox potential in a sediment depth of 2-3 cm.

Fig. 2-11 Diver with sediment sample in PVC tube (left). Samples were analysed with Probes immediately after the sample was obtained (right) (Photos: K.-H. Runte 2015)

Material of the undisturbed sediment surface was dried (*Fig. 2-12*) and used for CN analysis for the determination of the content of PON and POC. After sampling, the tube was removed to register grain size, consistency, colour and smell of the sample.

Fig.2-12 Drying sediment samples (left). Removal of the tube after sampling (right) (Photos: K.-H. Runte 2015)

3 RESULTS

In this chapter, results of dimensional analysis and model simulations are presented. The dependence of the ratio between settled and emitted material (*Mb/Ms*) on *Re*, *Ws** and n is expressed in the form of empirical equations.

Results of sediment analysis are compared to simulated deposition rates to estimate the threshold for carbon deposition, before sediment quality starts to deviate from ranges measured in the reference samples.

The found relation is used to estimate the holding capacity of existing fish farms in Pegametan Bay. Actual standing stock is assessed and compared to estimated holding capacities. An application example is presented which proposes a fish farm arrangement adjusted to the ecological carrying capacity in Pegametan Bay. Finally, results of sediment analysis are presented.

3.1 DIMENSIONAL ANALYSIS

Dimensional considerations on the fate of particulate organic farm wastes show that the *Mb/Ms* ratio is a function of *Re* and the settling velocity of waste which is represented by the dimensionless settling velocity *Ws**. The functional relationship can be expressed as follows:

$$\frac{Mb}{Ms} = \phi\ (Re, Ws^{*})$$ .... *Equation 43*

Re describes the ratio of inertial to viscous forces and is a measure for the degree of turbulence as shown in *Equation 44*. Inertial or accelerating forces are expressed by a characteristic water depth (*h*) and flow velocity (*V*). The viscous or shear force is represented by the kinematic viscosity of water (*v*).

$$Re = \frac{Vh}{v}$$ .... *Equation 44*

Low *Re* numbers indicate laminar flow where viscous forces are dominant and the fluid motion is smooth and constant. High *Re* values indicate turbulent flow which is dominated by inertial forces and characterised by eddies, vortices and random velocity fluctuations which cause turbulent mixing. Most natural flows are turbulent. The higher *Re* the larger the dispersion of particulates in the water. In this study, *Re* is defined as average value based on mean depth-averaged flow velocity and mean water depth and is taken to represent the mean dispersive conditions at a location.

The dimensionless settling velocity *Ws** is expressed after Dietrich (1982) considering the settling velocity of particulate wastes (*Ws*), relative density (*s-1*), kinematic viscosity of water (v) and gravitational acceleration (g) as shown in *Equation 45*.

$$Ws^* = \frac{\mathrm{Ws}^3}{(\mathrm{s}-1)\mathrm{g}\nu} \quad \text{Equation 45}$$

*Ws** is derived assuming a constant average *Ws* of the particulate waste fraction (including waste feed and faeces) of the fish farm. The variables v, g and $(s-1)$ are set to constant values of $1*10^{-6}$ m^2s^{-1}, 9.81 ms^{-2} and 1.65 respectively.

3.2 NUMERICAL MODELLING

The FLOW model was used to simulate the hydrodynamic conditions of a neap to neap tidal cycle in Pegametan Bay for different values of bottom roughness (*n*). *Fig. 3-1* exemplarily presents average *Re* values within the model domain calculated from simulated mean depth-averaged flow velocities and mean water depths (*n* = 0.03 $sm^{-1/3}$).

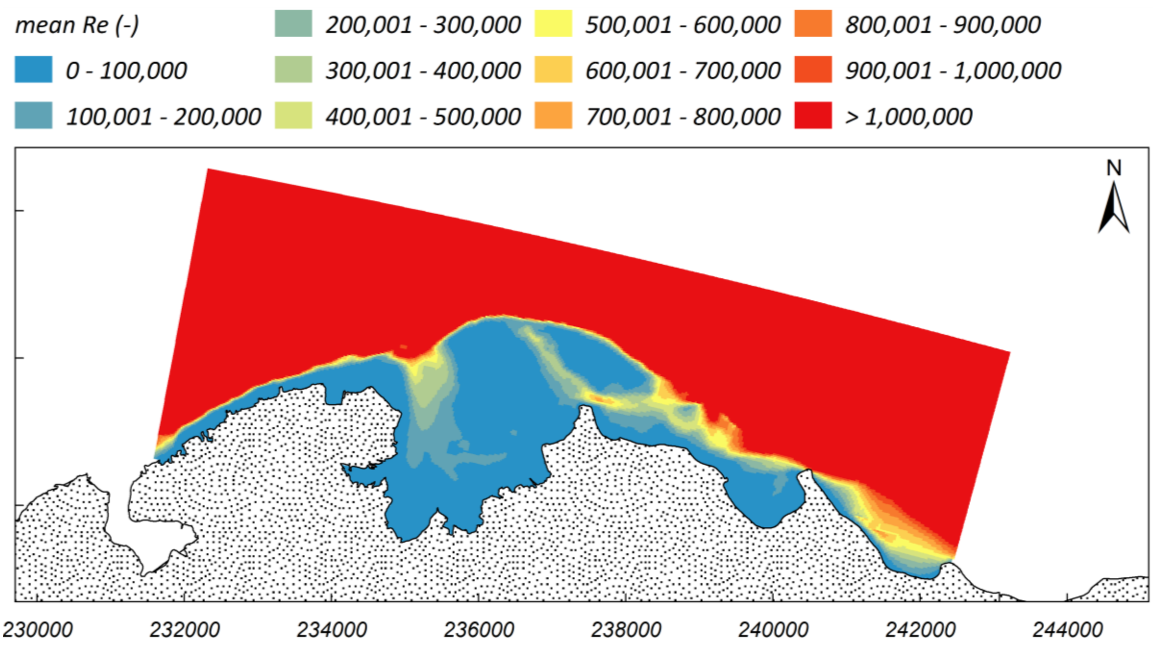

Fig.3-1 Average Reynolds numbers based on simulated hydrodynamics in Pegametan Bay (n = 0.03 $sm^{-1/3}$)

In the inner Pegametan Bay, resulting *Re* values are below 100,000 in the reef area and between 100,000 and 900,000 in the channels. Outside the reef-channel areas *Re* values are larger than 900,000.

A WAQ model was used in conjunction with a FLOW model to simulate the deposition rates of POC being discharged from 30 locations of different dispersive character, expressed by average *Re*. The model was run for a range of *Ws** corresponding to *Ws* values of 0.01 to 0.10 ms^{-1}. *Fig. 3-2* exemplarily shows computed POC deposition rates at two locations with different average *Re*.

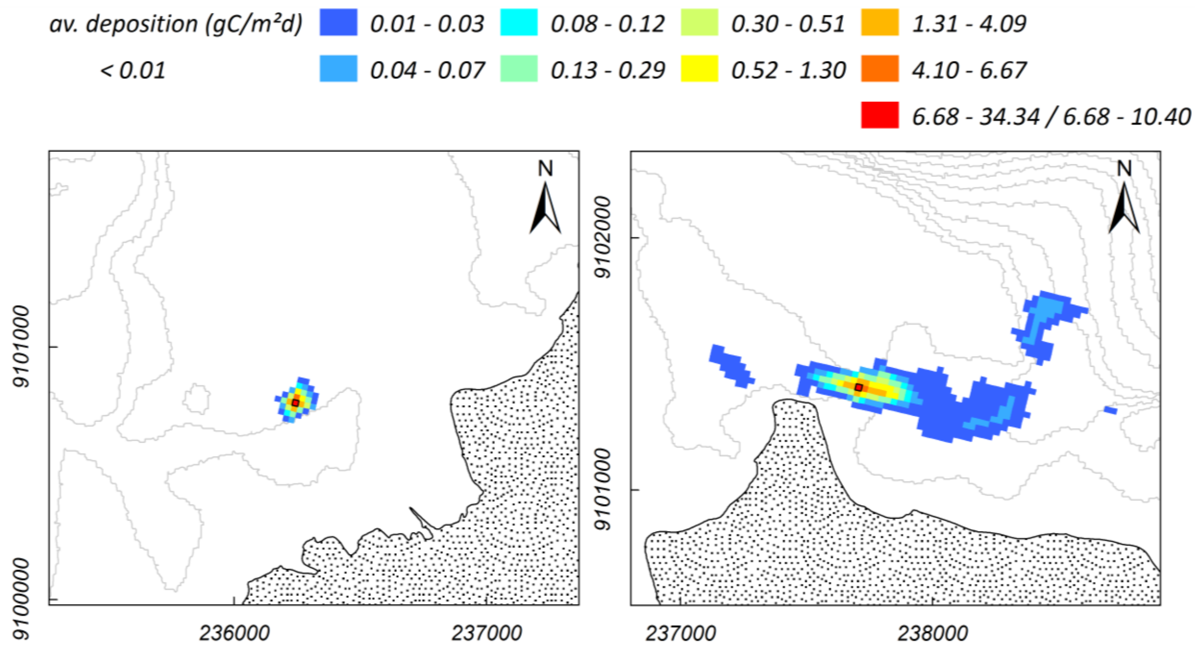

Fig.3-2 Computed mean sedimentation rates of POC with a constant average settling velocity of 0.01 ms^{-1} at two discharge locations characterized by relatively low (left) and high (right) average Re (n = 0.03 $sm^{-1/3}$). Discharge locations are indicated by framed squares. Please note different maximum deposition for low Re (34.3 $gCm^{-2}d^{-1}$) and high Re (10.4 $gCm^{-2}d^{-1}$).

At the location with relatively high average *Re* (679,430), POC is spread over large area in comparison to the location with low average *Re* (62,898). The highest average deposition rate occurs directly underneath the discharge (farm) point, irrespective of *Re*. For further analysis, POC deposition rate (*Mb*) is defined to be the highest average deposition rate in the affected area. *Fig. 3-3* exemplarily presents the simulated *Mb* values at thirty investigated points for a mean settling velocity of 0.04 ms^{-1} together with average *Re* values based on n = 0.03 $sm^{-1/3}$. The graph shows that for given values of *Ws** and *n, Mb* generally decreases with increasing *Re*.

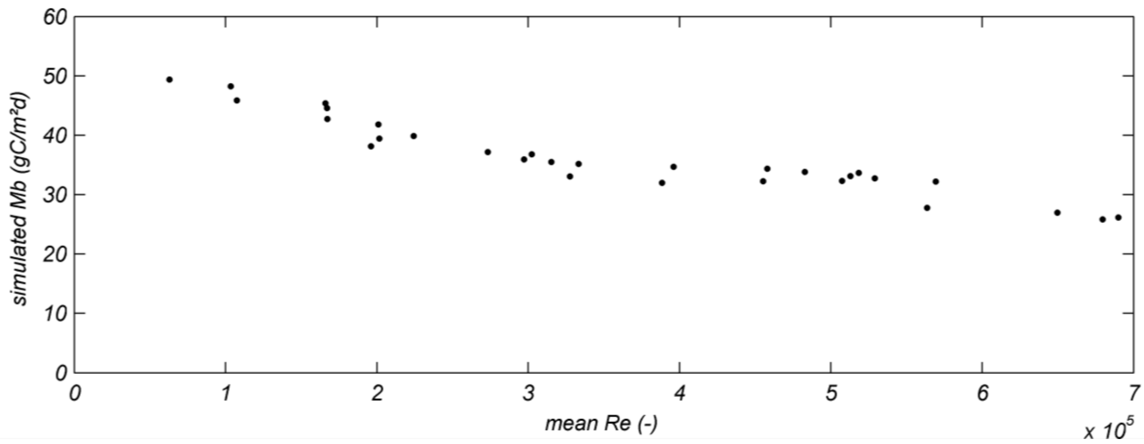

Fig.3-3 Computed maximum average sedimentation rates (Mb) of particles with a constant average settling velocity of 0.04 ms^{-1} at points of different Re (n = 0.03 $sm^{-1/3}$)

3.3 CONSOLIDATION OF RESULTS FROM DIMENSIONAL ANALYSIS AND NUMERICAL MODELLING

The results of dimensional analysis and numerical modelling are combined by presenting the model results in the relationship found from dimensional considerations. *Fig. 3-4* shows the relation of *Mb/Ms* ratio to *Re* at 30 stations for different *Ws**. Each of the graphs in the figure pertains to a constant value of *n*. The *Mb/Ms* ratios are calculated from the model results. *Mb* is defined to be the simulated maximum average daily deposition rate occurring in the area affected by particulate carbon deposition. *Ms* is the pre-defined discharge rate from the discharge point in the model. *Re* values represent the average *Re* values at the discharge points in the model.

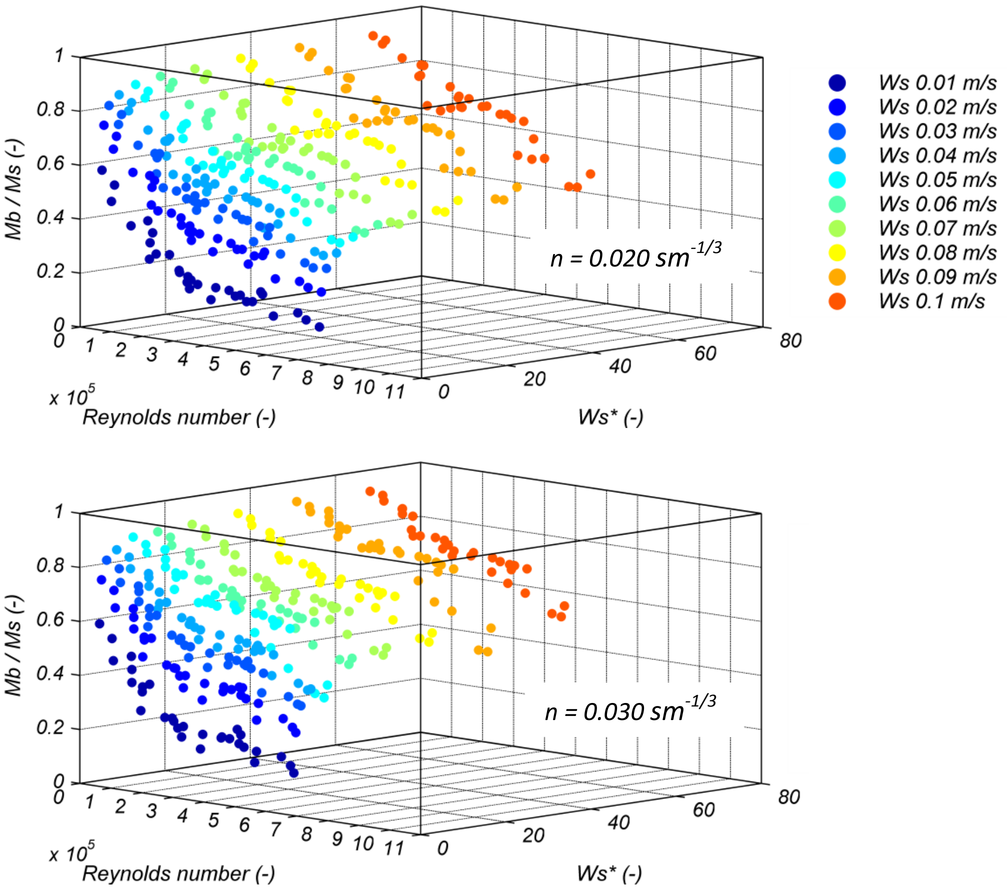

Fig.3-4 Simulated ratio of settled and emitted organic carbon (Mb/Ms), average Reynolds number (Re) and non-dimensional average settling velocity (Ws) for different Manning roughness (n). Ws* is additionally presented as Ws (colour scale) for easy graphical interpretation.*

The non-dimensional presentation as shown in *Fig. 3-4* is successful in bringing the parameters into a meaningful relation. As *Mb* increases with decreasing *Re, Mb/Ms* ratios increase with decreasing *Re*. At a location of specific *Re*, increasing *Ws** causes higher *Mb* and hence larger *Mb/Ms* ratios. Higher roughness in terms of increased *n* values, generally leads to decreased flow velocities and thereby reduces *Re* and simultaneously increases *Mb/Ms* ratios.

The dependence of *Mb/Ms* on *Re, Ws** and *n* as shown in *Fig. 3-4* is expressed in the form of empirical equations. Multiple regression analysis was performed to arrive at the equations in the following form:

$$\frac{\mathrm{M_b}}{\mathrm{M_s}} = -0.4472 \cdot \log(\mathrm{Re}) + 0.1525 \cdot \log(\mathrm{Ws^*}) + 2.9557 \qquad \text{......................... } \textit{Equation 46}$$

for n = 0.020 $\mathrm{sm}^{-1/3}$

$$\frac{M_b}{M_s} = -0.3797 \cdot \log(Re) + 0.1587 \cdot \log(Ws^*) + 2.6113 \qquad \text{............................ } \textit{Equation 47}$$

for *n* = 0.030 $sm^{-1/3}$

The equations are limited to:

$$\frac{M_b}{M_s} = \min(1, \max(0, -A \cdot \log(Re) + B \cdot \log(Ws^*) + C)) \qquad \text{............................... } \textit{Equation 48}$$

where A, B and C are the constants for different values of *n*.

Fig. 3-5 shows predicted and simulated *Mb/Ms* values for different values of *n*. The coefficient of determination is 0.9 and the root mean square error is 0.05 for both cases of *n*.

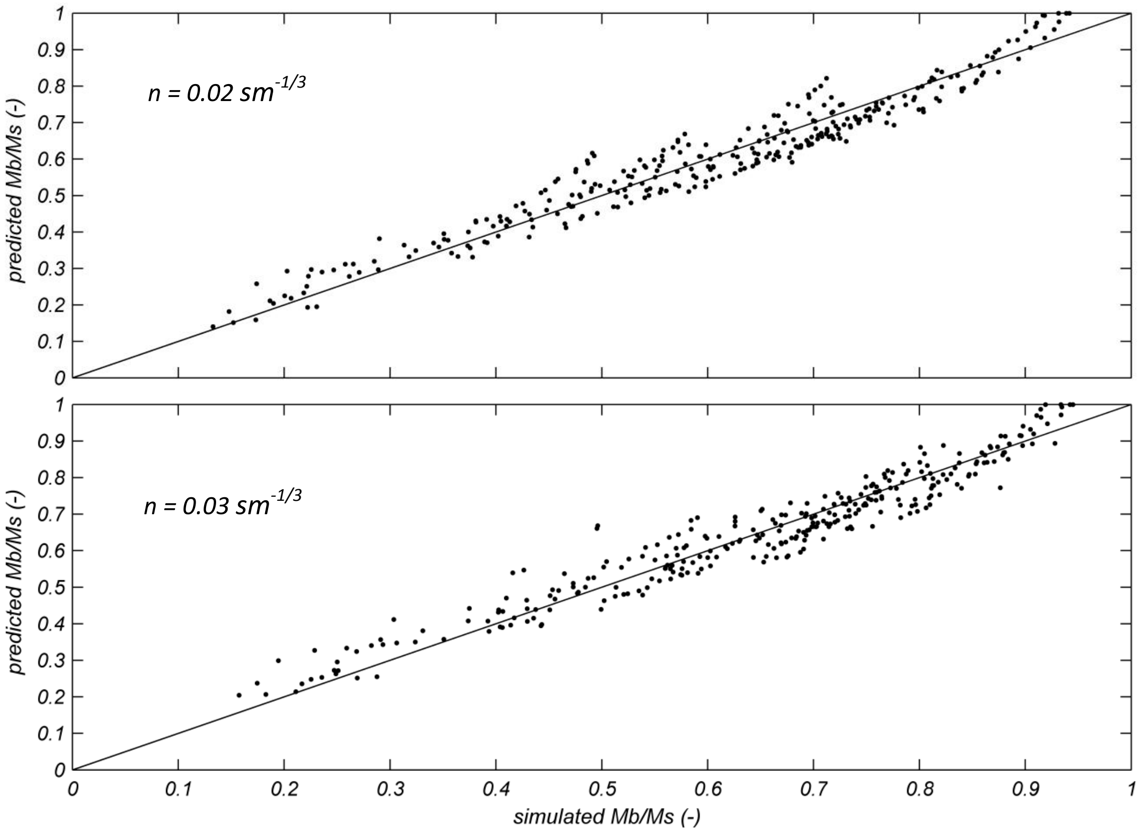

Fig.3-5 Simulated and predicted ratio of settled and emitted organic carbon (Mb/Ms), for different Manning roughness (n)

3.4 ESTIMATION OF THE ASSIMILATIVE CAPACITY IN PEGAMETAN BAY

The assimilative capacity of the benthic environment for organic matter enrichment is expressed by a threshold value for POC deposition. To define such a threshold value for Pegametan Bay, comparison of sediment quality measurements to simulated maximum mean deposition rates was made. For this purpose a particle transport model (WAQ model) was set up to simulate POC deposition rates resulting from the existing farm arrangement in Pegametan Bay. *Fig 3-6* presents the simulated average deposition rates.

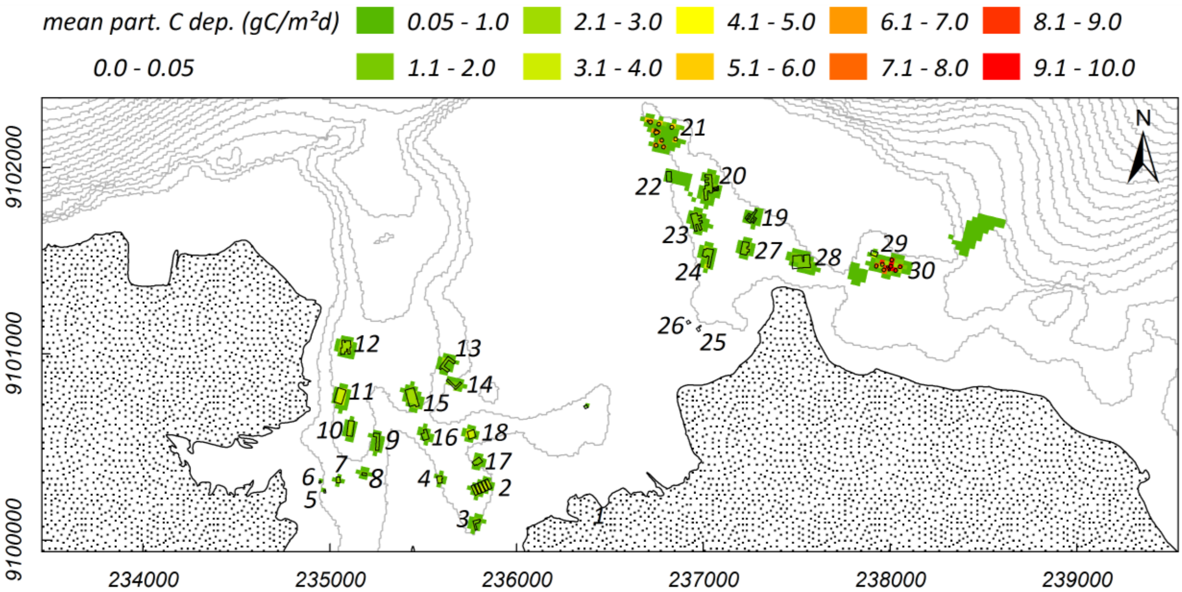

Fig. 3-6 Simulated average POC deposition rates below existing cages farms in Pegametan Bay

Average POC deposition rates directly below the farms range between 1 and 10 $gCm^{-2}d^{-1}$. Simulated maximum average POC deposition rates were compared to sediment sulphide concentration and redox potential observed in the sediments below the farms in Pegametan Bay. *Fig. 3-7* shows simulated carbon deposition rates together with measured values of the analysed parameters.

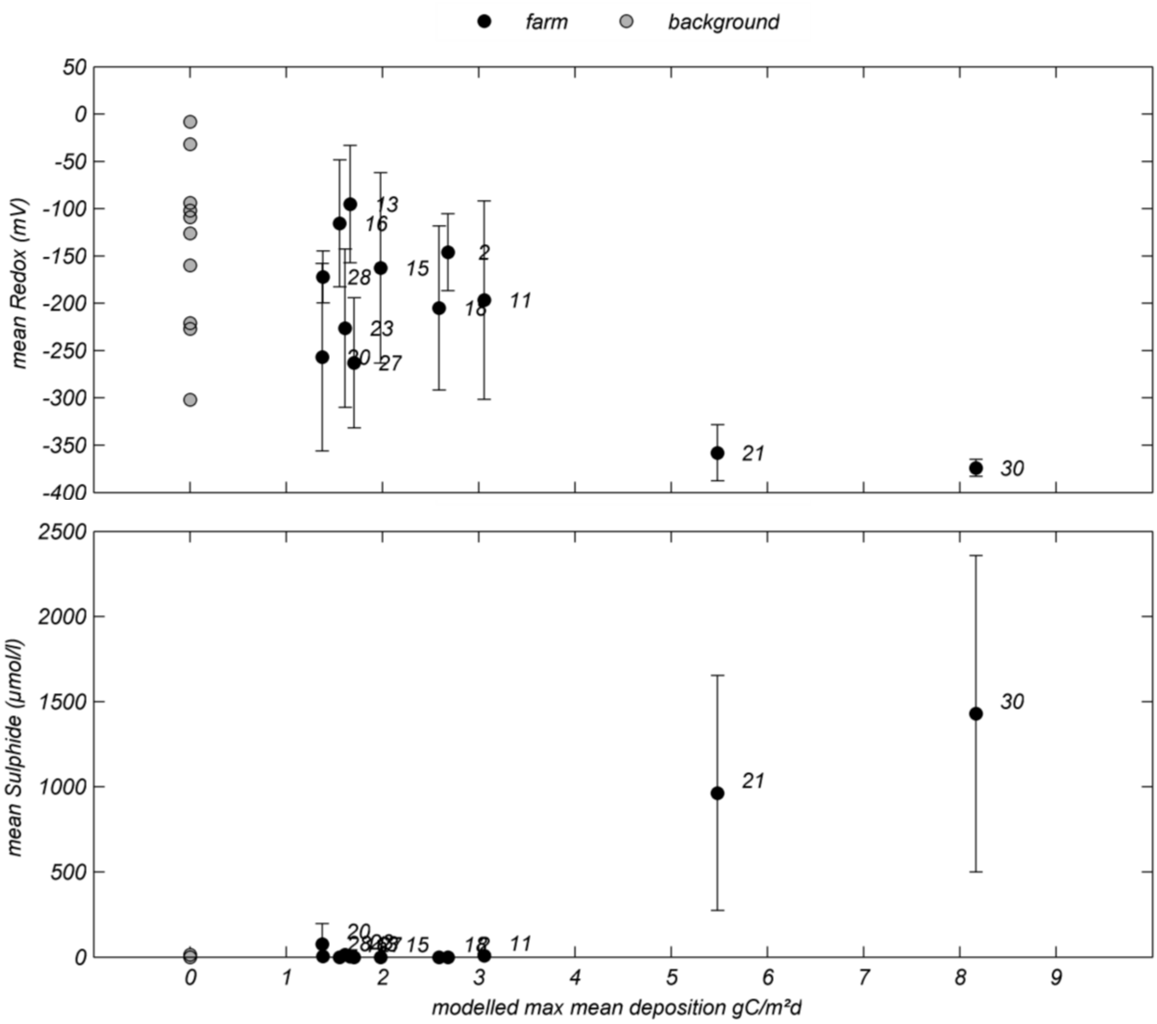

Fig. 3-7 Simulated POC deposition rates with mean redox (top) and sulphide concentrations (bottom) in the sediment samples

Black markers represent averages of the samples taken below the farms. Bars indicate the standard deviation around the mean. The model results are presented as the maximum of the temporal mean POC deposition rates occurring below each farm. Grey markers indicate values from reference areas, sampled at locations > 100 m away from the farms.

Sediment properties start to deviate from values found at the reference sites when deposition rates exceed values of around 4 $gCm^{-2}d^{-1}$. A threshold value of 4 $gCm^{-2}d^{-1}$ was therefore defined and applied for the following analysis presented in this study.

3.5 ESTIMATING HOLDING CAPACITIES FOR EXISTING FISH FARMS IN PEGAMETAN BAY

The functional relationship found in the Section 3.3 was used to estimate the holding capacity of existing fish farms. The method was applied to Pegametan Bay. The given standing stocks of the existing fish farms were assessed by comparing them to the calculated holding capacity.

Assuming a value of n = 0.03 sm$^{-1/3}$, *Equation 47* was used to derive the *Mb/Ms* ratio for a given average *Ws** for any location where average *Re* is known. For Pegametan Bay area, the FLOW model provides spatial information on hydrodynamic data and hence average *Re* and *Mb/Ms* ratio can be calculated for the whole model domain for a given value of *Ws**. In this study, *Ws** was defined, corresponding to an average settling velocity of 0.04 ms^{-1}. *Fig. 3-8* presents the calculated *Mb/Ms* ratio in the model domain of Pegametan Bay .

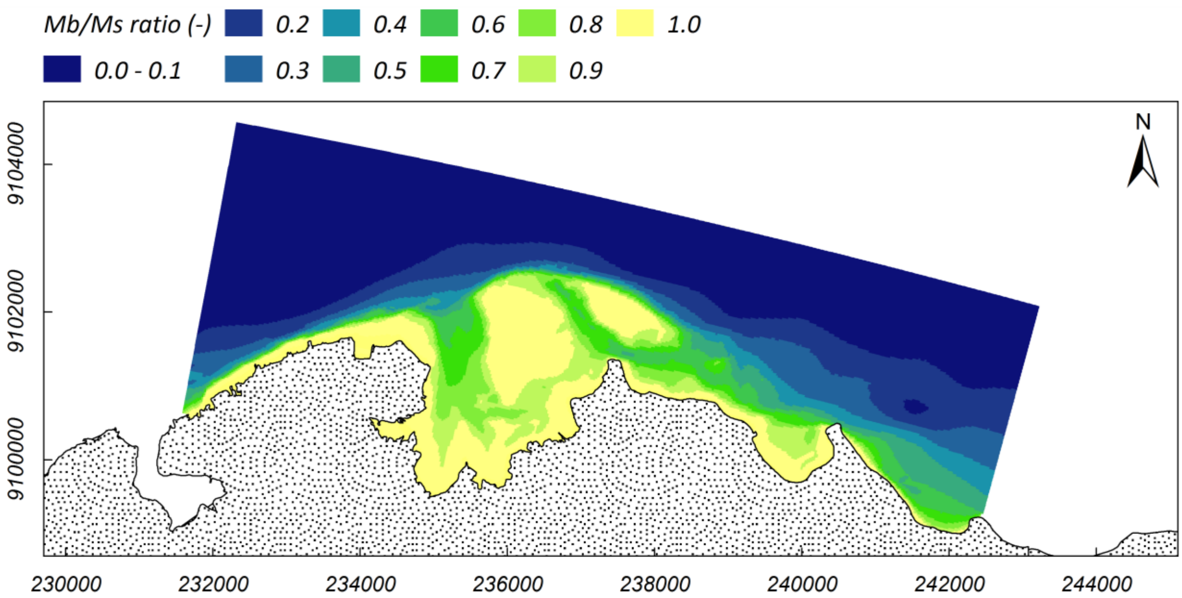

Fig. 3-8 Spatial distribution of Mb/Ms ratio in the Pegametan Bay model area for an average settling velocity of 0.04 ms^{-1}

Mb/Ms ratios directly depend on *Re* and hence the distribution of *Mb/Ms* ratios is similar to the distribution of *Re*. Higher values of *Re* cause larger dispersion and reduce *Mb/Ms* ratios. The lowest *Mb/Ms* ratios of 0 to 0.3 are therefore found in offshore areas. For the reef areas where flow velocities and water depths are low, *Mb/Ms* ratios of 0.9 to 1 were computed. In the channels *Mb/Ms* ratios lie between 0.3 and 0.9.

To avoid adverse effects on the benthic environment, deposition rates of POC (*Mb*) must not exceed bacterial decomposition rates of carbon. Maximum allowable POC emission rates (Ms_{max})

were derived using *Equations 40* and *41* in Section 2.6 for a threshold value for POC deposition of 4 $gCm^{-2}d^{-1}$. *Fig. 3-9* shows the spatial distribution of Ms_{max} in Pegametan Bay.

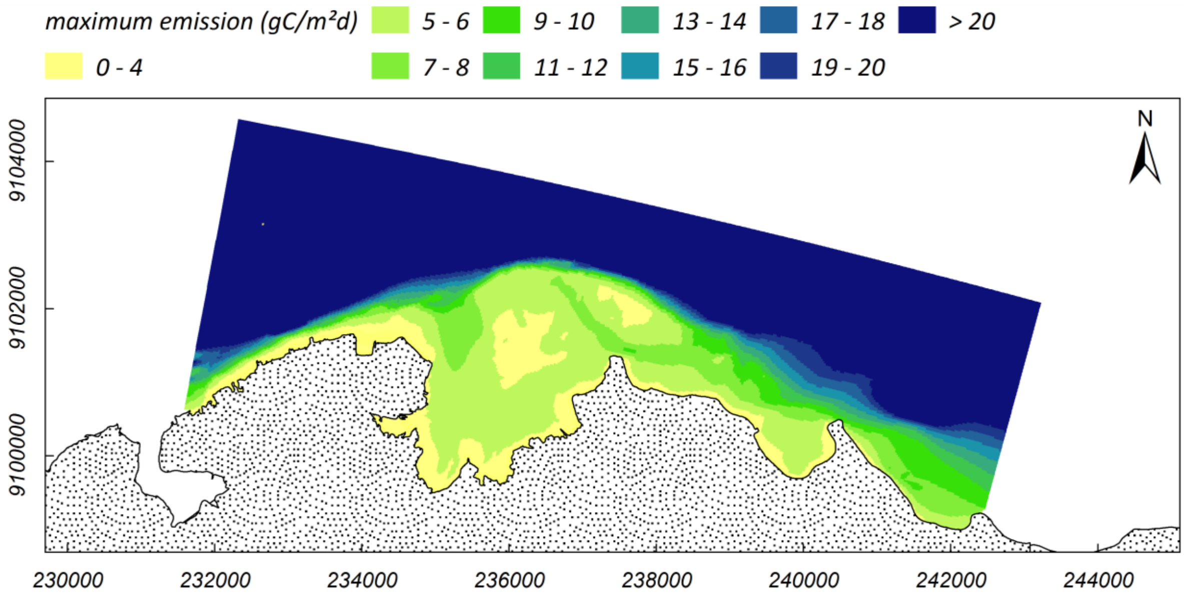

Fig. 3-9 Spatial distribution of maximum allowable emission rates (Ms_{max}) in the Pegametan Bay model area for a depositional threshold of 4 $gCm^{-2}d^{-1}$ and an average settling velocity of 0.04 ms^{-1}

Within inner Pegametan Bay, Ms_{max} lies below 4 $gCm^{-2}d^{-1}$ in the reef areas and between 4 to 12 $gCm^{-2}d^{-1}$ in the channels. Outside this area Ms_{max} values are up to 20 $gCm^{-2}d^{-1}$ and more.

Including production data presented in *Tab. 2-2* in Section 2.1, maximum average stocking densities were calculated as described in Section 2.6. *Fig. 3-10* presents the calculated maximum average stocking densities for cultured grouper in Pegametan Bay together with the existing cage farms.

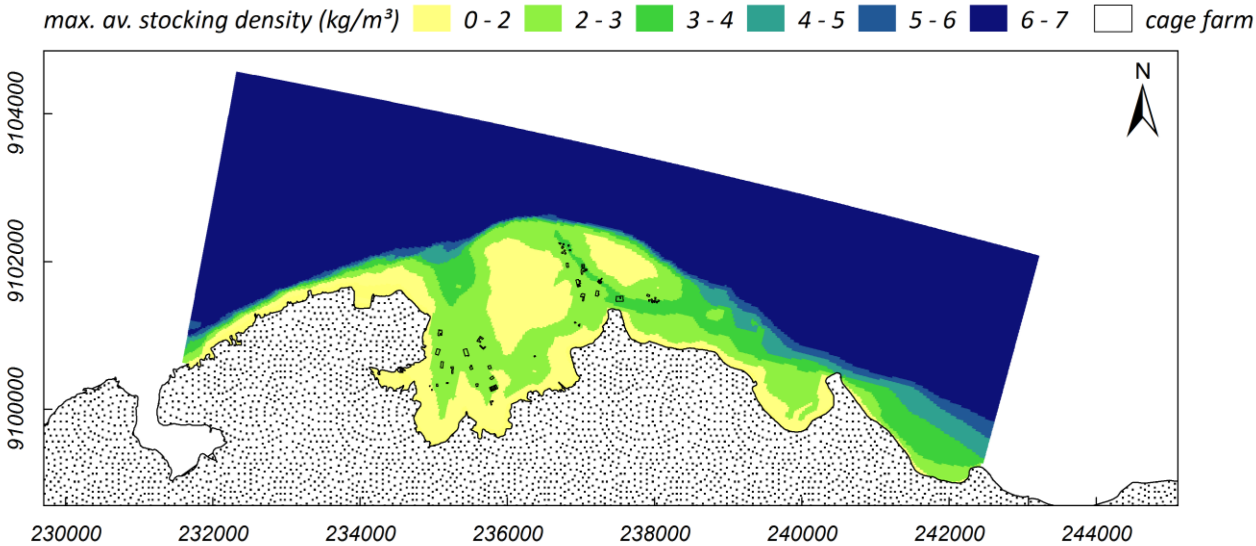

Fig. 3-10 Spatial distribution of maximum average stocking densities in the Pegametan Bay model area in the Pegametan Bay model area for a depositional threshold of 4 $gCm^{-2}d^{-1}$ and an average settling velocity of 0.04 ms^{-1}. Production type: see text.

Calculated maximum average stocking densities in the inner Pegametan Bay lie between 0 to 2 kgm^{-3} in the shallow reef area and between 2 to 4 kgm^{-3} in the channels. Maximum average stocking densities larger 4 kgm^{-3} and up to 7 kgm^{-3} are estimated for offshore areas where water depths and flow velocities are relatively high.

Farm dimensions of existing farms, according to *Tab. 2-1* in Section 2.1, were used to calculate holding capacities. *Fig. 3-11* shows the comparison of estimated existing standing stock present in the cage farms in Pegametan Bay to the calculated holding capacity.

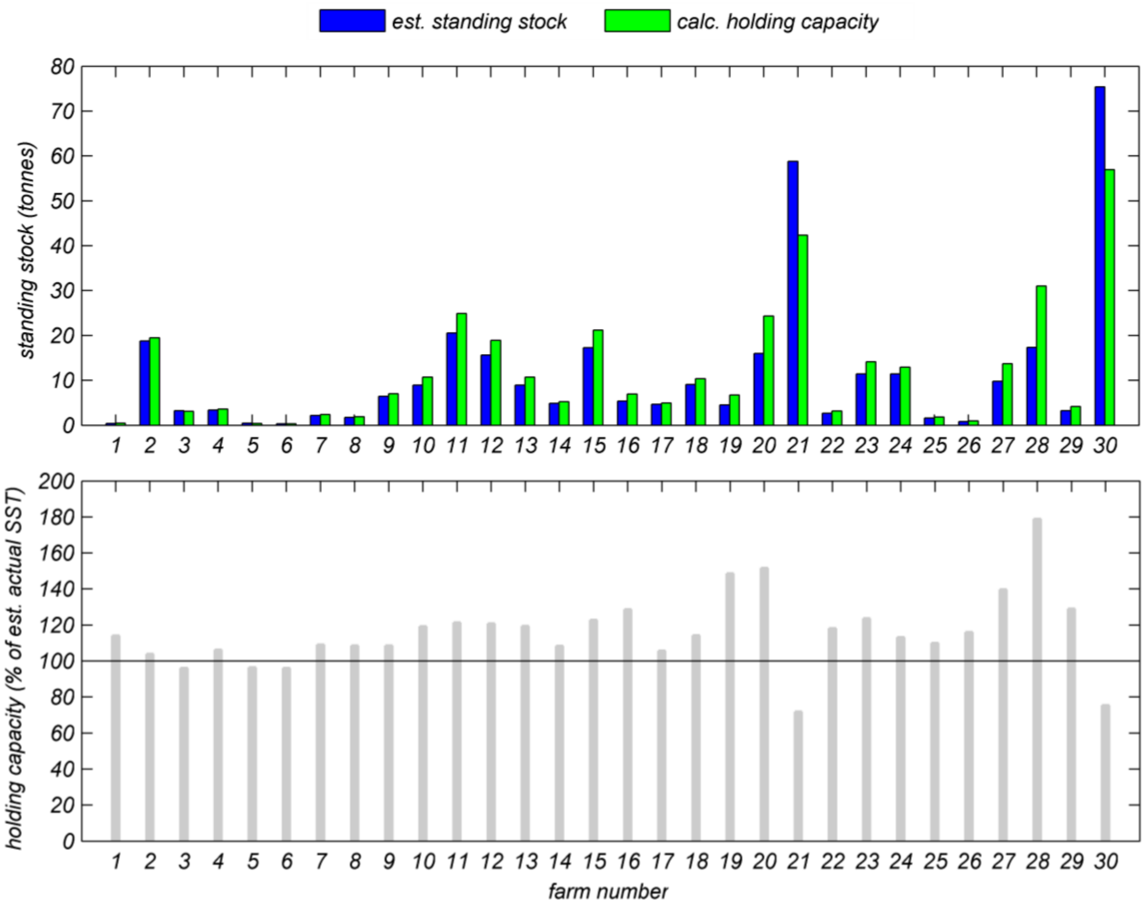

Fig. 3-11 Estimated existing standing stock and calculated holding capacity (top) and holding capacities expressed as percentage of the actual standing stock (bottom) for a depositional threshold of 4 $gCm^{-2}d^{-1}$ and an average settling velocity of 0.04 ms^{-1}

Under the given assumptions, most of the investigated farms have standing stocks around or below the calculated holding capacity. However, standing stocks in farms 21 and 30 clearly exceed the respective holding capacities of their location.

3.6 Proposal of a fish farm arrangement and estimation of the ecological carrying capacity in Pegametan Bay

The spatial distribution of maximum average stocking densities was used to propose a new farm arrangement in Pegametan Bay, assuming that there were no farms present in the bay. After defining the area suitable for grouper mariculture, farms were placed according to the best average stocking densities. Holding capacities of the proposed farms and the overall carrying capacity in the bay were estimated.

3.6.1 Suitability analysis

Suitability analysis was performed on the basis of suitability criteria as shown in *Tab. 2-7* in Section 2.7.1. In the following, the resulting suitable areas with respect to each criterion are presented and overlaid to result in the overall suitable area for grouper mariculture in Pegametan Bay.

WATER DEPTH

Minimum and maximum water depths were used to define appropriate locations for the prescribed mariculture type. *Fig. 3-12* shows the average water depth in Pegametan Bay of the 15 day modelled period. The maximum tidal range in the considered period is about 2 meters, resulting in maximum/minimum water depths of about +/- 1 meter of the mean water depth.

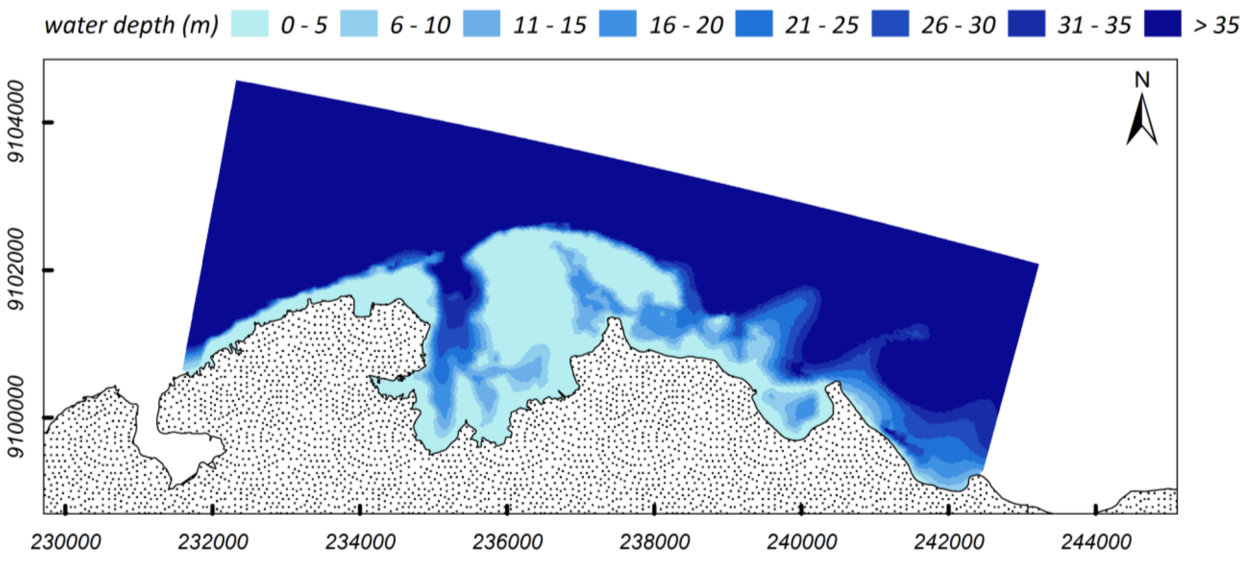

Fig. 3-12 Mean water depth in Pegametan Bay during the simulated 15 day period

Close to the coast average water depths vary between 10 and 30 meters in the channels and below 5 m in the shallow reef areas. Beyond the reef, the slope falls steeply to depths larger than 50 meters. *Fig. 3-13* shows the suitable area for net cage grouper mariculture with respect to water depths according to the criteria given in *Tab. 2-7.*

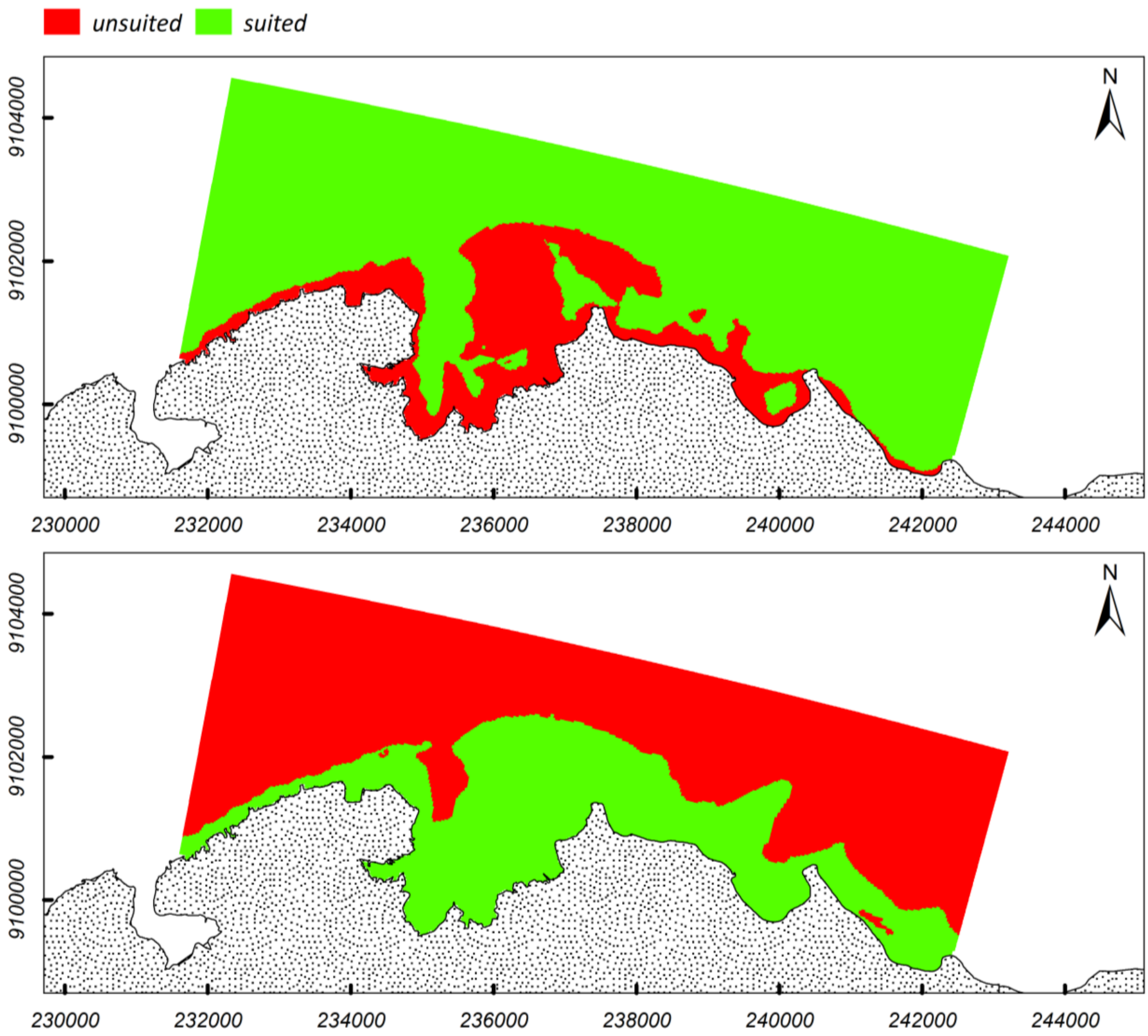

Fig. 3-13 Suitable area for net cage grouper mariculture in the Pegametan Bay model area, minimum (top) and maximum (bottom) water depth

CURRENTS

Average depth-averaged currents were used to define suitable locations. *Fig. 3-14* shows the average depth-averaged current velocities in Pegametan Bay of the 15 day modelled period.

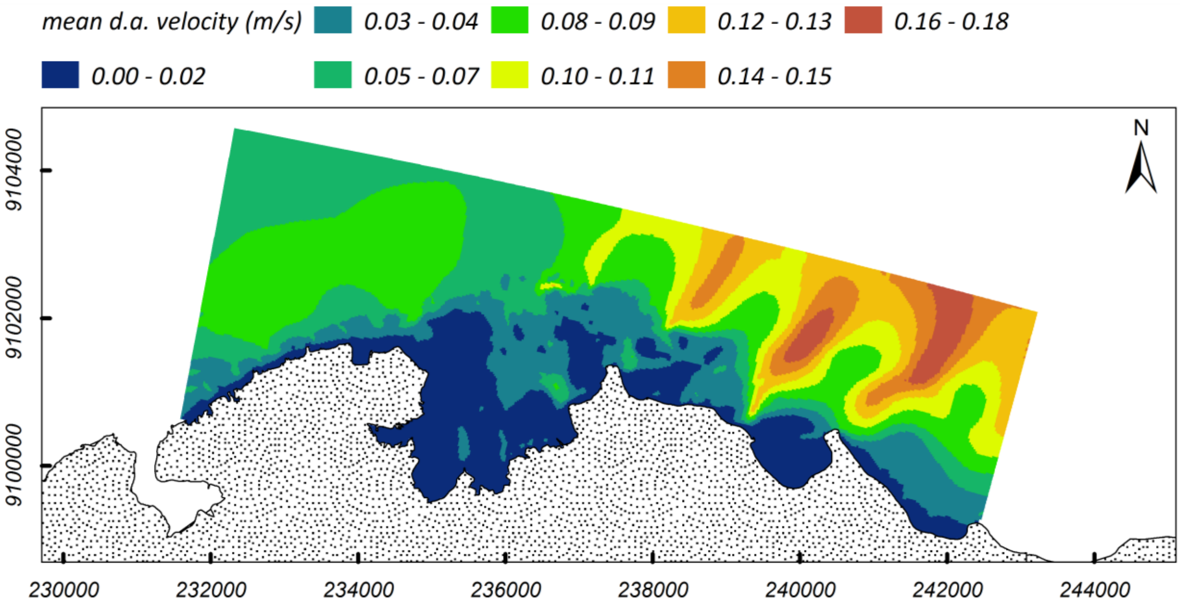

Fig. 3-14 Average depth-averaged (d.a.) currents in Pegametan Bay during the 15d simulated period

Mean depth-averaged currents in the inner Bay are mostly below 0.1 ms^{-1}. *Fig. 3-15* shows the suitable areas according to the criteria in *Tab. 2-7* with respect to water flow.

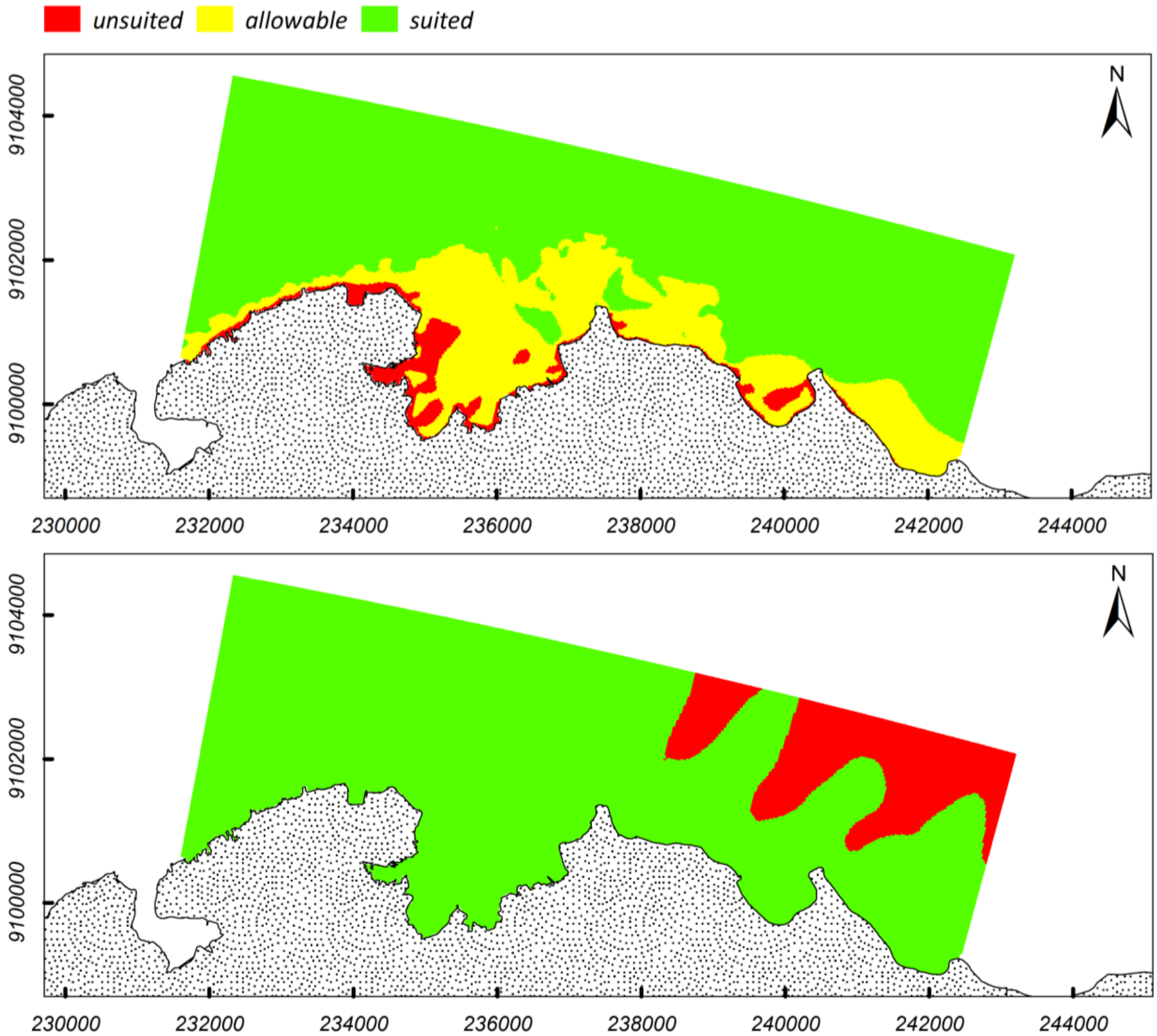

Fig. 3-15 Suitable area for net cage grouper mariculture in the Pegametan Bay model area, minimum (top) and maximum currents (bottom)

WAVE HEIGHTS

Fig. 3-16 shows the maximum significant wave heights (*Hs*) simulated during the wind event (15. March 2010) for Pegametan Bay area.

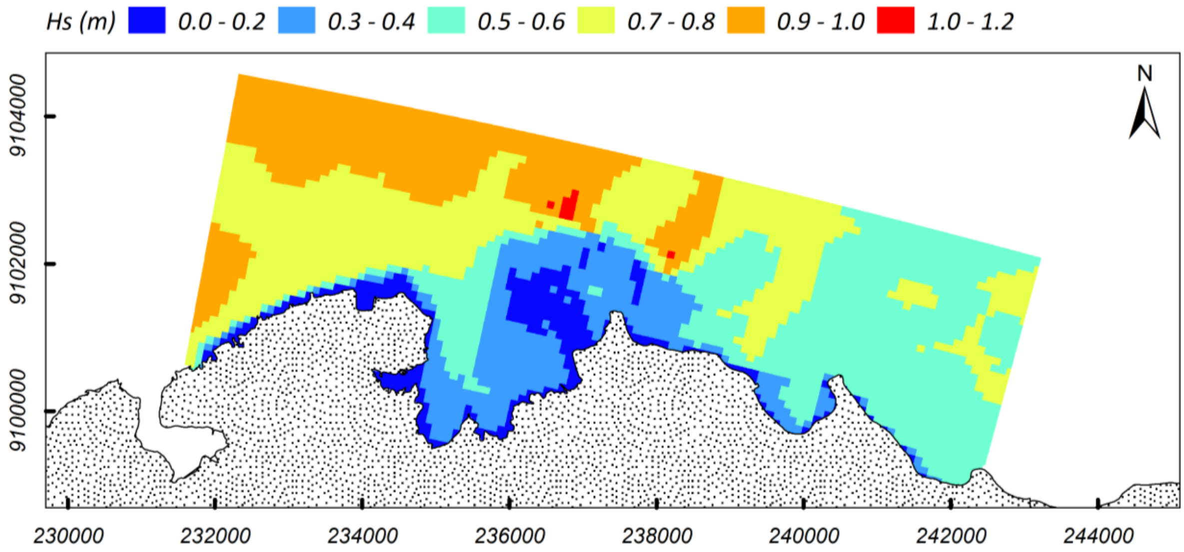

Fig. 3-16 Maximum significant wave heights (Hs) during a storm at the north coast of Bali in March 2012

Maximum significant wave heights are mostly below 1 m. In the inner bay which is sheltered by the coral reef, significant wave heights stay below 0.6 m. *Fig. 3-17* shows the suitable area according to the criteria in *Tab. 2-7* with respect to significant wave height.

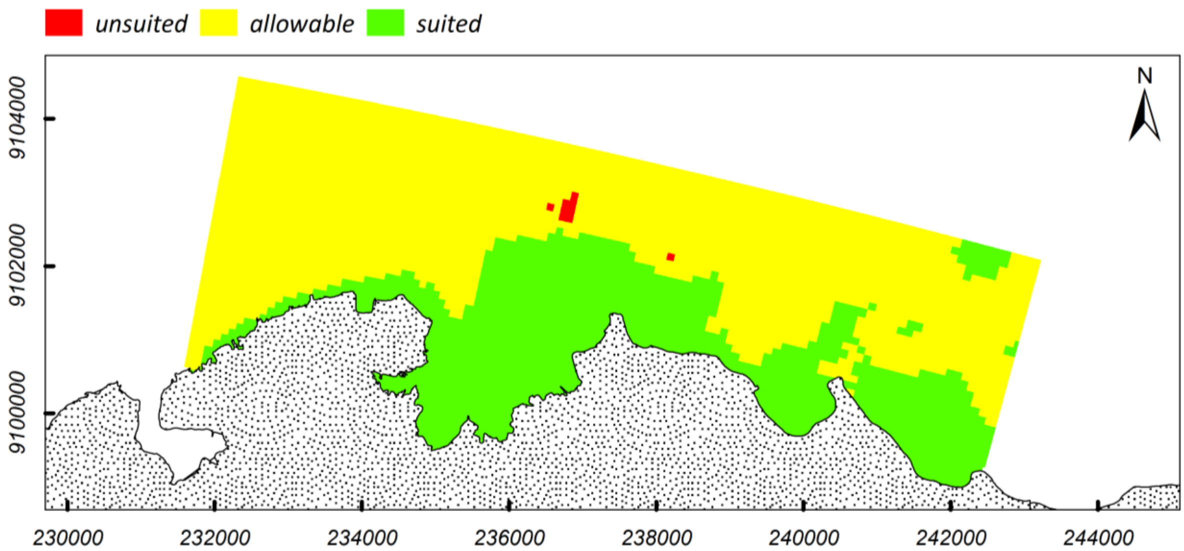

Fig. 3-17 Suitable area for net cage grouper mariculture in the Pegametan Bay model area, significant wave height

COASTAL USES

Regional planning for coastal uses is defined by the Indonesian Ministry of Maritime Affairs and Fisheries (KKP). *Fig. 3-18* shows the plan of coastal uses for North Bali and Pegametan bay. Locations of harbours, outlets from desalination ponds and fish ponds as well as the location of a small river discharging into Pegametan Bay are indicated on the lower map.

Most of the considered area is determined to be used for mariculture. For this study it was assumed that no mariculture is present in the bay and all designated area can be used for finfish mariculture. The outer, deeper areas are designated to small scale fisheries and in the eastern part, a zone for marine conservation is defined. Two traffic channels for local and regional transport are located in the study area. Several villages are present along the coast.

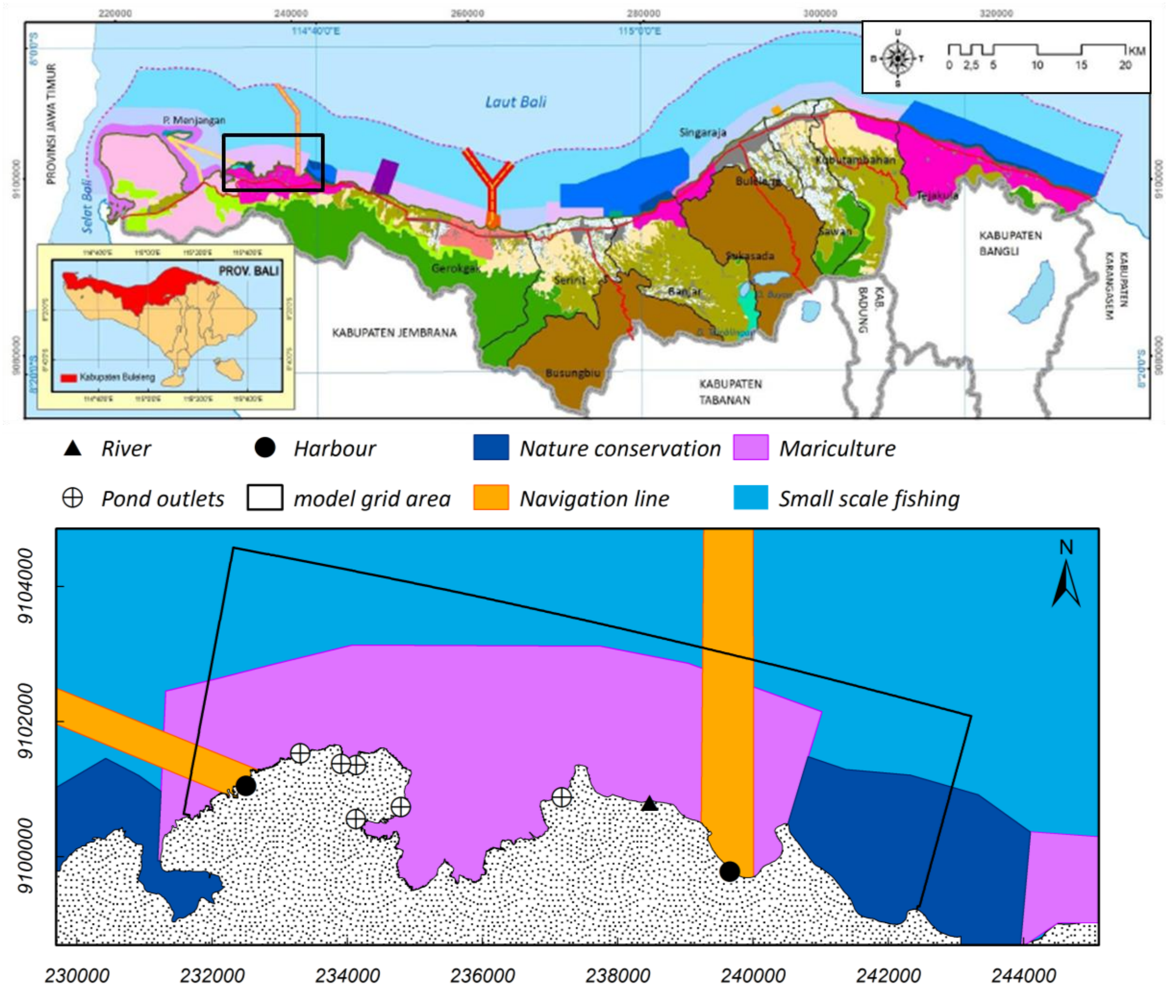

Fig. 3-18 Spatial planning of coastal uses in the Buleleng region, North Bali (top, Ministry of Maritime Affairs and Fisheries Indonesia 2014) and in Pegametan Bay area (bottom).

For suitability analysis, buffer distances to harbours, traffic channels and conservation zones were applied as shown in *Tab. 2-7*. For the outlets from desalination and fish ponds, as well as the river mouth, a distance of 250 meters was assumed. As the amount and dispersion of discharges from rivers and outlets underlie seasonal changes, this distance might need to be adapted on the basis of monitoring studies. The resulting suitable area considering coastal uses is shown in *Fig. 3-19*.

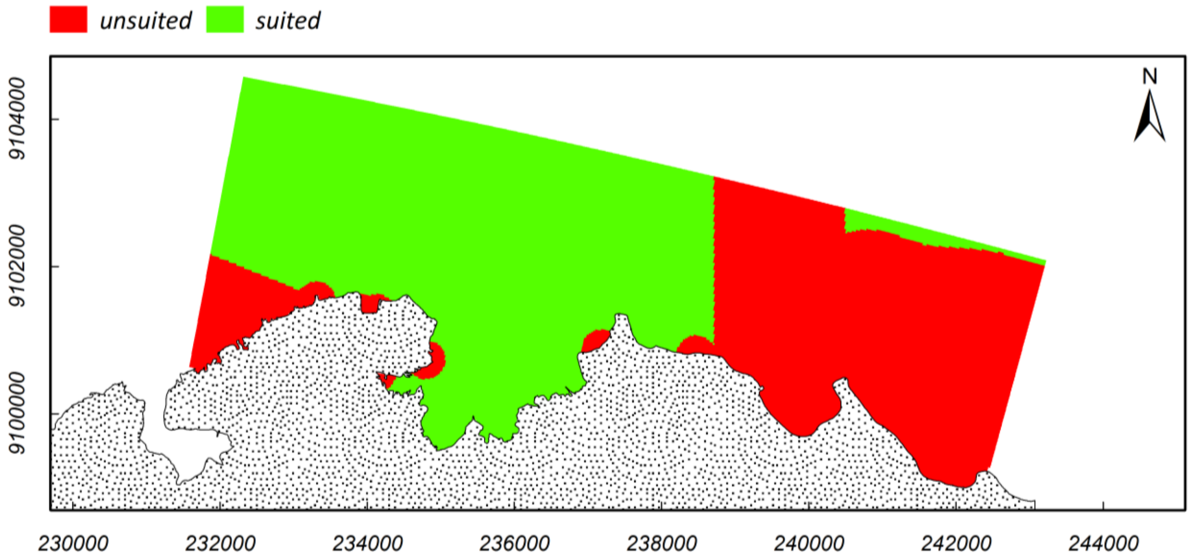

Fig. 3-19 Suitable area for net cage grouper mariculture in the Pegametan Bay model area, coastal uses

WATER QUALITY

Water quality measurements were collected at various locations in Pegametan Bay in a monitoring program by the Gondol Research Institute for Mariculture (GRIM) from February to November 2006 as well as from January to August 2008. Additional measurements were taken by the FTZ during measuring campaigns in April and December 2008, June 2009 and September 2012. *Tab. 3-1* summarizes the mean and standard deviation of all water quality measurements taken in Pegametan Bay.

Tab. 3-1 Mean and standard deviation of water quality measurements in Pegametan Bay

Parameter	*Unit*	*Average*	*Standard deviation*	*n*
Water temperature	*°C*	*29.03*	*1.22*	*337*
Salinity	*psu*	*32.44*	*2.66*	*316*
Dissolved oxygen	*mg/l*	*6.01*	*0.70*	*282*
pH	*log H+*	*8.25*	*0.15*	*174*
Secchi depth	*m*	*9.57*	*4.49*	*157*
NH4 Ammonium	*mg/l*	*0.017*	*0.023*	*277*
NO2 Nitrite	*mg/l*	*0.016*	*0.029*	*287*
NO3 Nitrate	*mg/l*	*0.077*	*0.022*	*282*
PO4 Phosphate	*mg/l*	*0.093*	*0.27*	*286*
Suspended sediment	*mg/l*	*0.16*	*0.47*	*191*

Measured average values lie in the allowable ranges according to the criteria given in *Tab. 2-7* and Pegametan Bay can be declared to be suitable with respect to the considered water quality parameters. It should however be considered, that most water quality parameters fluctuate with the seasons due to higher or lower temperature, insulation or freshwater input through rainfall and runoff. Similarly, the tolerance of the fish is influenced by environmental conditions. With respect to water quality, it is therefore necessary to keep monitoring on water quality parameters during fish farm operation.

SUITABLE AREA

Based on the parameters presented in the previous sections and the criteria shown in *Tab. 2-7*, the suitable area was found by overlaying as prescribed in Section 2.7.1. *Fig. 3-20* shows the suitable areas for grouper mariculture in Pegametan Bay. The total suitable area in Pegametan Bay is approximately 145 ha, of which about 64 ha lie in the western channel and about 81 ha are situated in the eastern channel.

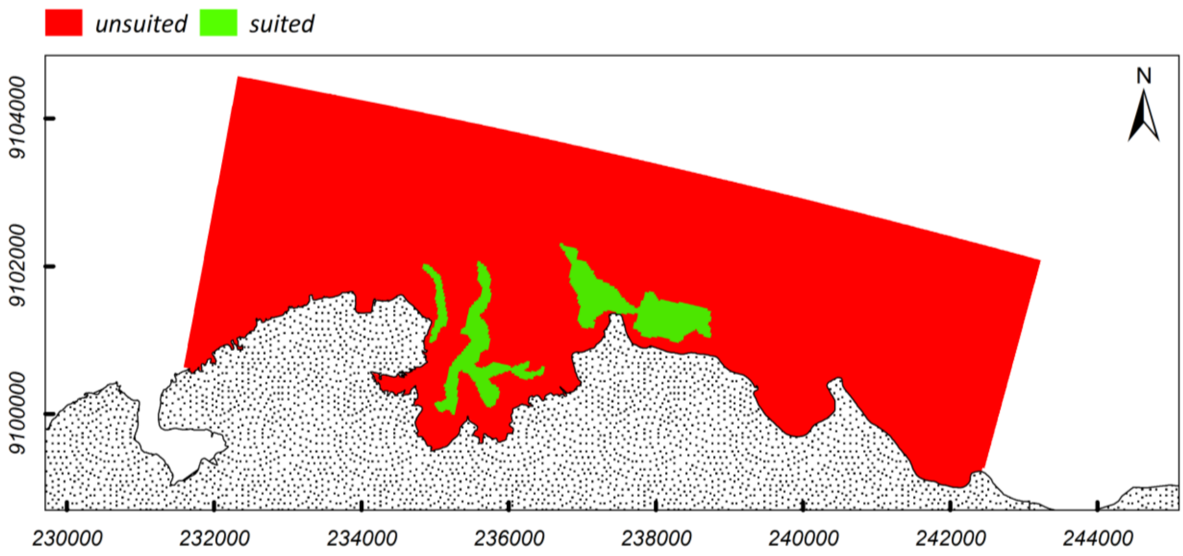

Fig. 3-20 Suitable area for net cage grouper mariculture in the Pegametan Bay model area

3.6.2 FARM PLACEMENT AND ECOLOGICAL CARRYING CAPACITY

Farms of anticipated production type and farm size were placed within the suitable area for grouper mariculture in Pegametan Bay. *Fig. 3-21* shows the locations of projected fish farms for grouper production (as defined in Section 2.1) of pre-defined dimensions of 100 cages. The farms are ranked according to their holding capacity. The labels indicate the ranking of the farm locations, with 1 having the highest holding capacity. To avoid mutual interference the farms were placed considering a buffer distance of 300 meters.

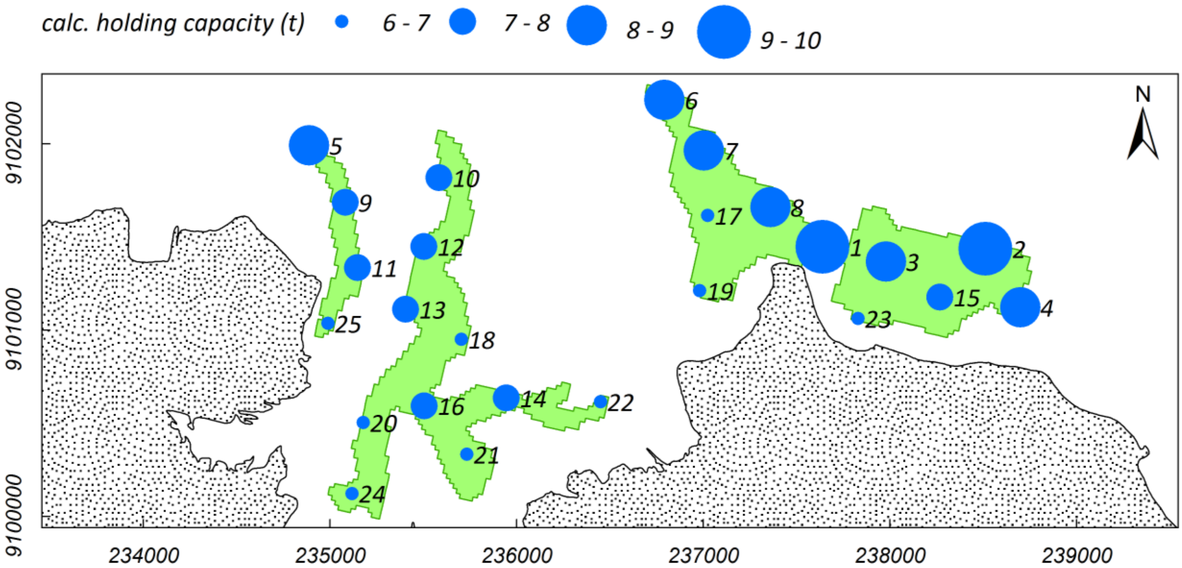

Fig. 3-21 Proposed farms and calculated holding capacities for grouper farms of 100 cages within the suitable area for mariculture (green). Average settling velocity = 0.04 ms^{-1}, threshold for POC deposition = 4 $gCm^{-2}d^{-1}$

Under the given assumptions, the proposed farm arrangement includes 25 farms with holding capacities between 6 and 10 tonnes. Maximum average stocking densities range between 2 to 4 kgm^{-3}. The overall ecological carrying capacity with respect to the deposition of POC to the sea floor is 185 tonnes.

3.7 SEDIMENT ANALYSIS

Sediment samples were collected underneath fish farms and at reference sites. Redox potential and concentrations of sulphide, PON and POC were determined. In *Fig. 3-22* and *Fig. 3-23* the measuring results are presented.

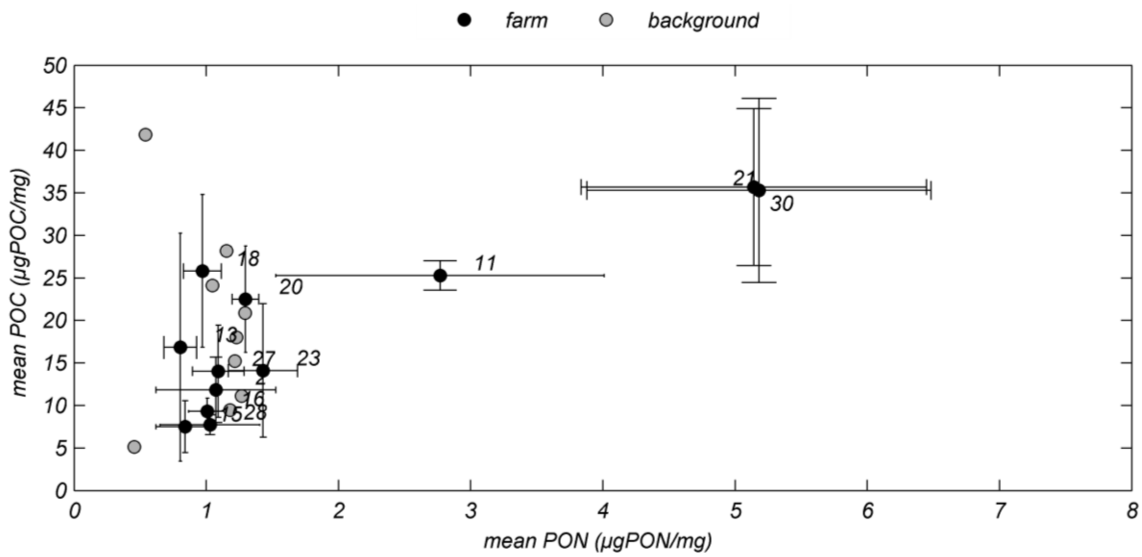

Fig. 3-22 Measured PON and POC concentration in samples below 12 fish farms and at reference stations in Pegametan Bay

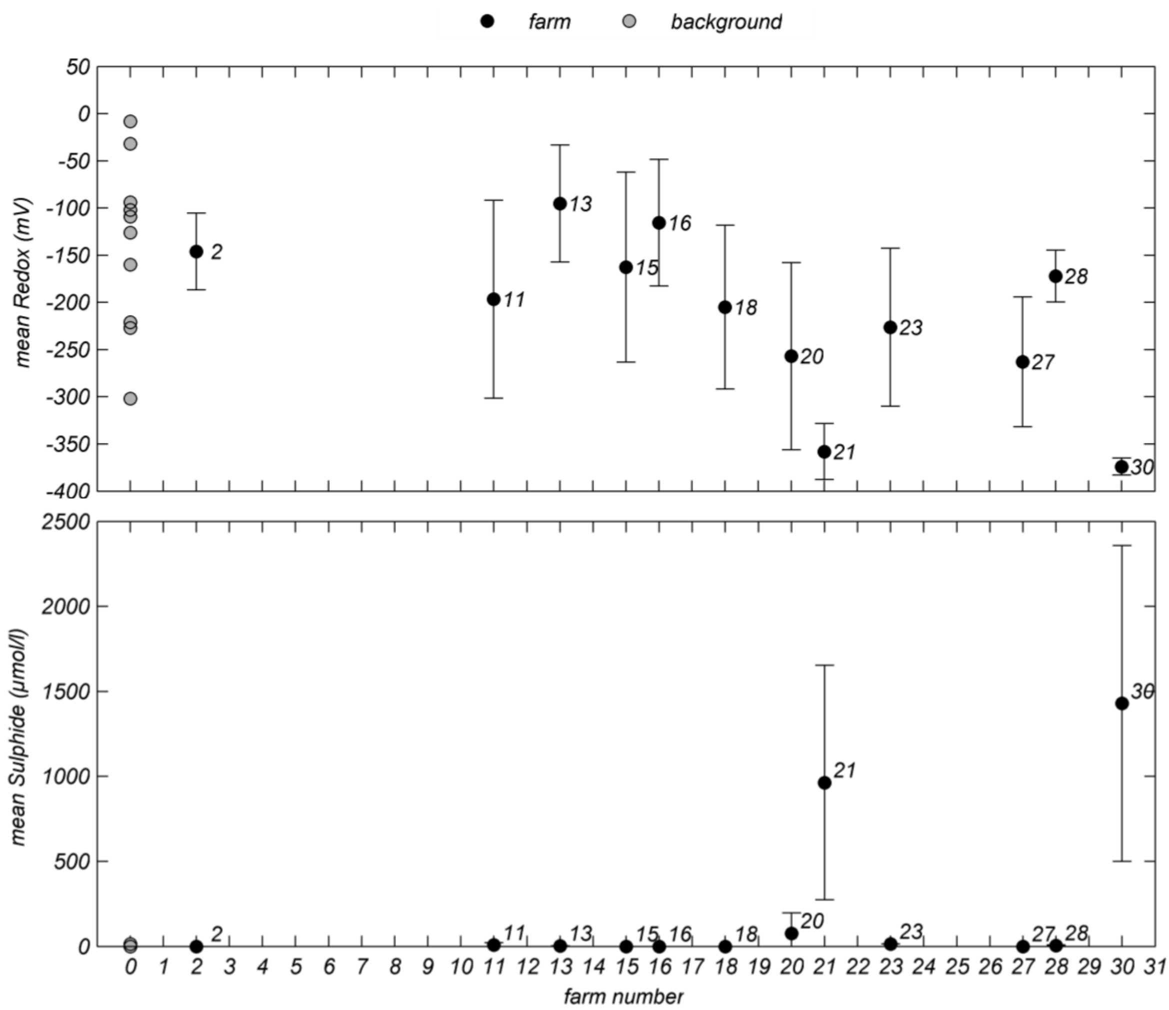

Fig. 3-23 Measured redox potential (top) and sulphide concentration (bottom) in samples below 12 fish farms and at reference stations in Pegametan Bay

In both graphs, two groups of consideration are shown. The first group, indicated by grey markers, represents conditions at the reference sites which are basically unaffected by farm emissions. The sediment samples show mean POC concentrations between 5 and 45 µgPOCmg^{-1} and PON concentrations below 1.5 µgPONmg^{-1}. Mean redox potential varies between 0 and -300 mV, indicating that oxygen conditions even in non-impacted sediments can be rather poor. Sulphide is not detectable.

The second group represents conditions underneath fish farms (black markers). Each value indicates the mean of various samples taken below one farm and bars indicate the standard deviation around the mean. Most of the sediment samples present mean values within the ranges found in reference areas. However, sediment samples taken below farms 11, 21 and 30 present higher mean PON concentrations of 2.7, 5.1 and 5.2 µgPON/mg respectively, of which the samples from farms 21 and 30 lie significantly above the values found in the reference areas. Furthermore, sediment samples below farms 21 and 30 show sulphide concentrations of about 1000 and 1500 µmol/l and very low redox potentials of < -350 mV.

Fig. 3-24 presents pictures of the sea floor at a reference location and below fish farm 21. At the reference site, the sea floor is characterised by carbonate sediments, which show signs of bioturbation by benthic infauna. No indications of organic waste are visible. Underneath farm 21 the sea floor is covered by organic debris with colonies of Beggiatoa bacteria which gain energy by oxidising sulphide from the sediment pore water. Sulphur is embedded intercellular and colours the colonies light grey. The holes on the surface are caused by outgassing.

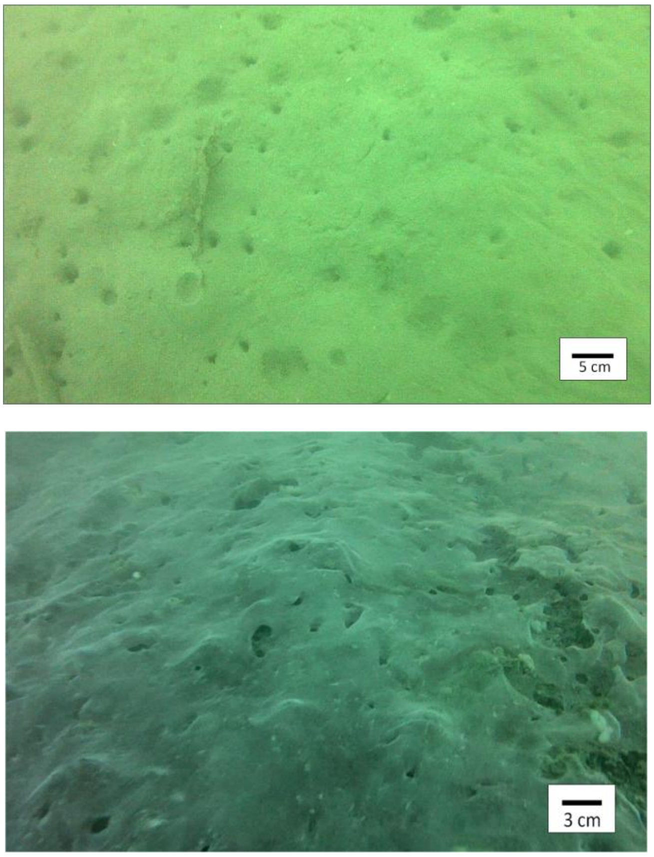

Fig. 3-24 Sea floor below a reference site (top) and below fish farm 21 covered with organic farm wastes and mats of Beggiatoa bacteria

4 DISCUSSION

This thesis proposes a practical method to estimate the carrying capacity of coastal environments for sustainable finfish mariculture operation with respect to POC deposition. The method aims to support decision making at feasibility stage by identifying the potential for mariculture development in designated areas.

The method considers the effects of hydrodynamic conditions on particulate waste fluxes from fish farms to the sediment and is significantly based on dimensional considerations of the physical key parameters involved. The ratio between the deposited and emitted organic waste (*Mb/Ms*), plays a decisive role. At a constant load, *Mb/Ms* gets smaller in areas characterised by higher Reynolds number (*Re*), because the fish farm wastes get more dispersed at higher flow velocities and /or over larger depths. Higher settling velocities, expressed in non-dimensional form *Ws**, increase the deposition load of particulate organic material and hence increase the *Mb/Ms* ratio. These general relationships are expressed by the functional relationship of the terms *Mb/Ms*, *Re* and *Ws**. The interdependencies of the functional groups derived from dimensional analysis were confirmed using simulated values for *Mb/Ms* and *Re* for pre-defined settling velocities (*Ws**).

A crucial part of the developed method is the definition of the assimilative capacity in terms of maximum allowable deposition rates of POC to the sea floor. To estimate the assimilative capacity in Pegametan Bay, simulated maximum average POC deposition rates were related to measured redox potential and sulphide concentrations. In previous studies this approach proved to be practical to estimate threshold values and to support the effectiveness of deposition models (Angel et al., 1995; Chang et al., 2014). It could be stated that model results were in meaningful agreement with the sediment quality measurements. Measured increased sulphide concentrations and decreased redox potential as indicators for high organic matter loading correspond well to high deposition rates simulated in the model.

The assimilative capacity was defined to be the maximum POC deposition rates before sediment quality starts to significantly deviate from the sediment quality at the reference sites. The comparison of simulated deposition rates to measured sediment quality parameters suggests that this is the case when deposition rates exceed values of approximately 4 $gCm^{-2}d^{-1}$.

Some studies exist, which estimate the assimilative capacity in terms of POC deposition to the sea floor. Most of them were conducted in temperate regions in Europe and America where sedimentation rates between 1 and 5 $gCm^{-2}d^{-1}$ were identified to be the threshold before negative effects are visible or measureable in the sediment (Backman et al., 2009; Chamberlain and Stucchi, 2007; Findlay and Watling, 1997; Hargrave, 1994; Kutti et al., 2008; Piker et al., 2002). Comparatively few studies provide quantitative estimates on the assimilative capacity with respect to organic enrichment in (sub-) tropical marine environments. Krost (2007) investigated organic matter breakdown and benthic communities below two fish farms in a high energy environment in Riau, Indonesia. Due to the strong dispersion of the farm wastes, sediments below the farms were largely unaffected and decomposition rates were relatively low at 0.5 to 2 $gCm^{-2}d^{-1}$. The actual capacity of bacterial degradation might have been higher than the deposition rate of organic waste. Angel et al. (1995) measured decomposition rates of 1 to 5 $gCm^{-2}d^{-1}$ in sediments of the oligotrophic Gulf of Aqaba. The authors also compared the visually affected area below a fish farm in the with results of a deposition model, concluding that POC loadings up to 4 $gCm^{-2}d^{-1}$ did not cause obvious pollution affects but were balanced by natural decomposition processes in the Gulf. The threshold of 4 $gCm^{-2}d^{-1}$ estimated in this study lies within the ranges published in literature. As the assimilative capacity may vary corresponding to different local conditions it is necessary to get estimations as accurate as possible for each investigated area. However, considering the uncertainties included in the estimation of local assimilative capacities, makes it indispensable for a sustainable mariculture operation to be accompanied by adapted monitoring programmes.

The developed method was applied to define holding capacities of existing farms in Pegametan Bay. By comparing the existing standing stock of the fish farms with their estimated holding capacity, it becomes evident that most of the fish farms are operating below or close to the holding capacity of their location. However, standing stocks in farms 21 and 30 clearly exceed the holding capacity in the area of operation. Accordingly, waste deposition rates below these farms were expected to exceed the environmental assimilative capacity in the area causing observable impacts in the sediment by organic enrichment.

The assessment based on the presented method, was generally confirmed by the sediment quality parameters measured in the bay. Sediment analysis revealed increased concentrations of PON and POC in the sediments below farms 21 and 30. In particular, the excess of particularly bound nitrogen in warm, oxygen rich, oligotrophic tropic environments, indicates that the re-mineralisation processes of organic waste driven by bacteria are unable to keep pace with the nutrient supply from the fish farm. At farms 21 and 30 this is reflected by the anoxic conditions and the appearance of sulphide in the sediment's pore water. Existence of sulphides indicates that bacterial sulphate reduction is in progress, leading to a rapid decrease of sediment quality and significant slowdown of the degradation process of organic wastes. A typical signal is the smell of hydrogen sulphide and the blackening of the sediment caused by iron sulphide. As could be expected, the sediments found underneath farms 21 and 30 show the lowest redox potentials actually measured in the bay.

The measuring results also show that low redox potentials are not necessarily a signal of fish farm impact. Reference data, collected in unaffected areas of Pegametan Bay, show ranges from 0 to -300 mV. This might be due to the fact that many sediments found in the channels are very fine grained, muddy and of plastic consistency. According to the low permeability of such sediments, the diffusion of oxygen from the sea water into the sediment is supposed to be naturally very low. Moreover, POC concentrations alone are not considered to be a key indicative for farm impacts as organic material from coastal vegetation could have reached the area and be embedded in the sediment.

The developed method can be applied on several levels of detail. Maps of *Mb/Ms* ratio, as shown in *Fig. 3-8* in Section 3.5, give a more general impression on the possible degree of impact on the benthic environment. At this level the results can already support decision making when mariculture areas need to be defined or when several areas are compared in their potential for mariculture development. If information on the assimilative capacity with respect to organic matter loading is available, *Mb/Ms* ratios can provide information on maximum allowable emission rates of POC. Latter can be translated into maximum average stocking densities for a pre-defined production type.

The presented method assumes simplifying average stocking densities over the entire farm area. It includes the possibility that in some farm parts and over some periods the stocking densities are higher than the proposed stocking density. This implies that some local impacts on the sea floor may occur, which cannot be resolved by the applied method. Actually, such possible pattern of polluted and unpolluted areas underneath fish farms could not be observed by the divers. It is assumed that local impacts, which are restricted to some periods within the production cycle, may be gradually compensated by the natural system.

In the application example presented in Section 3.6, new cage farms were defined consisting of 100 cages each. Regarding this scenario, recommendations are given on the intensity of production in terms of stocking density for a given production type. The pre-defined number of cages is considered to be a variable to include an anticipated farm type with respect to farm size. If the area of interest is more diverse in its potential for cage mariculture, spatially varying cage numbers of farms can be defined. At some dispersive locations, an expansion of the farm size could be possible without expecting adverse effects. At locations at which low maximum stocking densities are recommended, it may be more feasible to decrease the size of a farm. Recommendations on size and orientation of individual farms lie outside of the scope of the thesis. It may require socio-economic considerations and more detailed analysis of the effect of farm size on the environmental, and should be considered in following concepts of research.

In this context, it should be considered that cage nets and structures may have local influence on the flow and currents are likely to be slowed down inside the cages and in the wake of the cages (Løland, 1993). The WAQ model does not consider cage effects upon water flow. Increased drag in the cage would increase flow velocities underneath the cages and consequently lead to more waste dispersion and lower deposition rates. With respect to cage effects, the calculated deposition rates may therefore be overestimated by the model. Further research should be conducted, including a drag coefficient to investigate the effect on average Reynolds numbers. Possibly, a factor can be derived adapting average Reynolds numbers at a location, to consider general cage effects. This field of research should also include cumulative cage effects, leading to recommendations with respect to the maximum number of cages in a farm.

As the method presented is sensitive to variations of input variables, particular emphasis should be placed on the collection of accurate data. Fish production parameters may show high variability depending on operational and environmental conditions. Variations in feed type and FCR have direct effect on the carbon emissions (*Ms*) leaving the farm and hence on the results. Also the assumed average settling velocity influences the results. In this study *Ws* was estimated to be 0.04 ms^{-1} based on values published in related papers. It may vary for different species and/or feeding types. To clarify the effects of different *Ws*, *Tab. 4-1* exemplarily provides ranges of maximum average stocking density and holding capacity for variable average settling velocities in the applied example in Section 3.6.

Tab. 4-1 Ranges of calculated maximum average stocking densities and holding capacities for different assumptions taken with respect to average settling velocity (Ws)

Average Ws (ms^{-1})	*Calc. max. average stocking density (kgm^{-3})*	*Calc. holding capacity (t)*
0.02	*3 - 5*	*7 - 15*
0.04	*2 - 4*	*6 - 10*
0.06	*2 - 3*	*5 - 9*
0.08	*2 - 3*	*5 - 8*
0.10	*2 - 3*	*5 - 7*

Higher average *Ws* represent higher *Ws**, leading to increased *Mb/Ms* ratios. Hence, maximum average stocking densities and holding capacities decrease with increasing *Ws*.

Tidal velocities in Pegametan Bay were found to be fairly low. Hence, the significance of resuspension of organic wastes from the sea floor was considered to be quite low. In high energy environments the chosen settings, not including resuspension, may overestimate actual POC deposition rates. In such areas, resuspension of organic wastes may play a more significant role for the definition of holding capacities and should be considered in future research.

Biochemical processes influencing the mass balance of the emitted organic material from the fish farm are not taken into account in the WAQ model simulations. Leaching of nutrients can increase dissolved organic material and decrease organic load of deposited solids. Chen et al. (2003) found that faecal pellets of Atlantic salmon lose about 22 % of carbon by leaching after 5 minutes of sinking. Wild fish have been observed to assemble around floating net cages and to feed of the wasted feed which can reduce the impact on the benthic system. It was estimated, that wild fish aggregations around sea cages with grouper and rabbit fish in Sulawesi consumed 27 % of the lost pellets (Sudirman et al., 2009). Katz et al. (2002) observed a mean carbon removal rate of 20.6 $gm^{-2}d^{-1}$ by bottom feeding of gray mullet below fish farms in the Gulf of Aqaba, Red Sea. Taking in account such processes may significantly reduce the carbon load to the sediment below the cage farms and alter *Mb/Ms* ratios. For the stage of development, the method takes a conservative approach embedding the consequence that the marine environment might be less impacted.

The consideration of first-order physical processes makes the method applicable in regions with similar hydrodynamic conditions as given in the study area Pegametan Bay, i.e. the method applies to tidally mixed, relatively shallow coastal systems. To improve the empirical description of the functional relationship between *Mb/Ms* ratio, *Re* and *Ws** found in this study, results of validated FLOW models of other regions are planned to be used in conjunction with WAQ models to extend the range of correlating values of *Re, Ws** and *Mb/Ms.*

Extensive data is rarely available when feasibility studies for mariculture development are carried out. In this case, practical methods, as the one introduced in this study, can be a valuable guideline. Hydrodynamic properties, such as velocity and depth are relatively easily obtained through measurements and modelling, which has become more feasible since codes are being provided open source. The developed method is intended to be part of a decision support system for sustainable finfish mariculture operation and to be used in combination with other methods estimating carrying capacity with respect to different impacts fish farms may have on the marine environment. Furthermore, the method can help to adapt farm management to the ecological holding capacity. It can be used as a first step to organise and plan mariculture operations before more complex models are selectively applied and specific surveys are conducted.

5 CONCLUSIONS

A practical method was presented to estimate the ecological carrying capacity of marine fish farms with respect to POC deposition to the sea floor.

- Dimensional considerations concluded that for a given value of bed roughness, the ratio of deposited to emitted particulate fish farm wastes (*Mb/Ms*) is a function of the local Reynolds number (*Re*) of the flow and a non-dimensional characteristic settling velocity of the particulates (*Ws**).
- The functional relationship forms the basis of the developed method and could be confirmed by results of numerical flow and particle transport models.
- The method calculates maximum average stocking densities for a pre-defined maximum allowable deposition rate and fish production type, and is suited to give first assessments of the holding capacity of fish farms, to optimise farm locations and to estimate the ecological carrying capacity with respect to POC deposition to the sea floor.
- The focus on first order physical processes makes the method general and easily applicable in different coastal waters with similar hydrodynamic conditions to the study area. Further research is recommended, to strengthen the empirical relationship and to extend the applicability of the method to other coastal systems.
- Few input parameters are necessary for the proposed method to give an initial assessment of the production potential for mariculture in an area. This makes the method especially suited to be applied at the feasibility stage and in regions where field data for input into more complex models are generally not available.
- In combination with spatial hydrodynamic information, the method provides instant overview of the mariculture potential by identifying the intensity of fish production at which sustainable operation is provided. Thereby, it forms an ideal basis for the definition and planning of mariculture management zones.
- Further research is recommended, to consider resuspension of deposited material, biochemical processes having effect on the deposition of particulate organic matter in the water column and cage effects on the flow.
- Extension of the method to enable the estimation of the maximum size of the farms is needed.

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Erklärung

Ich versichere an Eides statt, dass die vorliegende Abhandlung ausschließlich unter Verwendung der angegebenen Hilfsmittel entstanden ist und, abgesehen von der Beratung durch meine akademischen Lehrer, nach Inhalt und Form meine eigene Arbeit darstellt. Zudem habe ich weder diese noch eine ähnliche Arbeit an dieser oder einer anderen Hochschule im Rahmen eines Prüfungsverfahrens vorgelegt oder veröffentlicht.

Kiel, den …………………………………… ....

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