October 2016

Seychelles Islands Physical Oceanography and Aquaculture Development Zones Modelling

Submitted to:
Golder Associates Africa (Pty) Ltd.

DRAFT FOR COMMENT

REPORT

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1.0 OBJECTIVES

This report has been produced by Golder Associates Ltd. (GAL) for Golder Associates Africa (Pty) Ltd. as part of the Environmental and Social Impact Assessment (ESIA) for the Implementation Phase of the Seychelles Mariculture Master Plan (MMP) as initiated by the Seychelles Fishing Authority (SFA). The objectives of this report are:

1) To review the oceanographic and meteorological baseline conditions of the Seychelles (section 2.0);

2) To review of MMP studies and reports that pertain to oceanographic conditions and associated environmental impacts available at the time of study (October 2016) (section 3.0);

3) To assess potential impacts of offshore fish cage aquaculture in proposed Aquaculture Development Zones (ADZs) through idealized hydrodynamic and particle transport modelling of solid organic wastes release from the cages (section 4.0); and

4) To identify gaps and formulate recommendations in relation to understanding of the project site metocean conditions and potential water quality environmental impacts of fish cage aquaculture (section 4.2).

This report should be read in conjunction with the "*Important Information and Limitations of this Report*" as this forms an integral part of this document (section 8.0).

2.0 BASELINE METOCEAN CONDITIONS

Meteorological and oceanographic (metocean) conditions of the Seychelles Islands were recently documented through the National Marine Ecosystem Diagnostic Analysis (MEDA) of Seychelles conducted as part of the Agulhas and Somali Current Large Marine Ecosystems Project (ASCLME, 2012). We provide a summary of the baseline metocean conditions of the Seychelles region reported within this assessment, supplemented by a review of other relevant studies related to the climatic and oceanographic variability of the Seychelles Islands with a focus on the Mahé Plateau. This baseline review is focused on the following topics and parameters:

- Monsoon variability;
- Extreme weather and climate change;
- Ocean currents;
- Tides;
- Waves;
- Seawater temperature and salinity.

In addition, we review findings from ancillary environmental reports from government agencies pertaining to metocean events of interest (e.g. storms) and the impact of climate change on Seychelles Islands that should be taken into account in the implementation of the MMP within an ecosystem-based approach. The primary data sources for the Seychelles baseline environment review include the following:

- ASCLME 2012. National Marine Ecosystem Diagnostic Analysis. Seychelles. Contribution to the Agulhas and Somali Current Large Marine Ecosystems Project (supported by UNDP with GEF grant financing).

- Chang-Seng, D. 2007. Climate variability and climate change assessment for the Seychelles. GEF/UNDP/Government of Seychelles. Victoria, Seychelles.
- IXSURVEY. 2010. Environment and Social Impact Assessment Study (ESIAS) Seychelles. Document Ref. BIO/T1831_0.1_ESIAS_Draft.
- UNEP. 2008. Status of the Marine Environment Report. Seychelles. UNEP-GEF WIO-LaB Project Addressing Land Based Activities in the Western Indian Ocean. Compiled by Bijoux, J.P., Decomarmond, A. & Aumeeruddy, R. 192 pp.
- Vasco. 2009. Offshore Sand-Burrowing in Seychelles. Environmental Impact Assessment. Part 1: Description of the Project; Part 2: Description of the Environment; Part 3: Turbidity Generated by Dredging Operations.
- World Bank. 2013. Seychelles Damage, Loss, and Needs Assessment (DaLA) 2013 floods: a report by the Government of Seychelles. Washington DC: World Bank.

2.1 Monsoon seasonality

The climate of Seychelles Islands is warm (monthly mean temperature of 26-28°C) and can be classified as being humid tropical. No distinct dry season occurs throughout the year and even during the driest and coolest month in July the mean rainfall exceeds 70 mm (Chang-Seng 2007). Alternating monsoons generated by changes in the air pressure over the Indian sub-continent (Thurman and Trujillo 2004) dominate the seasonality. These changes in atmospheric pressure are driven by the lower heat capacity of rocks and soil compared with water. During northern hemisphere summer, the Asian mainland warms faster than the adjacent water creating low pressure over the continent and forcing air to move from the Indian Ocean onto the Asian landmass. During winter, the pattern is reversed and air over the Asian mainland rapidly cools creating high pressure and the movement of atmospheric masses off the continent and out over the ocean. The general monsoon patterns are as follows[1]:

- Southeast monsoon: relatively dry and cool season from May to October dominated by persistent southeast trade winds with maximum speeds in July and August (average speeds of 5-10 m/s). Precipitation during this period is normally light (70-190 mm/month) and rather short-lived.
- Pre-northwest monsoon: shift in wind from southeast to northwest that occurs in November and is associated with the onset of the rainy season (>200 mm) and very light winds (~3 m/s).
- Northwest monsoon: rainy season from December to March with increased precipitation in December and January (~300-400 mm/month). Winds at the Seychelles are generally light (~3 m/s) and predominantly from the west and northwest during this period. However, the northwest monsoon also corresponds to the cyclone season in the southwest Indian Ocean and storm surges and strong swells can hit the Seychelles during these months. For example, the large tropical storm *Felleng* which occurred on January 27–28, 2013 resulted in heavy rains (up to 184 mmm within 24 hrs) and caused severe flooding and numerous landslides across the country (World Bank 2013).

[1] Chang-Seng (2007) and ASCLME (2012) both report the monsoon variability as a gradient between a southeast and northwest monsoon based on the respective prevailing wind patterns. The latter nomenclature is also used here although classical notions of the Indian Ocean climate refer to a southwest and northeast monsoon based on oceanographic conventions (Novozhilov et al. 1992; Spencer et al. 2000; Encyclopædia Britannica 2016).

- Pre-southeast monsoon: calmest and warmest period of the year during the month of April. This is the transition period when the intensity of winds reduces significantly (~2.5 m/s) before reversing to the southeast.

2.2 Extreme weather and climate change

The Seychelles inner islands are typically considered as lying outside of the cyclone belt in the Indian Ocean (e.g. IXSURVEY 2010; ASCLME 2012). However, the recent assessment conducted by the Government of Seychelles (World Bank 2013) suggests the possibility that the cyclone belt and risk area is widening in the Indian Ocean, potentially putting the Seychelles in a more vulnerable position with respect to cyclonic development. The assessment concluded that there is a 50-80% likelihood that rainfall during the Northwest monsoon will increase on an annual basis given the measured increasing trend of +13.7 mm per year (or +1.8% per year compared to an annual rainfall of approximatively 700-800 mm). The development of new coastal infrastructures, including roads, public buildings and industrial facilities, should therefore include planning for minimizing risks associated with extreme weather events (World Bank 2013).

The 2013 assessment conducted by the Government of Seychelles (World Bank 2013) also concluded that during the majority of the El Niño/La Niña years, an extreme weather event typically occurred over the Seychelles. Severe drought during the La Niña phenomenon of 1998-1999 caused acute shortage of freshwater resulting in the close down of public establishments (ASCLME 2012). In 1997-1998, the strongest El Niño ever recorded caused a 40% loss of revenue from the tuna fisheries sector (Robinson et al. 2010) and generated massive coral bleaching in the shallow reefs of the Seychelles granitic islands (Spencer et al., 2000). With global warming, other tropical oscillations could be altered, such as modifications in the Indian Ocean Dipole that is expected to lead to stronger easterly winds south of the equator during the austral spring and faster warming of sea surface temperatures in the western Indian Ocean compared with the eastern basin (Cai et al. 2013).

The recent study of Khan and Amelie (2015) further discusses the high level of vulnerability of Seychelles Islands to climate change as well as the potential economic implications. In addition to the severe El Niño/La Niña of 1997-1999 and *Felleng* storm of 2013, recent extreme weather events include the Indian Ocean tsunami in 2004, heavy rainfall and coastal flooding on Mahé in 2004, tropical cyclone in 2006, and tidal flooding on Mahé in 2007 and 2012.

2.3 Oceanography

The Seychelles Bank is a shallow and low-lying plateau with average water depths less than 100 m and average topographic elevations of 2 to 6 m above the seabed. The bank extends approximatively 320 km by 150 km (4-5°S, 54-57°E) representing the northern-most part of the Mascarene Plateau (Fisher et al. 1967). The bank is relatively isolated and is surrounded by the deep Indian Ocean reaching depths of thousands of meters. The sea floor of the Seychelles Bank (or Mahé Plateau; UNEP 2008) has been mapped to some degree and hard substrate is known to make up approximately 45% of the plateau (UNEP 2008; IXSURVEY 2010). The rest of the plateau is made up of soft sediments of different categories of which muddy sand and mud were mapped as being the most common within the UNEP (2008) marine environment report (Figure 1). According to UNEP (2008), the main islands of Mahé and Praslin are apparently both located in a zone dominated by mud sediments, while the island of Silhouette is located in the muddy-sand zone. More recent data collected as part of the offshore Sand-Burrowing project (VASCO 2009) and MMP field survey (see section 3.0) around the inner islands show that the bed substrate varies between course sand, coral rubble and shell grit to medium and fine sand. The map of UNEP (2008) provided below could thus be updated as part of the MMP implementation phase.

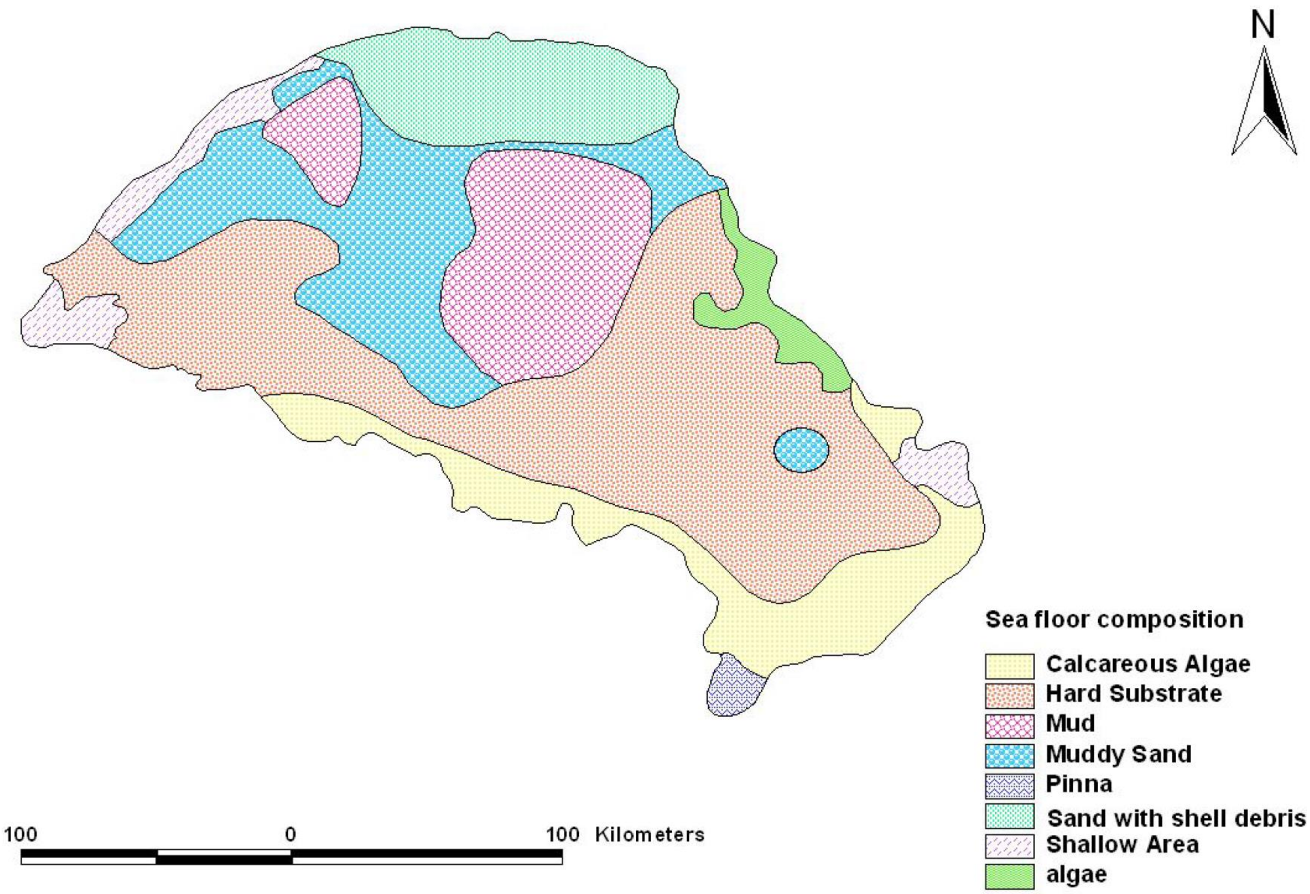

Figure 1: Sea floor composition of the Seychelles Bank (source: UNEP 2008)

2.3.1 Ocean currents

From a broad ocean circulation perspective, the Seychelles Bank is in the center of the northern Indian Ocean Gyre, a large-scale circulation pattern that changes with the seasonal monsoon (Novzhilov et al. 1992; Spencer et al. 2000). During the northwest monsoon from November to March, the Seychelles are influenced by the eastward-flowing Equatorial Counter Current (ECC) which is flanked to the north and to the south by the westward-flowing North Equatorial Currents (NEC) and South Equatorial Current (SEC) (Figure 2). The ECC flows between 2 and 8°S contrary to similar equatorial countercurrents of the Pacific and Atlantic oceans which flow north of the equator. During the northern hemisphere summer (southeast monsoon from April to October), the winds reverse with southeast trade winds becoming dominant. As a result, the ECC disappears and is replaced by the Southwest Monsoon Current (Figure 2), which flows from west to east centered on 6-10°N and is fed by the northward Somali Current that flows along the coast of Africa with velocities approaching 1-2 m/s (Thurman and Trujillo 2004). The SEC remains present in both seasonal monsoon contexts.

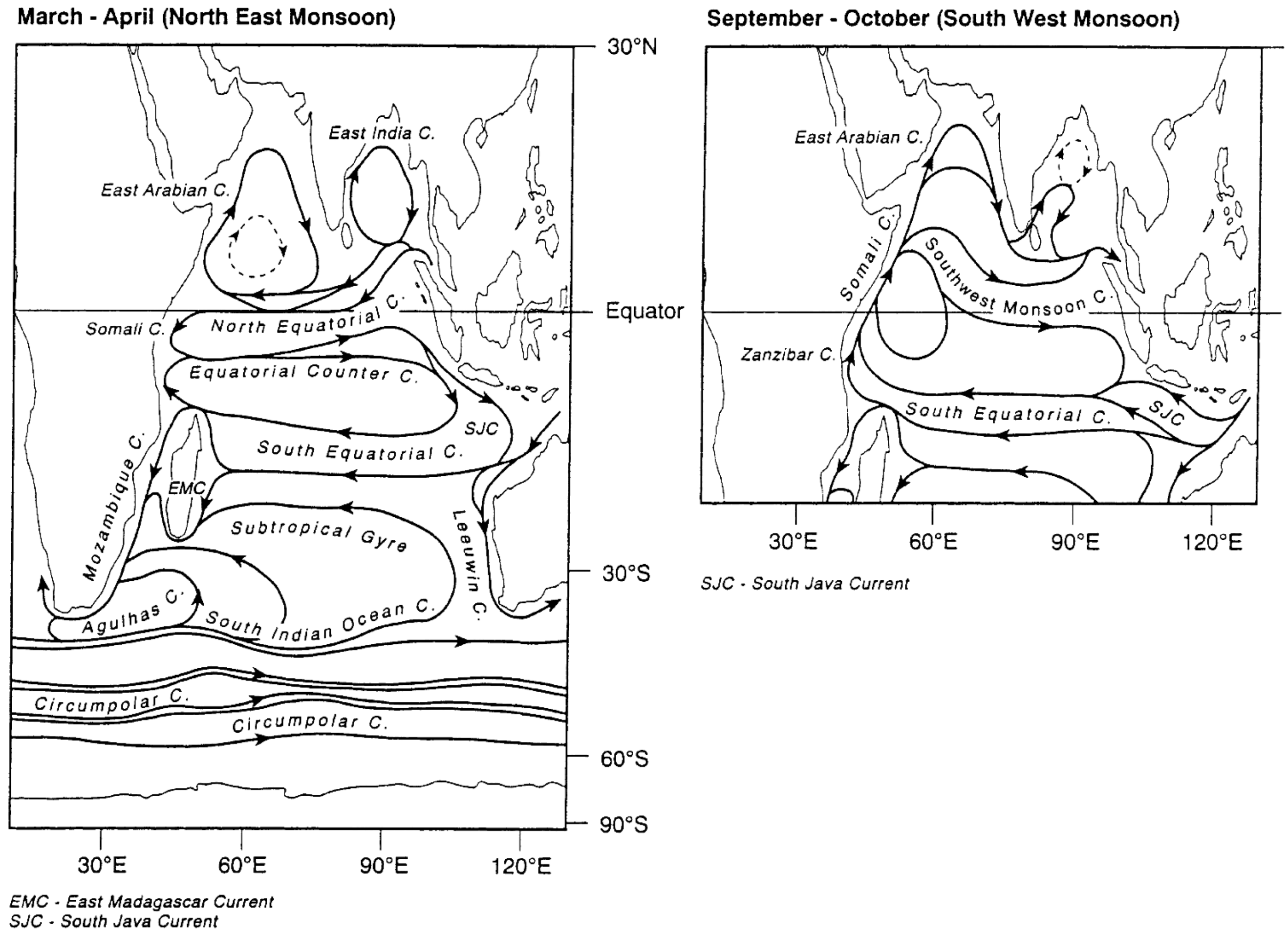

Figure 2: Surface currents in the Indian Ocean in March to April (late northeast monsoon) and September-October (late southwest monsoon). Adapted from Spencer et al. (2000).

The MEDA assessment (ASCLME 2012) reports that there has been very limited study on coastal currents in Seychelles waters, with most studies conducted around Mahé. One of the few studies on coastal currents of the inner islands is reported in Novozhilov et al. (1992) within which currents were recorded by current meters in the water column and in the bottom layer (0.5 m above the bottom) over a duration ranging from 17 h to 8.5 days from January to March 1989. Target study areas included the granitic islands of Mahé, Praslin and La Digue, but did not include Silhouette Island. On the open south coast of Praslin Island, relatively strong currents were measured, with mean current speeds of 17-21 cm/s and maximum speeds reaching 28-32 cm/s. At sites protected from wave action, movement of water near the bottom becomes progressively weaker with current speed not exceeding 4-5 cm/s at St. Anse Bay on the western point of Praslin. Stronger coastal currents were typical of shallow bottom sites between islands, such as between Cerf and St. Anne Islands near Mahé where near bottom speed ranged from 15 to 22 cm/s as a result of tides constriction in narrow channels. Mean current speeds in subsurface layers of outer reef slopes are 30-40 cm/s and near the bottom currents rarely exceed 5-10 cm/s.

A SFA technical report on Beau Vallon Bay (Grandcourt 1995) also reports measurements taken by two current meters deployed at 10 m depth in August 1989 and January 1990 in the context of a sewerage feasibility study.

In August 1989, current readings ranged from 5 to 25 cm/s flowing to the ENE. In January 1990, one of the two current meter provided a reading of 5 cm/s to the SSW, while no data was available for the second current meter.

In April 2009, ocean current data were acquired over a 7-day period in the northwest and southwest borrow areas of Mahé as part of an impact assessment related to sand dredging (Vasco 2009). Current speed and direction were measured with Nortek acoustic wave and current profilers (AWAC). Measurement depths and deployment locations are not provided. Results showed that currents flowed to the northeast at mean speed of 10 cm/s in the northwest burrow (range 1-20 cm/s); and to the southeast at mean speed of 18 cm/s in the southwest burrow (range 2-36 cm/s). Currents were considered calm (<8 cm/s) at 44.1% of the time in the northwest borrow and 20.4% of the time in the southwest borrow. These measurements were acquired during the pre-southeast monsoon, which is considered the calmest period of the year.

Based on satellite altimeter data, monthly-mean current speeds at the surface around Mahé vary from 10 to 14 cm/s during the southeast monsoon, while they vary from 15 to 27 cm/s during the northwest monsoon (ASCLME 2012). Such monthly averages do not provide insights on the short-term variability and actual range of current speeds. Furthermore, they are applicable to the near-surface layer only and are based on a global model that has not been validated locally (Bonjean and Lagerloef 2002). A search conducted by Golder reveals that no current meter/ profiler data are available for the Seychelles Bank within the Global Ocean Currents Database (Sun et al. 2015), the main repository for worldwide ocean currents observations. The MEDA assessment concludes that the lack of information on relevant coastal hydrodynamic processes is a matter of concern due to the importance of the coastal zone to Seychelles' socio-economic development. This concern appears to have been partly addressed by recent initiatives from the Seychelles National Oceanographic Data Centre (SNODC; http://www.nodc-seychelles.org/en/). The SNODC aims at archiving important marine datasets and is currently developing a hydrodynamic model for the region in collaboration with SFA. However, **long-term measurements of sea level and ocean currents to support model calibration and validation in the coastal zone are needed**.

2.3.2 Tides

The tidal regime of Seychelles at a local scale is better characterized than the current speed and direction dynamics. Tide gauge measurements in the archipelago have been initiated in 1962 at Port Victoria (ASCLME 2012). The tide gauge network expanded over the years to the Seychelles Coast Guard jetty (1987), the Seychelles International Airport at Pointe Larue (1993), and to Denis Island (2009). Vertical datums based on sea level variation at the Seychelles International Airport station are provided in Table 1. Accurate information on water level trends and variability is critical for many coastal applications, including mapping, marine management, and coastal engineering. Oscillations in current speeds at open sites around the inner islands (e.g. south coast of Praslin) are also tightly linked to tidal processes with typical periods of 12 and 6h (Novozhilov et al. 1992). Dive charter operations concur that tides are a key driver of ocean currents around Mahé (Hecht, T. personal communication.

Table 1: Seychelles sea level variation based on the time-series acquired with an automatic tide gauge at Pointe Larue (source: ASCLME 2012).

Tide	Elevation above Chart Datum (m)
Highest Astronomical Tide (HAT)	2.10
Mean High Water Spring (MHWS)	1.63
Mean High Water (MHW)	1.45
Mean High Water Neap (MHWN)	1.27

Tide	Elevation above Chart Datum (m)
Mean Water Level	1.10
Mean Low Water neap (MLWN)	0.81
Mean Low Water (MLW)	0.63
Mean Low Water Spring (MLWS)	0.45
Lowest Astronomical Tide (LAT)	0.20

The 2013 assessment conducted by the Government of Seychelles (World Bank 2013) identifies sea level rise as a major threat to the economy and livelihoods of Seychellois people given the numerous infrastructure located along the coastal plains and reclaimed land. Chang-Seng (2007) suggests an annual sea-level trend anomaly of +1.46 mm with a standard error of ± 2.11 mm per year on Mahé Island, which is consistent with the global average sea-level rise of +1.8 mm per year over 1961-2003 period. Sea level variability is also influenced by episodic storm surges and swells. As mentioned in section 2.2, the inner islands of the Seychelles archipelago are traditionally known to be not affected by cyclones (IXSURVEY 2010; ASCLME 2012). Rarely, tropical cyclones that form in the southeast of Seychelles generate heavy swells that affect the coasts (Duvat 2009). The cyclone *Felleng* was one of these rare events that formed south of the archipelago (EUMETSAT 2013). Swells could have their origin at a few hundreds or thousands kilometres and reach the islands if the fetch conditions are favourable.

2.3.3 Waves

During the Northwest monsoon from November to April, offshore waves generally approach the coast from the NNE and remain relatively low to moderate (monthly average significant wave height of 1.1 m), with only 9.5% of the significant wave height being more than 2 m. The dominant wave direction during the Northwest monsoon contrasts with the dominant wind direction which is from the WNW during this period (ASCLME 2012). During the Southeast monsoon, waves are higher than during the Northwest monsoon and generally approach the coast from the SSE (in accord with the southeast trade winds) with monthly-average significant wave heights of approximatively 2.4 m from May to October (ASCLME 2012). According to IXSURVEY (2010) citing the report of Cazes-Duvat (1999), swell heights during the Southeast monsoon are small (<2 m) 60.1% of the time, moderate (2-4 m) 37.2% of the time, and rough (>4 m) 2.7% of time.

Unusually large waves for the Seychelles were also associated with the tsunami generated by the earthquake that occurred off the west coast of Sumatra (Indonesia) on 26 December 2004, which travelled 5,000 km before reaching the Seychelles Bank. By midday on 26 December an extreme low tide occurred throughout the inner Seychelles Islands and tsunami waves ranging from 2.5 m to 4 m in height came ashore on the east coast of Praslin and Mahé islands (UNEP-ATDF 2005). However, the most extreme significant wave heights observed near the Seychells were likely associated with the tropical cyclone *Felleng* of late January 2013 (World Bank 2013). This cyclone caused peaks in significant wave height up to 11.5 m nearby Madagascar during its transit over the southern Indian Ocean (EUMETSAT 2013). However, no quantitative statistics on wave height and periods for this event could be sourced for the Seychelles Bank because of the lack of real-time ocean monitoring systems in the region.

Regional wave forecasts for the Seychelles are produced by Indian National Centre for Ocean Information Services (INCOIS) and are available online through the Seychelles National Meteorological Services (SNMS; http://www.meteo.gov.sc). Marine forecasts are updated daily and provide warnings and 24-h forecast of wind, maximum and average wave height, wave period, and sea state. The INCOIS forecasts are however not validated locally and according to SNMS (Vincent Amelie, pers. comm., April 2016), these forecasts are very crude and not reliable. The Seychelles Nation newspaper reported in May 2015 that the first wave-rider buoy was to be installed in Seychelles to strengthen local wave/swell observations and to improve the performance of the Indian Ocean forecasting models, particularly in the region of Seychelles (Seychelles Nation 2015). SNMS reported in March 2016 that the wave rider buoy had been successfully deployed in Seychelles waters (SNMS 2016). This initiative lead by the Regional Integrated Multi-Hazard Early Warning System (RIMES) for Asia and Africa in collaboration with INCOIS and local partners (e.g. SFA, SNMS) was also a response to the 2004 tsunami and *Felleng* cyclone events which forced Indian Ocean countries to rethink their metocean services and how these could be more coordinated and efficient. Data delivered from the wave rider system includes wave height and direction, sea surface current, sea surface temperature, mixed layered depth and depth of the 20°C isotherm. These data are currently being analyzed so that they can be used to validate the INCOIS model forecasts. Proper formatting of these data is also underway in order to be available in real-time in the public domain and guide marine operations around the inner islands of Seychelles (Vincent Amelie, SNMS, pers. comm., April 4 2016).

2.3.4 Temperature and salinity

Sea surface temperatures in Seychelles follow air temperature patterns and range from 26 to 31°C, with warmest temperatures reached in March-April (ASCLME 2012). Deeper subsurface south subtropical intermediate water has a temperature of 12-14°C and a temperature gradient of 2.2 to 2.4°C per 10 m (Novozhilov et al. 1992). Salinity in the deep Indian Ocean surrounding the Seychelles Bank occupies a narrow range from 34.5 to 35.5 (practical scale) throughout the water column (Schott and McCreary 2001). In the near-shore zone, salinity patterns and variability are poorly documented, but the MEDA 2012 assessment reports average salinity for Beau Vallon, Port Victoria and along the East Coast of Mahé to range from 32.7 to 33.1 due to freshwater inputs near the coast. Novozhilov et al. (1992) reports higher salinities of 35.2-35.3 near La Digue and about 35.1 on the south coast of Praslin. In addition of the sources mentioned above, some historical temperature-salinity profiles for the Seychelles Bank and surrounding waters are available in the World Ocean Database (https://www.nodc.noaa.gov/OC5). The vast majority of them were collected by mechanical and expandable bathythermographs prior to 1980.

During the Northwest monsoon, the clockwise (cyclonic) circulation at the meeting point of WNW and SE winds that generate the ECC and SEC is responsible for the formation of a peculiar oceanic structure called the "Seychelles–Chagos thermocline ridge" (centered on 5-10°S and 50-70°E; Vialard et al. 2009). This feature is created by the surface divergence associated with the clockwise circulation which is compensated for in its center by upwelling. This upwelling brings cold and nutrient-rich thermocline water to about 50-100 m depth (Vialard et al. 2009). Positive sea level anomalies of +0.3-0.4 m can be measured as a result of this upwelling. However, this upwelling dome is distinct from those observed in the Pacific and Atlantic oceans as sea surface temperature remains warm, enabling strong air-sea interactions. The upwelling of deep waters can be primarily discerned by a thickening of surface waters and positive sea level anomaly (Novozhilov 1992; Vialard et al. 2009).

3.0 REVIEW OF MARICULTURE MASTER PLAN STUDIES

This section aims at providing a critical review of the specialist studies and reports collated by SFA as provided to Golder prior to September 29, 2016. Our review focuses on reports and legislative products of the MMP and how they address environmental particularities of the Seychelles Islands and potential farm sites. From the 57 MMP products listed in Table 6 of the summary MMP document developed by SFA (SFA 2016a), 40 of these products were provided to Golder as of March 29, 2016. Addition datasets from various sources (Excel files and ASCII Text files), reports and documents on international aquaculture policy were also provided. According to SFA (2016a), the MMP has also been through a peer-reviewed process in April 2015, but the documents that resulted from this peer-review process were not made available to Golder.

Among the available MMP products listed in Table 6 of SFA (2016a), Golder identified 5 specialist reports that directly pertain to the metocean context of the MMP and to how the biophysical constraints are addressed within the MMP. The relevant documents listed in SFA (2016a) that are summarized and reviewed below are the followings:

1) Stocktaking and diagnostic survey of mariculture in the Seychelles

2) Proposal to declare certain offshore areas as designated aquaculture development zones

3) Bio-Physical Assessment for Mariculture Master Plan

4) Seychelles Hatcheries: potential sites, size, production capacity and the way forward.

5) Marine Assessment Report on the location of water intake pipe for the Aquaculture Development Zone (ADZ) on Ile de Romainville, Seychelles

In addition, two supplementary MMP documents detail the potential industry scenarios (or “carrying capacity scenarios”) and the final selection of the ADZs around the inner islands of Seychelles. These two additional documents were both developed by SFA and are:

6) Seychelles Fishing Authority. 2016b. Seychelles Industry Capacity Projections. Mariculture Master Plan Supporting Document. July 25 2016. 34 pp.

7) Hecht, T. 2016. Selection of Aquaculture Development Zones (ADZs) Around the Inner Islands of Seychelles and their Ecological Carrying Capacity. Site Selection Report. September 6, 2016. 127 pp.

The 7 documents listed above are reviewed in the following subsections in a chronological manner. Findings and validation of existing information or conclusions reached by the various documents are identified. Gaps in knowledge or methodological are highlighted throughout the review, but are further summarized in section 4.2 together with the outcomes of the impact assessment of aquaculture cages presented in section 4.0.

3.1 Stocktaking and diagnostic survey of mariculture in the Seychelles

This document was prepared by SFA and is dated of September 2011. It represents a preliminary assessment of the bio-physical conditions related to opportunities for mariculture around the inner islands of Mahé, Praslin and Silhouette. The assessment presents briefly the results from two ship cruises (sampling period and methods are not mentioned) that helped identifying potential cage culture sites. Bathymetry and depth were assessed by echo soundings and substrate type was assessed by video recordings and verified by in situ samples. Field data from these surveys are actually not presented in the report. Sites are not identified and no quantitative data or characterization results are further provided in this document. The report nevertheless diagnoses that the inner Seychelles islands have suitable areas and sites for cage culture: “*Bio-physical conditions are similar if not superior to other regions where tropical marine fish farming is practiced*”. The report also concludes that further work needs to be undertaken to confirm the suitability of the sites during the SE monsoon season.

3.2 Proposal to declare certain offshore areas as designated aquaculture development zones

This document dated of 2013 presents the results of two site selection cruises undertaken in 2009 (scoping study, exact dates unknown) and two additional cruises in 2013 (September 9-16 and October 1-4, 2013). Sampling periods, target sites and general methods are provided. 16 sites were visited and coordinates are provided and correspond to the initial ADZs (Figure 3). The primary approach at each site was to assess bathymetry by echo sounding and sediment composition through video transects and samples taken with a small Eckman Grab. In 2013, water column profiles were acquired with a YSI sonde (temperature, conductivity, salinity, and dissolved oxygen in mg/L). Ancillary data supplement this core dataset, including wind data as measured at the Seychelles International Airport as well as wave and current speed data derived from remote sensing analyses (exact data source not mentioned). Measured current speed ranges from 9 to 33 cm/s with a mean of 19 cm/s. Wave height is from 1.0 to 2.5 m. The geographical delimitations of these datasets is not provided. These values, however, correspond to the typical expected values for the Seychelles as described in section 2.3. The 2013 cruises were affected by rough sea conditions, which hindered side scan sonar and ROV surveys at 4 sites (sites 4, 5, 6 and 11). The water column and wave data are presented as bulk statistics for each parameter and for all sites at once. The wind speeds are presented as monthly averages (range 1.0-11.3 m/s). Percent of sand is given (range 20-100%) for each site where sampling was possible (12 sites out of 16).

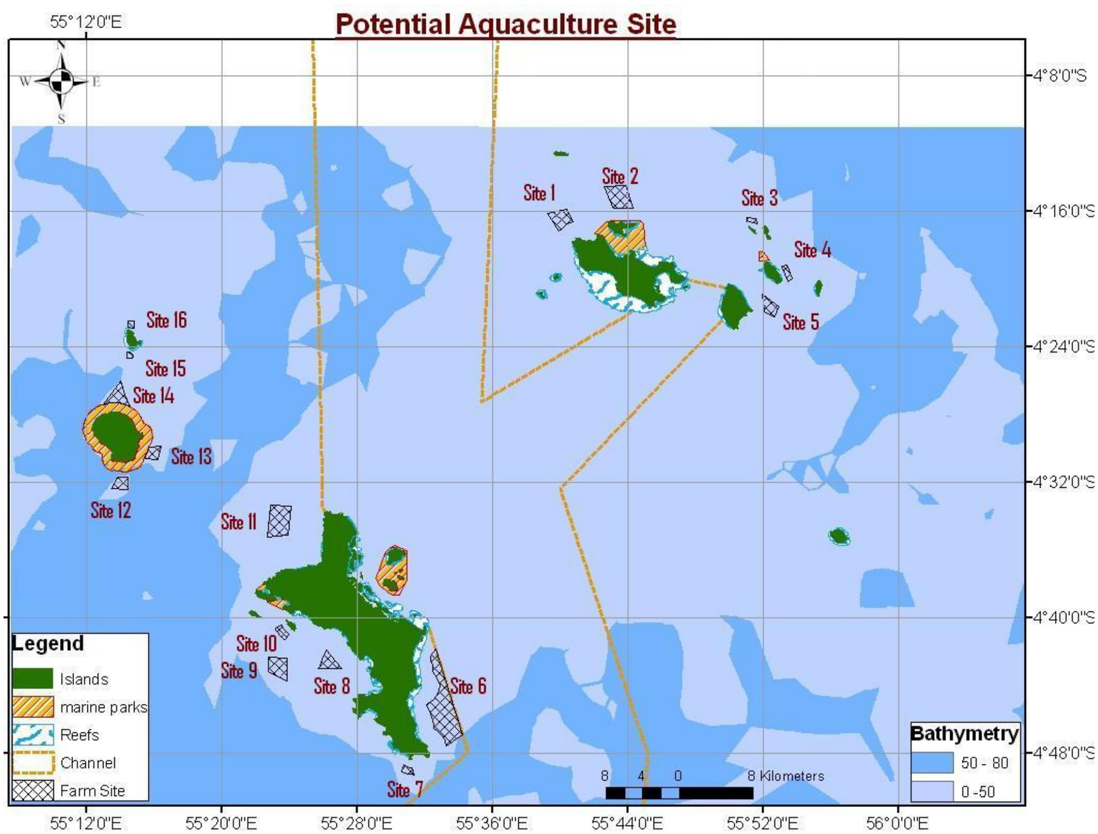

Figure 3: Map of the initial 16 potential aquaculture development zones of the Seychelles Mariculture Master Plan. It should be noted that Sites 7, 12, 13 and 15 were finally rejected due to the presence of coral reefs. Moreover, Sites 9, 10, 14 and 16 were reduced in size by between 20 and 40%.

Results are related to the optimum conditions for open sea cage culture as described by Bald et al. (2002), a 2-page site selection protocol for open sea cages in the Mediterranean Coast of Spain. The summary table of Bald et al. (2002) for environmental factors and the ranges in which they can be considered good, medium or bad for aquaculture development is provided in Table 2. The main conclusion is that theoretically no significant impact on the water and a limited impact on the seabed if the fish would occur if the fish are be farmed under international Best Management Practices according to Helsley (2007). On the basis of this conclusion, it was recommended that all 16 sites should be designated ADZs and states that it will be up to SFA and the Department of Environment to decide whether a further Environmental Impact Assessment would still be required.

Table 2: Summary table for environmental factors and the ranges in which they can be considered good, medium or bad for aquaculture development in the Mediterranean Sea (Bald et al. 2002)

FACTOR	GOOD	MEDIUM	BAD
Exposition	Partial	Sheltered	Exposed
Wave height regime	1 to 3 m	<1 m	>3 m
Bathymetry (depth,)	>30 m	15 to 30 m	<15 m
Current Velocity	>15 cm s^{-1}	5-15 cm s^{-1}	<5 cm s^{-1}
Water contamination	Low	Medium	High
Maximum temperature	22 to 24ºC	24 to 27ºC	>27ºC
Minimum temperature	12ºC	10ºC	<8ºC
Average salinity	25 to 35	15 to 25	<15
Salinity (fluctuation)	<5	5 to 10	>10
Dissolved oxygen (%)	>100	70 to 100	<70
Slope (%)	>3	1 to 3	<3<10
Substrate	Sand or gravel	Mixed	Mud
Trophic condition	Oligotrophic	Mesotrophic	Eutrophic
Fouling	Low	Moderate	High
Predators	No	Some	Abundant

3.3 Bio-Physical Assessment for Mariculture Master Plan

This is a report prepared by SFA (oceanographer Calvin Gerry) and dated of 2013 that further discusses the results provided in the previous proposal document. The discussion is centered on the percentage of sand at each site and seven of the sites are identified as being composed of sand at 75% or more (i.e. a factor that can be considered good for aquaculture development, Table 2). This discovery of a sand-dominated sea bottom at each site contradicts previous geological mapping of the area (UNEP 2008) that previously stated that consolidated mud sediments could be primarily found around Mahé (see section 2.3). Salinity-temperature data are also detailed in the report and are in the expected range for the region (mean temperature from 25.5 to 28.8 ºC, and salinity from 32.7 to 34.0; similar to literature). The report concludes that additional side scan sonar survey is highly recommended to obtain better information of the bed composition at the different sites and to survey the sites for which no data seta are available. SFA also advises that appropriate oceanographic time-series data need to be collected to provide insights on the oceanographic properties of the sites over seasons. No other available MMP document provides information on potential additional side scan sonar survey or on the initiation of oceanographic time-series measurements since 2013.

3.4 Seychelles Hatcheries: potential sites, size, production capacity and the way forward

This documents focuses on the environmental constraints related to the potential sites of the hatchery in Mahé (dated of November 2013, by Simon Daniel, SFA). The key objective is to assess the context of the potential hatchery sites through a characterization of the prevailing winds, currents, wave action, hydrology, shore line processes, water quality, and sediment quality. Three sites are assessed: Providence, Aurore and St. Anne Island. The fieldwork for this assessment was undertaken from September 22 to October 6, 2013 and overlaps with the dates of the fieldwork mentioned in the ADZs proposal and bio-physical assessment documents. General information on the oceanographic context is given without exact quantification or references to data source/sampling procedures. Examples of such generalization comprise:

- Sea surface current direction is south to north all year round outside of the harbour in Providence; generally, from north to south at St. Anne Island depending on tides; and is south-north in the groin area of Aurore Island with a build-up of litter/ marine fishing debris observed in the south at the sampling time.;
- Seabed is generally flat and the substrate is generally sandy in Providence; predominantly scattered reef and sand at St. Anne; and also consists of scattered reef and sand at Aurore Island, although the site appears heavily infested with sea urchins and covered by seaweed;
- Prevailing winds on Mahé Island are the northwest trades from October to March and the southeast monsoon from April to September, as know from the climatology.

Although water samples were collected as part of study, no water quality data are actually mentioned as the samples were still under process at the time of the completion of the report. Golder could not identify any MMP product describing the baseline conditions in water quality at any of the potential farming or hatchery sites as based on samples collected in 2013. Most of the discussion is on negative and positive aspects of each potential hatchery site in relationship to the presence or absence of the infrastructures needed for a typical hatchery site. The report does not recommend one site more than one another, but Golder understands that as of 2016 the Providence site south of Victoria has been selected for a pilot project cage operation and grow-out facility according to the SFA presentation to stakeholders of February 3, 2016. One of the recommendations highlighted with respect to Providence was that a water quality monitoring program for hydrocarbon should be implemented because this area is heavily industrialised and fuel/oil contamination of incoming water may occur (e.g. a fuel slick was noticed on the surface of the water during the sample collection). Also the water abstraction point (suction end of the intake pipeline) needs to be at least 100 m offshore in order to reduce friction losses and impact on operational and capital cost. However, this site presented advantages such as existing commodities (e.g. drainage channel, jetty) and a rationale describing that biodiversity and biosecurity were not at risk for this location.

3.5 Marine Assessment Report on the location of water intake pipe for the Aquaculture Development Zone (ADZ) on Ile de Romainville

This document authored by Fisheries and Marine Consultancy Services, Mahé (2015) provides a site survey undertaken around the Ile de Romainville (artificial island just in front of Victoria) on February 19-20, 2015 by snorkelling. The goal of this survey was to map the seabed off the east coast of Isle de Romainville and to determine the most suitable path along which to lay a pipe for the provision of a higher water quality to a potential land-based aquaculture development zone from the shore. The main results of the snorkelling survey indicates that both the north and east of Ile de Romainville meet the requirement for the entrance of an intake pipe. During the survey, seawater on the north and north-eastern portion of Ile de Romainville was affected by high concentration of phytoplankton resulting from high nutrient input into the area from the effluent being discharged from a tuna canning factory. About half way down the eastern side of the island, the water started clearing up and visibility increased to about 10 m. This resulted from mixing with clean water coming through the Cerf Island Channel and wave action along the southern part of the island. Hence, the preferred option for the pipe (i.e. option 1, “highly recommended”) is a location south side of Ile de Romainville where water is clear, where there is no reef and where the rock armouring of the island makes direct contact with a sandy bottom which gentle slopes away in deep waters.

Therefore, this document identifies Romainville Island as a good location for the development of a hatchery cluster. Its seaward side is more exposed than any of the other reclaimed islands and would provide better water quality. Results from this study appear to support the development of a small-scale inshore project to accommodate an entry point into the aquaculture sector by local Seychellois investors (cf. inshore aquaculture zone).

3.6 Seychelles Industry Capacity Projections. Mariculture Master Plan Supporting Document

This document provides a summary of the carrying capacity scenarios and the aquaculture development and production envisaged under each scenario and, using assumptions, outlines the expansion of the industry that may be realised under different physical, environmental, societal, and licensing constraints. Three scenarios are proposed, namely the low-, mid- and high-road scenario. These three scenarios are thoroughly detailed in terms of financial, regulatory and logistic implications in the document and within an Excel companion file. Figure 4 provides a summary of these scenarios in relationship to each target aquaculture zone. The three scenarios are vastly different and result in different impacts in the Seychelles. In particular, it was stressed how a project-specific ESIA must be completed for each proposed project in the inshore zone because many sensitivities exist within this zone and the potential conflicts with tourism are substantially higher than for the ADZ and offshore zones.

AQUACULTURE ZONE	SPECIES	PRODUCTION SYSTEMS	ENVIRONMENTAL AUTHORISATION & DETAILS	CARRYING CAPACITY SCENARIOS
Land-based zone	Ornamental finfish (Pomacentridae spp., Pomacanthidae spp., Acanthuridae spp., Chaetodontidae spp.) Sea urchins (*Tripneustes gratilla*) Finfish fingerlings (Grouper spp., Snapper spp.) Pearl oyster spat	Pump-ashore flow-through systems Recirculating aquaculture systems (RAS)	Each project will require its own ESIA; specific sites for hatcheries and production systems to be determined per project. Only the Research & Development facility, Broodstock Acclimation & Quarantine facility and pilot cage will be assessed as part of the Golder Associates ESIA (Feb-Oct 2016).	
Inshore zone	Pearl oysters (*Pinctada margaritifera*) Finfish (Grouper spp., Snapper spp.)	Oyster longlines Cages; serviced daily from land	Each project will require its own ESIA, sponsored by SFA. Cage culture of finfish reserved for local residents.	
ADZs	Finfish (Grouper spp., Snapper spp.)	Cages; serviced daily from land	Finfish cage culture within ADZs being assessed as part of Golder Associates ESIA (Feb-Sept 2016).	
Offshore zone	Finfish (Grouper spp., Snapper spp.) only	Cages; serviced by offshore-based automated feeding barges	Each project will require a site specific ESIA, which the project proponent will fund.	

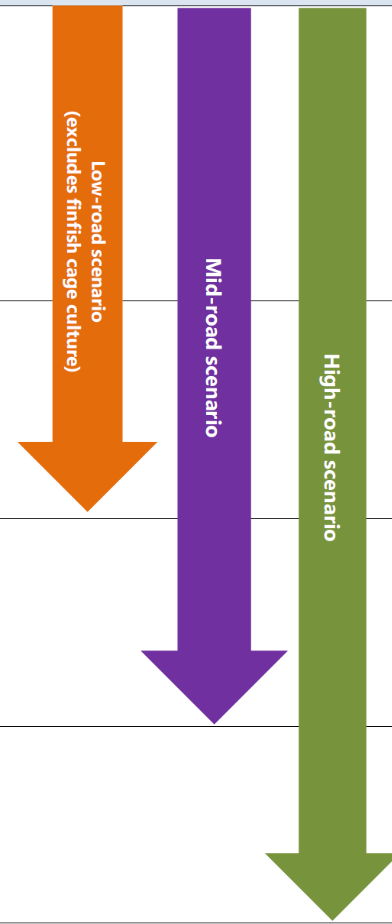

Figure 4: Summary of carrying capacity scenarios and ESIA requirements with respect to each aquaculture zone.

3.7 Selection of Aquaculture Development Zones (ADZs) Around the Inner Islands of Seychelles and their Ecological Carrying Capacity. Site Selection Report

This recent report (Hecht, T. September 2016) focuses on determining the suitability of the maritime zone for cage culture and the selection of appropriate areas where they could be deployed. Additionally, the report provides a modelling study that was conducted using the Norwegian MOM model (Modelling – Ongrowing – Monitoring), calibrated for Grouper fishes, in order to assess carrying capacity of the ADZ sites for finfish aquaculture.

The bio-physical scoping exercise described in section 3.2 and 3.3 previously identified 16 potential ADZs around the inner Seychelles islands with an approximate total surface area of 61 km^2. Those potential sites were selected based on several limiting criteria including a 2-km exclusion zone around the coast of inhabited islands, a 1-km exclusion zone around MPAs, mitigating visual impact, avoiding conflict with the sport diving sector and artisanal fisheries, avoiding restricted areas such as shipping lanes and fibre optic cables, selection of areas with a suitable sand dominated seabed, avoiding coral reefs and seagrass meadows and other sensitive areas, choosing areas with a suitable depth and bathymetry and seeking partial protection from the SE Monsoon winds. The site selection report further distillates this information and provides an analysis of all available physical and biological oceanographic, meteorological and hydrographic data collected as part of the MMP process.

Of the original 16 aquaculture development zones 25% were ultimately rejected, mainly because of the presence of coral patches. The other 12 zones have a sand dominated seabed and were not affected by the exclusionary criteria (Figure 5). The finding about the sand-dominated sea bottom around Mahé contrasts with previous geological mapping of the area that determines muddy sediments as the primary sediment type (UNEP 2008). Average depth of the selected sites is 40 m (range 25-62 m). The 12 zones provide a total of 53.2 km^2 for the initial development of the aquaculture sector. Eight of the 12 sites are relatively well sheltered from the SE Monsoon, one is partly sheltered (site PLD4) and three are not protected (sites PLD5, M1 and M54). A sheltered and protected site will be less exposed to stronger waves and currents that could develop during the SE monsoon, but are expected to result in lower waste dispersal and environmental impact, improved fish welfare and a better product quality.

Based on the FAO site classification guide and the limiting criteria for offshore cage culture in the tropics (Cardia and Lovatelli 2015; Table 3) as well as the average and maximum oceanographic conditions of the Mahé plateau obtained through the MMP field survey, related reports and literature, the site selection report concludes that fish cage culture is eminently feasible around the inner islands of the Seychelles.

Table 3: FAO site classification guide (Cardia and Lovatelli 2015) as extracted from Hecht (2016).

Feature	Coastal	Off the coast	Offshore
Location/hydrography	<500m from coast >10m depth at Spring low tide Within sight of land Usually sheltered	0.5-3km from coast 10-50m depth at Spring Low Tide. Often within sight of land. Somewhat sheltered	>2km from the coast Generally within continental shelf area, possibly open ocean >50m depth
Environment	Hs usually <1m Short wind fetch	Hs <3-4m	Hs 5m or more. Variable wind periods.

Feature	Coastal	Off the coast	Offshore
	Localised coastal currents, Possibly strong tidal streams	Localised coastal currents, some tidal stream.	Possible less localized current effect.
Access	100% accessible. Landing possible at all times	>90% accessible on at least once daily basis. Landing usually possible.	Usually >80% accessible, landing may be possible, every 3-10 days
Operation	Regular, manual involvement, feeding, monitoring	Some automated operations (e.g. feeding, monitoring).	Remote operations, automated feeding, distance monitoring system function

The MOM modelling study conducted as part of the site selection report of Hecht (2016) aimed to estimate the monthly maximum production of fish that can be sustained given a set of environmental conditions, feeding regimes, and sea cage arrangements. The model used generic oceanographic data for the Mahé plateau and average prevailing oceanographic conditions from Vasco (2009) to provide a preliminary assessment of conservative annual production limits. A review of the input data for the Seychelles MOM version 3.2 model (Table 20 of Hecht 2016) was conducted to assess any inconsistency with respect to what is generally known from the region in terms of metocean conditions. Values for current speed variability, wind and seawater density were within the range of acceptable values. The model was run for three different water depths (25, 35 and 55 m), each with a best, mid and worst case scenario. For this purpose, the following parameters were varied accordingly, viz. Current standard deviation, Dissolved O2 in bottom layer, Dimensioning current surface layer, Dimensioning current bottom layer, Lowest acceptable DO in cages, Lowest acceptable DO at the bottom and food conversion ratio.

The MOM model output predict that the maximum annual production of fish that can be sustained under all scenarios is 42.92 tpa/ha, a rate approximatively 4 times higher than the proposed precautionary production limit of 10 tpa/ha. This proposed precautionary production limit value for the Seychelles Islands was estimated based on a comparison with other areas where aquaculture has developed and assuming that a production of 1000 tpa / km^2 (10 tpa/ha) could be defined as conservative. Under all current speed scenarios used as part of the MOM modelling, the maximum annual production yields a carbon flux to the sediment that is apparently 0 g C m^{-2} yr^{-1}.

The conclusion is that the significantly higher production capacity than the precautionary limit (>4 times greater) adds confidence that the proposed production limit is adequately conservative to cover for any possible short comings in baseline data. Nevertheless, it was recommended that a precautionary principle of 10 tpa/ha limit **should not be exceeded until actual farm monitoring data become available that may support an increase in the rate of production per unit area**.

Hecht (2016) proposes that long-term monitoring of operational sites should include video-recorded observations of benthic substrates, hydrographic information, water quality measurements, sediment analysis, and benthic community assessment. Sampling and data collection must occur at intervals that capture seasonal variation in circulation, water quality, and other environmental characteristics. The aquaculture permit should clearly define the frequency, format, content, and distribution of monitoring reports and identify which agency shall review the reports (Price and Beck-Stimpert 2014).

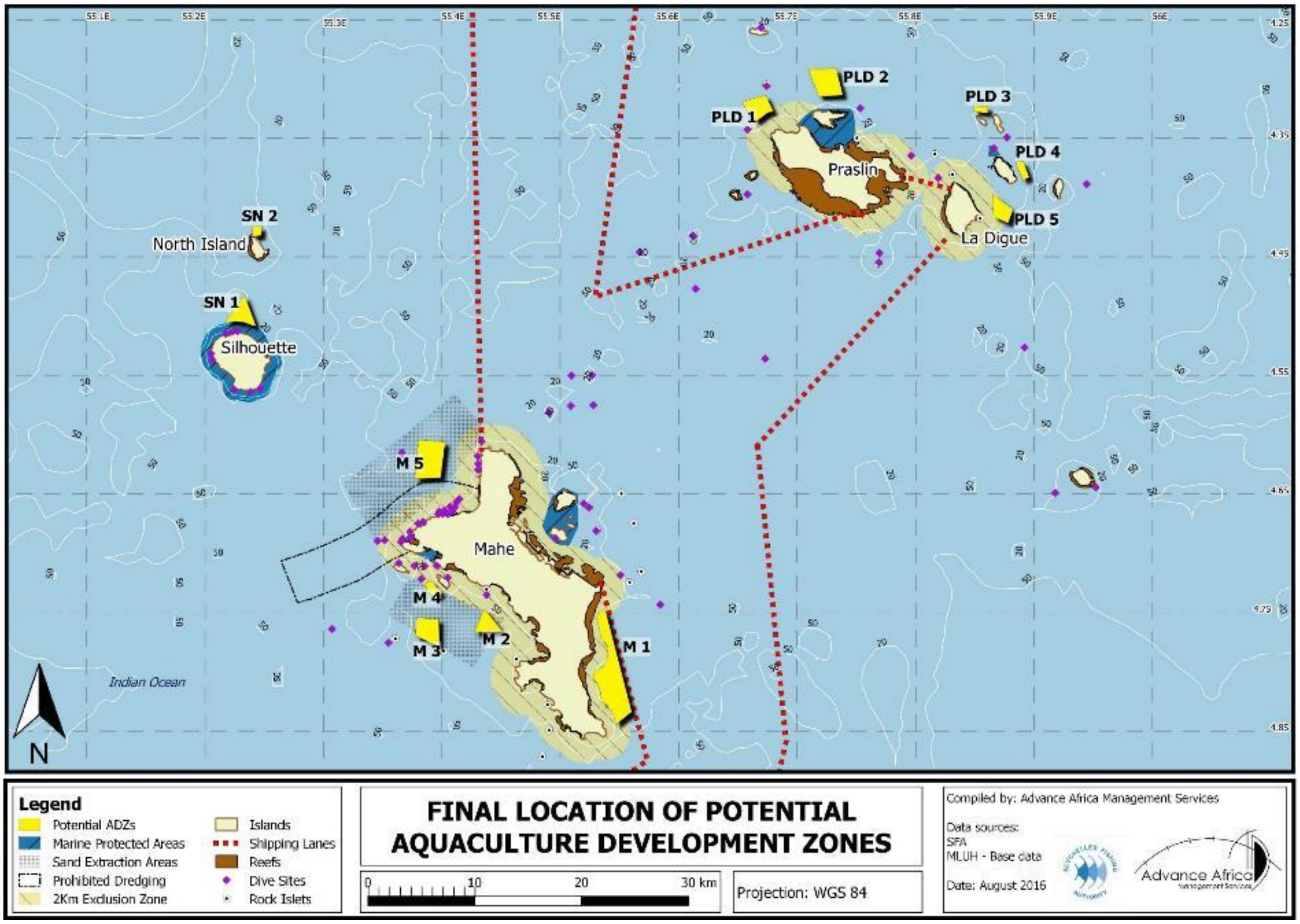

Figure 5: Final location of potential ADZs (source: Hecht 2016).

4.0 IMPACT ASSESSMENT OF ADZ DEVELOPMENT

The review of the baseline environment and MMP field studies and reports conducted in sections 3.0 and 4.0 show that the inner Seychelles Islands have adequate meteorological and oceanographic conditions to initiate ADZ development and sustain aquaculture activities in the short-term. The suitability of the offshore zone for cage culture was based on an analysis of the oceanic conditions around the inner islands from various sources and considered in relation to benchmarks as outlined in the guidelines of Bald et al. (2002) and Cardia and Lovatelli (2015). However, the actual impact of ADZ development on the coastal and marine environment will ultimately depend on the selected carrying capacity scenario (Figure 4) and level of industrialization required to support this scenario over time. In turn, the selection of a given carrying capacity scenario should be reassessed during the operational phase as understanding of the project viability is expected to evolve through environmental monitoring of fish farms and the acquisition of additional metocean data (as further detailed in section 5.0). Although the ADZs were carefully selected based on international aquaculture guidelines and an evaluation of all data available from site surveys and ancillary sources, the lack of long-term data as well as the inadequate environmental monitoring and real-time analysis systems on the Mahé plateau currently limits the decision-making process and underscores the need to proceed cautiously.

Indeed, the paucity of data is the main reason why the site selection report of Hecht (2016) recommends to start the MMP project with the precautionary principle in mind. The precautionary principle implies to initiate the cage culture development on the basis of a maximum of 1000 tonnes per square kilometre of fish production for the inner Seychelles (or 10 tpa/ha), although a theoretical 42.92 tpa/ha could be sustained according to the outputs of the MOM model. Furthermore, Hecht (2016) concludes that the negative impacts of cage culture on the water column and the bottom can be mitigated by best management practices (BMPs) and working in water with a depth of at least twice the depth of the net cage (>24 m) and average current speeds > 7cm/s. Under such conditions, nutrients will likely be diluted within a few hundred meters and dispersed for natural assimilation, although this remains to be fully assessed.

Hence, a large impact of the ADZ development is the potential for detrimental effects on the marine environment due to release of organic wastes from the aquaculture cages, such as feces, uneaten food and excreted fluids. However, modern Best Management Practices for cage culture have significantly mitigated the impacts of fish cage culture that were problematic about 20 years ago. The nature and magnitude of organic material releases could determine multiple physical and biological changes in the water column and on the seabed, primary through nutrient enrichment and increased oxygen consumption (Price and Morris 2013). Transport of organic matter release through wind-wave action and ocean currents is also an important aspect since organic wastes produced within a given ADZ could be advected and affect remote areas.

In order to evaluate the impact of particulate organic waste releases from culture cages under different carrying capacity scenarios, we developed a general hydrodynamics advection-dispersion model with an integrated Lagrangian particle transport model approach, as described in section 4.1.Due to limited availability of site specific oceanographic data suitable for modelling, an idealized modelling approach was selected. The model simulates the trajectory of organic wastes as conservative tracers in the environment. It is based on the approach of Ali et al. (2013) for a Lagrangian particle tracking simulator which uses the local flow field, simulated by an ocean model, for advection of the particles and random walk to simulate the turbulent diffusion. This approach was chosen to provide an idealized and physical representation of waste trajectory under distinct oceanographic scenarios without the need of implementing direct uptake and elimination (DUEL) processes (Hakanson, et al. 1998). As such, the model simulates an unchanged quantity of waste released and dispersed in the water column which is based on an assumed maximum fish production per cage.

The purpose of using a purely physical approach is to provide a preliminary and conservative assessment of particle dispersion around a given cage site under minimum and maximum conditions in terms of wind and current speed. Through the elaboration of simulations conducted within the framework of the worst-case scenario as part of the ESIA, it should be regarded as the initial step toward a more comprehensive assessment of aquaculture waste trajectory, fate and effects on the marine ecosystem of the inner Seychelles.

The model uses; a specified particle size distribution, specific gravity, and dry density representative of freshly deposited material for the solid waste. Settling velocity is calculated by the model. The spatial setup of this model was based on a limited domain representation of the ocean water column over the Seychelles Bank. Neither organic fluid releases and potential resuspension of particles on the seabed nor the direct consumption of faecal and feed particles by fish and other biota in the water column and on the substratum were not assessed as part of this modelling task and need to be addressed to increase the level of confidence in the model predictions..

The impact of organic waste releases from aquaculture cages is classified as an impact occurring during the operational phase of the project. The duration of this phase for purposes of this assessment has been set at 25 years. It is expected that the initial project would develop into a stable sector that could continue to grow for many years. As such, consequence of impacts of organic wastes are derived by considering the following criteria for the operational phase of the project:

- Extent or spatial scale of the impact;
- Intensity or severity of the impact;
- Duration of the impact;
- Potential for mitigation;
- Acceptability;
- Degree of certainty/probability;
- Status of the impact; and
- Legal requirements.

The sections below present an assessment of the potential impacts during the operational phase using the calculations and rating system, as provided in Table 4 and Table 5. The impact ranking matrix is applied to outputs of the hydrodynamic model to assess the impacts of particulate organic wastes. Mitigation measures and preliminary management plan are provided in section 4.2.

Table 4: Impact ranking matrix

Occurrence		**Severity**	
Probability of occurrence	Duration of occurrence	Magnitude (severity) of impact	Scale / extent of impact

- Note: To assess each impact, the following four ranking scales are used

Probability	**Duration**
5 - Definite/don't know	5 - Permanent
4 - Highly probable	4 - Long-term
3 - Medium probability	3 - Medium-term (8-15 years)
2 - Low probability	2 - Short-term (0-7 years) (impact ceases after the operational life of the activity)
1 - Improbable	1 – Immediate
0 - None	
SCALE	**MAGNITUDE**
5 - International	10 - Very high/don't know
4 - National	8 - High
3 - Regional	6 - Moderate
2 - Local	4 - Low
1 - Site only	2 - Minor
0 - None	

- The significance of the two aspects, occurrence and severity, is assessed using the following formula:
- **SP (significance points) = (magnitude + duration + scale) x probability**
- The maximum value is 100 significance points (SP). The impact significance points are assigned a rating of high, medium or low with respect to their environmental impact as follows (Table 5):

Table 5: Significance ratings

SP >75	**Indicates high environmental significance**	**An impact which could influence the decision about whether or not to proceed with the project regardless of any possible mitigation.**
SP 30 – 75	Indicates **moderate** environmental significance	An impact or benefit which is sufficiently important to require management and which could have an influence on the decision unless it is mitigated.
SP <30	Indicates **low** environmental significance	Impacts with little real effect and which should not have an influence on or require modification of the project design.
+	Positive impact	An impact that is likely to result in positive consequences/effects.

4.1 Hydrodynamic modelling of waste dispersion from culture cages

4.1.1 Model description and input conditions

An idealized and limited domain hydrodynamic model of the ocean water column representative of a 400 by 1000m parcel of the Seychelles Bank was developed using the commercially-available Flow-3D hydrodynamic model coupled with a particle-tracking module. The selected length of the domain was intended to be long enough to track particle dispersion in a conservative manner (no degradation, no dissolution and no consumption) over a time scale sufficient for the majority of particulates to settle to the seabed or disperse to negligible concentrations while being advected by the current. The model domain was discretized using a fixed resolution grid of 10 m (across current) by 5 m (along current) in horizontal and 5 m in vertical dimensions, respectively. The model was developed with the goal of simulating waste dispersion from a single fish cage assuming maximum fish production. No interactions with neighboring cages within the same ADZ were considered at this time. Also, resuspension of particles was not assessed directly and the modelled particles were set to adhere to the bottom when reaching the sea bed. A fixed water column height of 25 m was used with vertical resolution of five equal layers to capture the distribution of the waste plume. The particles were however followed with an individual Lagrangian approach, meaning that particles could move through space at sub-grid scale. The depth of 25 m was chosen as the minimum depth anticipated for cage aquaculture in the Seychelles and would therefore represent the most conservative conditions in terms of dispersion and potential for seabed accumulation. Uniform density and temperature were assumed throughout the water column. The hydrodynamic model was used to drive particulate transport calculations accounting for advection, dispersion, settling and accumulation on the sea floor assuming a fixed bed.

The following four scenarios were developed:

- Sim01: Faeces transport with weak ambient current and typical wind.
- Sim02: Faeces transport with strong ambient current and monsoon wind.
- Sim03: Uneaten food transport with weak ambient current and typical wind.
- Sim04: Uneaten food transport with strong ambient current and monsoon wind.

Model inputs with applicable references and rationale for the four scenarios are provided in Table 6. Particulates were released into the water column at the location of the cage based on estimated production rates for food and fecal solids. The maximum release rate of fish feces and uneaten food (worst case scenario) was based on available information from the MOM model outputs (e.g. Hecht, 2016) and assumptions based on relevant aquaculture literature (see Table 6). The maximum release rates of fish feces and food pellets were based on a total of 236 kg of feces produced and 671 kg of wasted food per ton of fish production over 206 days as detailed in the Site selection report (see Table 21 in Hecht 2016).

In order to prescribe a realistic release rate per culture cage, a conversion factor assuming a maximum fish production of 12.5 kg per cubic meter of cage per year was calculated based on Doglioli (2004). Although the latter study is for a culture of Gilthead Sea Bream and Sea Bass fish, we assume as part of this modelling task that a maximum fish production rate of 12.5 kg m^{-3} yr^{-1} is applicable for Grouper aquaculture in Seychelles. Further work would be needed to test the impact of a varying fish production rate per cage. As a comparison, the review of Hargrave (2005) provides a value of 10 kg m^{-3} yr^{-1} for finfish aquaculture in single net pen cages. The MOM model predicts a maximum carrying capacity of 4292 tonnes per km^2 per annum (42.9 tpa/ha). However, based on the precautionary principle the MMP has recommended that farms should in the first instance be limited to 10 tpa/ha until such time as monitoring data show that production per unit area could possibly be increased (Hecht 2016). For this modelling exercise the higher MOM production limit of 4292 tonnes per year per km^2 was used. For a total potential production of 4292 tonnes of fish per year per km^2 at a production rate of 12.5 kg m^{-3} yr^{-1} would comprise approximatively 8 culture cages each, with a total annual production of 47.1 tons of fish per cage of 3,770 m^3 (Table 6). Such production rates represent approximative values to provide context to our model simulations and should not be compared directly with the MOM outputs. Hence, the maximum production of 47.1 tons of fish production per cage per year should be regarded as a maximum value that may represent the upper limit of the

ADZ carrying capacity scenarios for the Seychelles if moving forward with the production of 4292 tonnes of fish per year.

For each scenario, a population of Gaussian-distributed particles representing 8 days of feces or 8 days of food pellet release was prescribed as an initial condition. This represented 1.1 kg of feces from Sim01 and Sim02 and 3.3 kg of uneaten food pellets for Sim03 and Sim04. The 8-day constraint was chosen to approximate operational conditions of the aquaculture cage during maximum operations. Each scenario started with the release of evenly-distributed particles within a fish cage of 12 m depth by 20 m diameter (Hecht 2016). The initial release within the cage took place over 200 seconds and the total simulation duration was 2000 seconds. Particles were traced with distance from the cage using the advection-dispersion module of Flow-3D.

The trajectory of uneaten food and fecal matter wastes were assessed for covering a size spectrum ranging from juvenile fish with food and feces of 2 mm diameter to adult finfish with food and feces of 10 mm diameter. Density of particles was obtained from the appropriate literature (Table 6). Settling velocity of waste releases in the water column was calculated by the model based on particle and ambient condition properties.

Model boundary conditions were applied to generate steady state currents within the model domain to cover two extreme oceanographic conditions: (1) weak current scenario at 5 cm/s to evaluate accumulation of solid waste on the seabed in a very calm setting (Sim01 and Sim03); and (2) strong current scenario at 30 cm/s to evaluate maximum horizontal displacement during a NW monsoon storm (Sim02 and Sim04). Current speed values were based on the available data for the Seychelles (Vasco, 2009).

Table 6: Input Conditions of Flow-3d Waste Dispersion Scenarios. Each scenario was assessed for a water column depth of 25 m.

	Sim01	Sim02	Sim03	Sim04	Rationale	Reference
Parameter	**Fish Feces**		**Uneaten Food Pellets**			
Wind (m/s)	1.08	7.77	1.08	7.77	To account for a range from calm wind to strong NW monsoon wind	Chang-Seng (2007); Hecht (2016)
Ambient Current Velocity (m/s)	0.05	0.30	0.05	0.30	Table 14 Site Selection Report with references to Sand Mining ESIA	Hecht (2016); Vasco (2009)
Ambient Diffusion Coefficient (m^2/s)	1.00	1.00	1.00	1.00	Coefficient for particle-tracking models of aquaculture waste dispersion	Salama and Murray (2013)
Seawater Density (kg/m^3)	1021	1021	1021	1021	Seawater density at 28 deg C and 33 PSU near inner islands	ASCLME (2012); Hecht (2016)
Cage Volume	3770	3770	3770	3770	Net pen cage (cylindrical) of 20 m diameter X 12 m height	Hecht (2016)
Fish production (tonne/cage/year)	47.1	47.1	47.1	47.1	Assuming maximum production of 12.5 kg fish per cubic meter of cage per year	Doglioli et al. (2004)
Particle Release Rate (kg/day/ton fish production)	1.15	1.15	3.26	3.26	Maximum rate of feces and wasted food generated per ton of fish production	Hecht (2016)
Particle Diameter (mm)	2-10	2-10	2-10	2-10	Gaussian particle size distribution to cover feces and pellet range	Moccia et al. (2007); Reid et al. (2009)
Particle Density (kg/m^3)	1037	1037	1024	1024	Median value for salmonid fish feces and uneaten food pellets	Moccia et al. (2007); Reid et al. (2009); Khater et al. (2014)
Particle Mass Flow Rate[1] (g/cage/day)	148.5[1]	148.5[1]	420.5[1]	420.5[1]	Calculation based on the maximum fish production per cage and maximum particle release rate per ton of fish	Hecht (2016); Doglioli et al. (2004)

[1]Note: For each scenario, a population of particles representing 8 days of feces or 8 days of food pellet release from a given cage was prescribed as initial condition. This represented in total 1.1 kg of feces from Sim01 and Sim02 and 3.3 kg of uneaten food pellets for Sim03 and Sim04.

4.1.2 Model results and interpretation

Results of feces and wasted food dispersion after an initial release from an idealized aquaculture cage are provided in this section. Figure 7 shows an example of the plume generated by waste dispersion for a strong wind and current scenario. Through a plan-view of the feces plume, the figure illustrates that particles can be carried up to 400-500m laterally before settling when currents reach 30 cm/s. For calm conditions, the plume remains primarily in the vicinity of the cage within a radius of approximatively 100 m.

For every model scenario, approximatively 85% of the initial food or feces release settles to the seafloor within the time-window of the simulation. The remaining 15% fraction is expected to be further advected and dispersed in the water column without having any significant impact on the marine environment. Since our model does not take into account degradation, out of cage consumption and dissolution processes, the resulting flux to the seabed and water column dispersion provided here can be considered very conservative. Modelling results should be regarded as a snapshot of the aquaculture cage environment at maximum fish production rate during the operational phase and representative of approximatively a 1-week time scale.

Table 7 provides a summary of the maximum accumulation rates of feces and uneaten food pellets on the seabed for each scenario. Figures 8 and 9 show examples of the accumulation patterns relative to the aquaculture cage. Accumulations of feces and food pellets at the seabed are respectively 1.7 and 1.4 times less concentrated in strong current conditions than in calm conditions. The difference can be explained by the greater dispersion of particles under strong wind and current conditions than in calm conditions.

Mass fluxes of feces and uneaten food can be converted into carbon fluxes using conversion factors of 28% for feces and 45% for food pellets (Doglioli et al. 2004). The range of the resulting carbon flux to the sea floor both feces and food pellets (total solid waste vertical flux) is **20-30 mg C m^{-2} d^{-1} for all scenarios**. This range provides a mean value of 25 mg C m^{-2} d^{-1} that is at least 6 times lower than the minimum particulate organic carbon loading rate to the seabed (180 mg C m^{-2} d^{-1}) reported by Price and Morris (2013) for various marine fish farms worldwide.

Table 7: Maximum accumulation rate of fish feces and uneaten food pellets at the seabed

Particle	Ambient conditions	Maximum particulate flux to the seabed (mg m^{-2} d^{-1})	Maximum carbon flux to the seabed (mg C m^{-2} d^{-1})
Feces	Weak wind and current (Sim01)	22.9	6.4
Feces	Strong wind and current (Sim02)	13.4	3.8
Uneaten food	Weak wind and current (Sim03)	50.8	22.9
Uneaten food	Strong wind and current (Sim04)	35.5	16.0

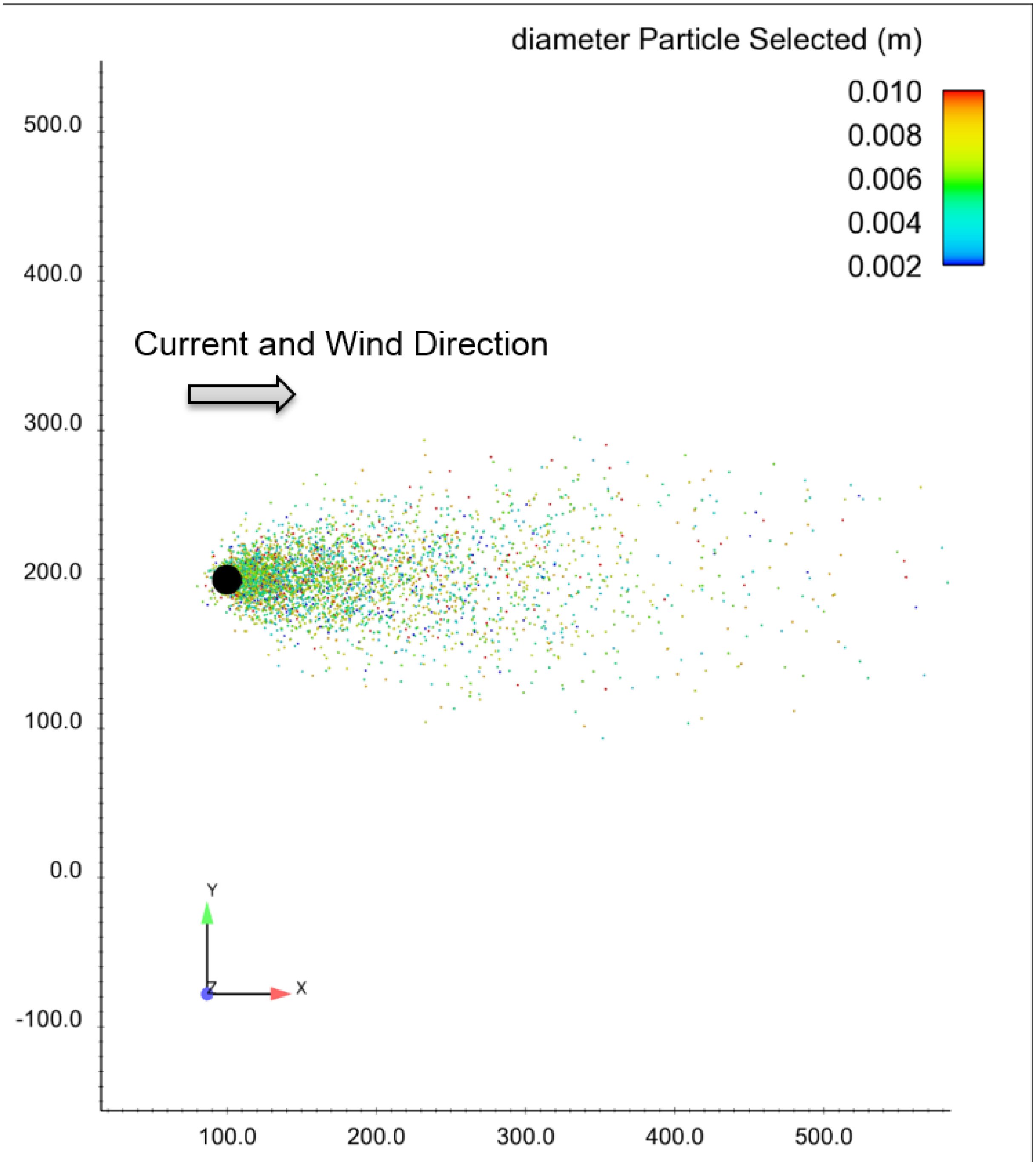

Figure 6: Example of Particle Dispersion from an Aquaculture cage as modelled with an idealized Flow-3D model (Feces dispersion under strong current scenario to show maximum dispersion plume)

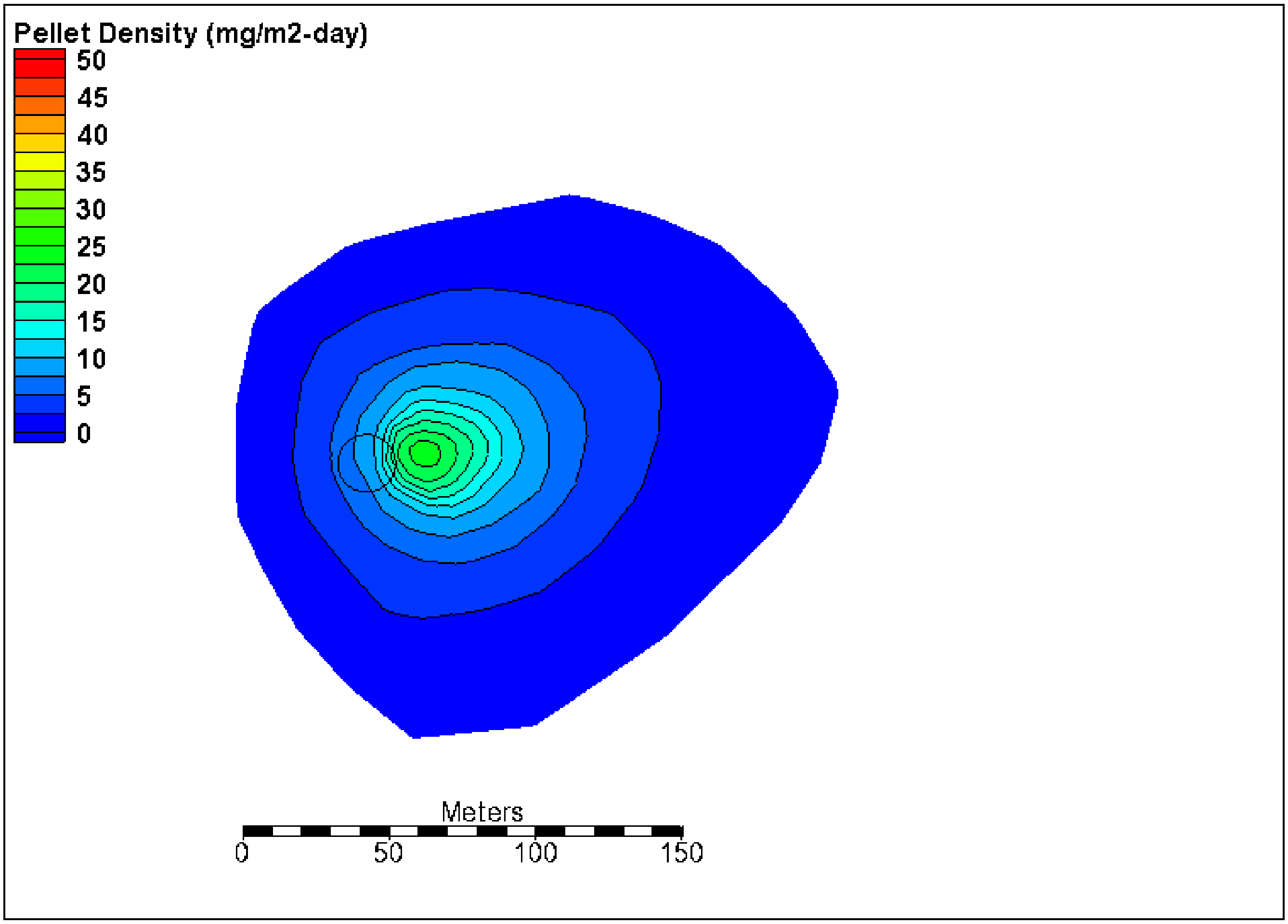

Figure 7: Pattern of seabed accumulation rate of feces for weak current scenario.

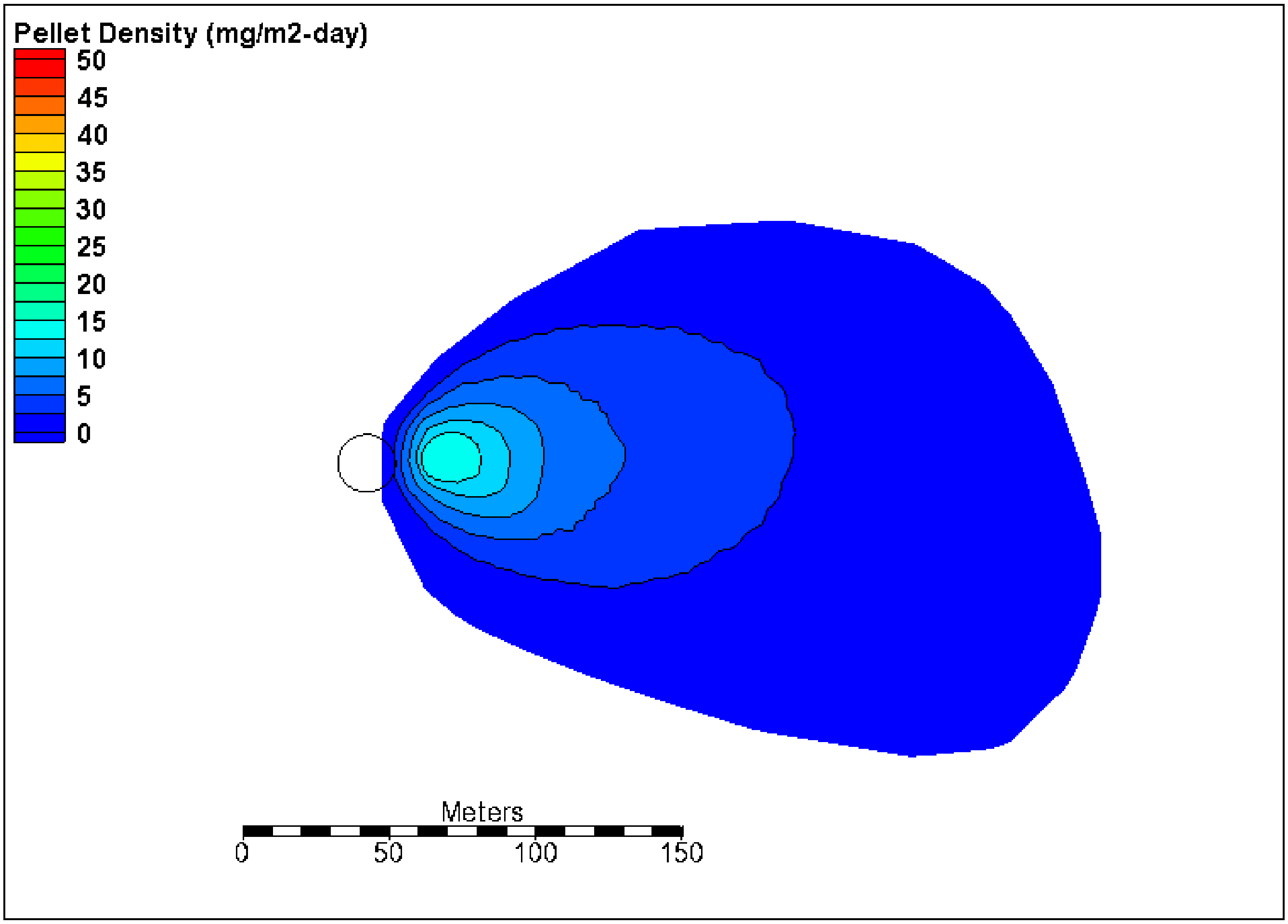

Figure 8: Pattern of seabed accumulation rate of feces for strong current scenario.

4.1.3 Summary and degree of confidence in prediction

Aquaculture cages are expected to produce particulate wastes comprised of feces and uneaten food pellets. An idealized modelling exercise was set up to evaluate the trajectory and accumulation of these wastes in the water column and on the seabed. The impact assessment was conducted using a theoretical fish production of 42.1 tons of fish per cage per year. Our estimates are based on fully-operational cages and can be considered as representative of the upper limit of the MMP carrying capacity scenarios. A conservative flux to the seabed of approximatively 25 mg C m^{-2} d^{-1} (or 9.1 g C m^{-2} yr^{-1}) was estimated based on idealized modelling runs. This would generate moderate impact on the environment as detailed below (*SP = 32*). The degree of confidence in prediction on the results is however low given that the actual fish production per individual cage is unknown at this stage and that biological processes were not constrained as part of the purely physical Flow-3D hydrodynamic and particle tracking model. Given the lack of bio-uptake and elimination processes in the model, the annual estimate of 9.1 g C m^{-2} yr^{-1} computed here would be expected to translate into a near-zero deposition rate. More complex simulations would be needed to increase the level of confidence on the prediction.

The impact on the marine environment of solid waste dispersion during the operational phase was assessed as being of ***moderate (SP = 32)*** significance in the context of the conservative simulation provided here. The following mitigation measures are recommended to reduce the impact to one of ***low (SP = 24)*** significance:

- Restrict cage operations to open water conditions depths >25 m; typical minimum current speeds >0.1 m/s; no coastal restrictions on circulation
- Locate down-drift from sensitive habitats (corals, seagrass)
- Rotate cage use and implement fallow intervals as part of production cycle

Degree of confidence in prediction of impact: Low

4.2 Mitigation measures and environmental management plan

The Marine Aquaculture and Sea Ranching Regulations (2015) in the Seychelles are very clear with respect to effluent and solid waste generation and disposal. License holders of aquaculture facilities, including processing facilities, shall ensure that solid waste from such facilities are disposed adequately. In addition, the Aquaculture Standards serve as an adjunct to the Marine Aquaculture and Sea Ranching Regulations (2015) and provide further regulatory detail that must be adhered to by farmers. Suspended solids from uneaten food and metabolic products from feces comprises the greater proportion of any kind of aquaculture wastes. Accumulation of solids on the seafloor below the cages or elsewhere as a result of advection/diffusion should thus be prevented. The effluent quality standards for aquaculture facilities in the Seychelles is provided in Table 8. The standard that relates to maximum solid waste concentration is highlighted.

Table 8: Effluent Quality Standards for aquaculture facilities.

Parameter	Maximum concentration in milligrams per litre (mg/L), unless otherwise stated (except pH)
Temperature	30°C measured at the point of discharge
pH	5.5 – 8.5
Suspended Solids	30
Biological Oxygen Demand at 20°C	30
Chemical Oxygen Demand	80
Free Chlorine (as Cl_2)	0.5
Phosphorus (as $PO4_3$)	5
Nitrate (as NO_3)	15
Nitrite (As NO_2)	1
Phenols	0.1
Chromium (total)	1.0
Arsenic (total)	0.1
Mercury (total)	0.05
Cadmium (total)	0.2
Lead (total)	0.9
Copper (total)	1
Zinc (total)	2

Parameter	Maximum concentration in milligrams per litre (mg/L), unless otherwise stated (except pH)
Iron (total)	5
Nickel (total)	1
Aluminum (total)	1
Tin (total)	0.1
Manganese (total)	2.0
Oil and grease	10
Total coliforms	500/100ml
Faecal coliforms	100/100 ml
Faecal streptococcus	100/100 ml
Salmonella	Must not be detectable in any 100 ml sample
Pesticides	In accordance with the law relating to

The impact of particulate organic waste releases (fish feces and uneaten food) during the operational phase of the project is summarised in Table 9 which provides a significance rating before and after mitigation. The operational phase is expected to be developed over a 25-year time-frame. The mitigation measures associated with this environmental impact is further described in Table 10.

Table 9: Environmental Impact Assessment Matrix for Solid Waste Dispersion from Culture Cages as part of the Seychelles MMP

POTENTIAL ENVIRONMENTAL IMPACT: WASTE DISPERSION FROM CULTURE CAGES	ENVIRONMENTAL SIGNIFICANCE											
	Before mitigation						After mitigation					
	M	D	S	P	SP	Rating	M	D	S	P	SP	Rating
Implementation of aquaculture cages in ADZs will generate solid organic waste releases in the marine environment that could adversely impact diverse physical and biological components of the marine ecosystem, both locally and remotely through advection.	4	2	2	4	32	**Moderate**	2	2	2	4	24	**Low**

Table 10: Mitigation and Monitoring Measures

Section No	Aspect (of Activity Service or Product)	Potential impact	Objectives	Performance Criteria	Mitigation measure(s)	Responsible person / party	Time-frame	Monitoring and Reporting Frequency
OPERATIONAL PHASE								
N/A	Marine Environment	Organic solid waste releases from culture cages	▪ Minimization of waste releases as a result of fish feeding; ▪ Minimization of organic solid accumulation on the seafloor;	No exceedance from effluent quality standards for aquaculture facilities	▪ Restrict cage operations to open water conditions depths >25 m; typical minimum current speeds >0.1 m/s; no coastal restrictions on circulation ▪ Locate down-drift from sensitive habitats (corals, seagrass) ▪ Rotate cage use and implement fallow intervals as part of production cycle	N/A	Duration of Operational phase (about 25 years)	Monthly (first year) and quarterly thereafter

5.0 DATA GAPS AND RECOMMENDATIONS

The suitability of Seychelles' maritime zone is the basic fundamental that determines whether it is possible to farm fish in cages in the region. The review of MMP products and literature studies presented above provides a certain level of confidence with respect to the met-ocean conditions that appear to be suited to aquaculture development. However, the vast majority of studies and findings of the data review presented herein underscored that more site-specific and long-term data should be collected to establish baseline conditions. Such conclusion appears to be a recurrent statement within studies targeting the Seychelles metocean conditions, in particular throughout the various MMP reports. As well, the impact of climate change including any potential shifts in the cyclone belt variability in the Indian Ocean should be taken into account when developing further strategy to strengthen metocean forecast and assessing aquaculture capacity for the Seychelles. **Long-term current and wave data are needed for baseline monitoring purposes but also for operational modelling validation**.

Fish welfare and the potential impacts of cage culture on the level of dissolved oxygen were identified as a key factor to determine an achievable maximum fish production up to 47.92 tpa/ha. Monitoring of the marine environment and water quality in the vicinity of fish farms is a pre-requisite for successful growth given the risks associated with eutrophication, sedimentation, increased oxygen and carbon demand, and ecological regime shifts (e.g. change in the structure and make-up of benthic communities). A precautionary principle of 10 tpa/ha was suggested as a starting point. Using an annual maximum production of 47.1 tons of fish production per culture cage in the inner islands of the Seychelles, modelling results show that on a weekly time scale this would result in limited solid waste accumulation on the seabed and negligible increases in suspended organic matter in the water column. Results show that a maximum potential flux of **30 mg C m^{-2} d^{-1}** would be reached within the worst-case scenario due to solid waste releases, on the assumptions that all particles settle on the seabed and that there is no consumption of any of the waste material by fish and invertebrates.

In order to validate the results of our idealized model runs, more advanced simulations should be developed to include bio-uptake and elimination processes in the water column and on the seabed. Such simulations could include further sensitivity analysis to be conducted using a greater range of scenarios of fish production, waste production, environmental conditions and physical assumptions (e.g. dispersion coefficient) than those used in the modelling exercise presented above. Also, in order to validate any model results, monitoring of actual fish farm effluents and their impacts on baseline conditions would be needed during the project, for example through the deployment of sediment traps below selected culture cages to estimate the settling flux and through seawater collection for the analysis of dissolved organic carbon and nutrients. This could be done at least initially as part of the pilot project near Mahé.

So far the impact assessment conducted here has been limited in scope and has focused on solid waste dispersion of feces and uneaten feed. The outcomes of our idealized modelling approach remains thus limited, in particular with respect to re-entrainment of deposited waste, trajectory of the dissolved fraction and impact on the ecological systems. The paucity of in situ oceanographic data and the lack of information on the theoretical fish production per culture cage in the Seychelles MMP hindered the development of a site-specific dispersion model. A second phase of predicting modelling for the sinking and resuspension flux of particulate waste material from fish farms and the benthic community impact of that flux could be undertaken, for example through NewDEPOMOD[2] modelling that has a focus on post-depositional particle behaviour.

Finally, the development of a more sophisticated regional hydrodynamic model coupled to a biogeochemical and particle tracking model would be needed to study the actual dispersion of fish farm waste from a given ADZ, including the dissolved fraction and influence on the biology.

6.0 CLOSING

We trust that this report meets your present needs. Should you have comments or questions, please contact the undersigned.

[2] http://www.sams.ac.uk/kenny-black/newdepomod

Report Signature Page

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