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Evaluación de la calidad de las playas de la costa del caribe mexicano, Quintana Roo, México. Un enfoque multidisciplinario.

Tesis que presenta

SAKTHI SELVA LAKSHMI JEYAKUMAR

Para obtener el grado de

Doctor en Ciencias en Conservación del Patrimonio Paisajístico

Directores de Tesis:

Dr. Jonathan Muthuswamy Ponniah

Dra. Diana Cecilia Escobedo Urías

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SAKTHI SELVA LAKSHMI JEYAKUMAR

Nombre y firma del estudiante

“தொட்டனைத் தூறும் மணற்கேணி மாந்தர்க்குக்

கற்றனைத் தூறும் அறிவு”- திருவள்ளுவர்

(In sandy soil, the deep you delve and reach the springs below;

The more you learn, the freer streams of wisdom flow- Thiruvalluvar)

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DEDICATION

Wholeheartedly, I dedicate this work to,

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ABSTRACT

The Mexican Caribbean coast is the paradise of Mexico encompassed with several discoverable things. The blue sea and white sand highlight the Caribbean coast magnificent from other beach destinations. The unique landscape of karstic terrain attains urban-tourism development since 1950 which attained its complete development by three stages. The final transformation of this region hoists several multi-star hotels with public and private beaches for tourism and recreational activities. The trend of grasping millions of national and international tourists every year has been increasing and the corresponding needs to meet out the user's demand. The intense uses of beach results in affecting the quality of natural and recreational resources. So, this study framed to evaluate the quality of beaches in the Caribbean coast using multi-elementary approach that includes elaborative analysis of tourism impact on the beaches, geochemical analysis of seawater for water quality, verification of present beach quality using indicators. During 2019 and 2020, a total of 56 water sample for dissolved trace metals and 23 water samples for nutrient analysis was collected in the intertidal zone from Cancun (Z1), Playa del Carmen (Z2), Tulum (Z3) and Cozumel Island (Z4). Meanwhile, a questionnaire survey was conducted among the tourists to perceive a varied observation on the present beach quality during the file work. The analysis of land use pattern implies complete change of indigenous land type into built up land dated from 1990. The intense land cover change results due to development of urban colonies and tourism near the coastal region. The Cancun and Playa del Carmen noticed with complete landcover changes. The parallel analysis of Tourist Urbanization Index (I_{TU}) and Beach Alteration Index (I_{BA}) indicate that the decadal alteration of original land coupled by anthropogenic and natural causes with whole deformation of the original land in the Caribbean coast. The results obtained through the seawater analysis for in-situ water characters, dissolved trace metals and nutrient concentrations aids to determine water quality of this region. The procured results on pH and conductivity were shows a significant variation among the zones. The seasonal variation of the dissolved oxygen shows their involvement for the remineralization of organic material results from the sargasso prevailed in this zone as a natural marine stressor. The major element like Ca and Mg were manifest their geologic origin by the dissolution of carbonate minerals, in addition to the removal of HCO_3^- from the water column. The in-situ parameter like pH and conductivity mainly governs the hydro-geochemistry of this zone. The dissolved trace metals concentration (Fe, Mn,

Cr, Cu, Ni, Co, Pb, Zn, Cd, Sr, V and As) varied between 2019 and 2020 for all the zones depends intense of anthropogenic activities and other environmental conditions. Z1, Z2 and Z3 have Sr and Pb, Z4 have Pb and Ni as highest concentration during 2019. For 2020. Z1, Z2 and Z3 have Sr and Pb and Z4 have Sr and Ni. The recycling of organic matter and the redox reaction contributes for Fe and Mn in this region. The seasonal variation of Cu, Ni, Pb manifests their reactive nature during the presence of Sargasso due to anoxic condition resulted from more organic load and corresponding redox conditions. The correlation analysis between the physico-chemical parameters and trace metals establish an inter-elemental for their behavior in the water column. The anoxic conditions and their successive changes in the water column mainly governs the elemental reaction of trace metals. However, the index of heavy metal evaluation present that this zone is not contaminated with the presence of heavy metal. Also, the presence of fecal bacteria was also under Mexican quality standards. The analysis of inorganic nutrients (DIN, DIP, DSi) impose an astonishing result for this region. It was evident that results of POM, TSS, BOD and DO mainly controls the nutrient and their behavior. The remineralization of organic material contributes more DIN in the form of NH_4 later by nitrification process. In general, the presence of inorganic nutrients (DIN, DIP and DSi) were also influenced by the sub-ground water and waste water discharge. The calculation of trophic status (TRIX) and coastal water quality using encountered results. The trophic status of the Caribbean region were eutrophic indicates the higher productivity, however, being an oligotrophic region, the changes in trophic status jeopardize the ecosystem. To an extent, the evaluation of beach quality using physical, pollution, biological and social indicators manifest the present beach quality was fair for private and blue flag certified beaches and poor for public and rural beaches. The beach quality standards followed by private and blue flag beaches aids in achieve fair beach quality. The beach goer's opinion on effectiveness of present quality standards describes the need for improvising quality standards by aggregation of some of the water quality parameters based on the most affecting factors which was evident through this study. Hence, it is clear that combined affects natural and anthropogenic impacts have affected the pristine delicacy of the Caribbean coast and the need for beach quality improvisation. Thus, this study paved an initial effort for the assessment of Mexican Caribbean beach quality using multi-elemental approach which impose an essentiality for developing new quality standards towards achieving sustainable beach quality and landscape.

RESUMEN

La costa del Caribe mexicano es el paraíso de México que abarca diversas cosas a descubrir. El mar azul y la arena blanca de dicha costa destacan de otros destinos de playa. El paisaje único del terreno kárstico ha alcanzado un desarrollo urbano-turístico desde 1950, mismo que se ha llevado a cabo en tres etapas. La transformación final de esta región enarbola varios hoteles de varias estrellas con playas públicas y privadas para actividades turísticas y recreativas. La tendencia a captar millones de turistas nacionales e internacionales cada año ha ido en aumento, así como las correspondientes necesidades de satisfacer la demanda de los usuarios. Los intensos usos de las playas afectan a la calidad de los recursos naturales y recreativos. Por lo tanto, este estudio se enmarca en la evaluación de la calidad de las playas de la costa del Caribe utilizando un enfoque multielemental que incluye el análisis del impacto del turismo en las playas, el análisis geoquímico del agua de mar en la calidad del agua, la verificación de la calidad actual de la playa utilizando diversos indicadores. Durante los años 2019 y 2020, se recogieron un total de 56 muestras de agua para determinar metales traza disueltos y 23 muestras de agua para el análisis de nutrientes en la zona intermareal de Cancún (Z1), Playa del Carmen (Z2), Tulum (Z3) y la isla de Cozumel (Z4), Así mismo, a la par se realizó una encuesta entre los turistas para conocer su punto de vista sobre la calidad actual de la playa. El análisis del patrón de uso del suelo trajo consigo el cambio completo del tipo de suelo indígena a suelo construido a partir de 1990. El intenso cambio de la cobertura del suelo se debe al desarrollo de las colonias urbanas y del turismo cerca de la región costera. En Cancún y Playa del Carmen se observaron cambios completos en la cobertura del suelo. El análisis paralelo del Índice de Urbanización Turística (ITU) y el Índice de Alteración de Playas (IBA) indicaron una alteración de la tierra original por causas antropogénicas y naturales con toda la deformación de la tierra original en la costa del Caribe. Los resultados obtenidos a través del análisis del agua de mar para las características del agua in situ: metales traza disueltos y las concentraciones de nutrientes, ayudaron a determinar la calidad del agua de esta región. Los resultados obtenidos sobre el pH y la conductividad muestran una variación significativa entre las zonas. La variación estacional del oxígeno disuelto mostró un efecto en la remineralización de la materia orgánica resultante de los sargazos que prevalecen en esta zona como un estresor marino natural.

Los elementos principales como el Ca y el Mg manifestaron su origen geológico por la disolución de los minerales de carbonato, además de la eliminación del HCO3- de la columna de agua. Los parámetros in situ, como el pH y la conductividad, rigen principalmente la hidrogeoquímica de esta zona. Las concentraciones de metales traza disueltos (Fe, Mn, Cr, Cu, Ni, Co, Pb, Zn, Cd, Sr, V y As) han variado entre 2019 y 2020 en todas las zonas, dependiendo de la intensidad de las actividades antropogénicas y otras condiciones ambientales. Z1, Z2 y Z3 tienen Sr y Pb, Z4 tiene Pb y Ni como mayor concentración durante 2019. Para 2020. Z1, Z2 y Z3 tienen Sr y Pb y Z4 tienen Sr y Ni. El reciclaje de la materia orgánica y las reacciones redox contribuyen a la presencia de Fe y Mn en esta región. La variación estacional de Cu, Ni, Pb manifiesta una naturaleza reactiva durante la presencia de sargazos debido a la condición anóxica resultante de una mayor carga orgánica y las correspondientes condiciones redox. El análisis de correlación entre los parámetros fisicoquímicos y los metales traza establece una inter elementalidad para su comportamiento en la columna de agua. Las condiciones anóxicas y sus sucesivos cambios en la columna de agua rigen principalmente la reacción elemental de los metales traza. Sin embargo, el índice de evaluación de metales pesados muestra que la zona no está contaminada por la presencia de metales pesados. Asimismo, la presencia de bacterias fecales estuvo por debajo de las normas de calidad mexicanas. Los análisis de nutrientes inorgánicos (DIN, DIP, DSi) dieron un resultado inesperado para esta región. Fue evidente que los resultados de MOP, SST, DBO y OD controlan principalmente a los nutrientes y su comportamiento. La remineralización de la materia orgánica aporta más DIN en forma de NH4 por el proceso de nitrificación. En general, la presencia de nutrientes inorgánicos (DIN, DIP y DSi) se vio influenciada por las aguas subterráneas y el vertido de aguas residuales. En cuanto a los resultados obtenidos mediante el cálculo del estado trófico (TRIX) y de la calidad del agua costera se tiene que el estado trófico de la región del Caribe fue eutrófico, lo que indica una mayor productividad, sin embargo, al ser una región oligotrófica, los cambios en el estado trófico ponen en peligro el ecosistema. La evaluación de la calidad de las playas mediante indicadores físicos, de contaminación, biológicos y sociales pone de manifiesto que la calidad actual de las playas es regular en el caso de las playas privadas y con bandera azul, y mala en el caso de las playas públicas y rurales. Las normas de calidad de las playas privadas y con bandera azul ayudan a conseguir una calidad de playa aceptable. La opinión de los bañistas sobre la eficacia de las normas de calidad actuales describe la necesidad de improvisar las normas de calidad mediante la agregación de algunos de los parámetros de calidad del agua en función de los factores que más afectan. Por lo tanto, está claro que los efectos combinados de los impactos naturales y antropogénicos han afectado a la delicadeza prístina de la costa del Caribe y la necesidad de improvisar la calidad de las playas. Por lo tanto, este estudio ha sido un esfuerzo inicial para la evaluación de la calidad de las playas del Caribe mexicano utilizando un enfoque multielemental que impone la necesidad de desarrollar nuevos estándares de calidad para lograr una calidad de playa y un paisaje sostenibles.

INTRODUCTION

Beaches are multi- dimensional systems operated with natural and human subsystems under continuous and dynamic with complex relationships (Botero, 2013). In general, the beach is defined as “the intertidal zone and the area above high tide mark composed of beach material like sand and mud”. The modern definition of beach is explained as the interactive zone where the lands meet sea forming a unique landscape with sand and rocks (Hawkes, 2020). The beaches are subjected to vigorous transformation due to several morphodynamic processes over a long period of time (Jackson & Short., 2020). Hence the beach landscapes are mainly governed by coastal elements such as waves, tides and sediments availability.

Morphologically, no two beaches are same, their width depends on slope, tidal range, prevailing winds and sediment types. The waves tend to produce three types of coastal currents as result of shoreward progression that plays a major role in transporting sediment in the surf zone. As a result of gravity waves there is a slow landward transport of water and break in the surf zone. The rate of this process is often related to the refraction pattern of the waves in the nearshore and surf zone. This refraction produces a current that flows parallel to the shoreline called longshore current or littoral current. This longshore current flows with a speed between about 0.3 and 1 ms^{-1}, which transport huge quantities of sediments framing the coastal landscape. The other governing factor of landscape is the tidal currents, which are the dominant force in transporting sediment over 31% of the shelf. The fundamentals for tide generation are gravitational force, centrifugal force and tide producing force. The tidal wave can undergo dramatic distortions due to Coriolis effects and shoaling effects. The tidal process is always associated with coastal landforms with a high fine sediment content present in mudflats, salt marshes, mangroves, estuaries and back barrier lagoons. These two factors solely govern the coastal landscapes over a long period of time forming various landscape such as coastal dunes, cliffs, headlands, bay and spits.

Amidst, the coasts host several landscapes, it serves as settling area for diverse habitats and settlement area for human the human for several purposes under various aspects. Ecologically, the coastal zone is an area of dynamic biogeochemical activity by limiting the space for human use. But the functional view of coastal zone is productive by simultaneous consumption and exchange process happens at high rate of intensity. The main characteristics of coastal zones is presented in figure 1.

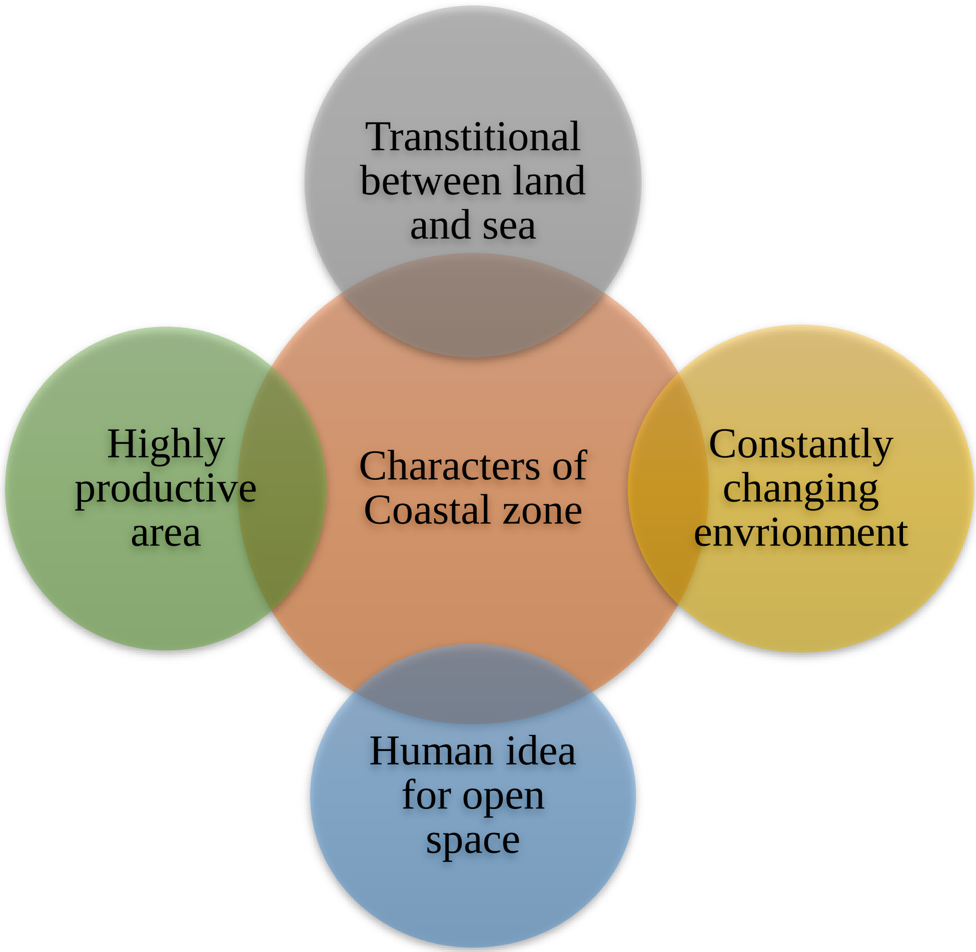

Figure1. Main characteristics of coastal zone (Adopted from Integrated Coastal Zone Management Status, Challenges and Prospective by Frank Ahlborn, 2018)

Characters and process of coast

The characteristics of coasts remain same in general, however depend on sea level variations, the earlier classification was given as submerged and emerged coasts. On the basis of tectonic position, it is classified as leading-edge coast and trailing edge coast (Johnson, 1919). Based on wave and tidal range the coasts are classified and their morphology varies by several physical factors. By the composition of beach material, the coasts are classified into mud and sandy coasts (Davis, 1974). The overall presentation of coastal classification is given by figure 2.

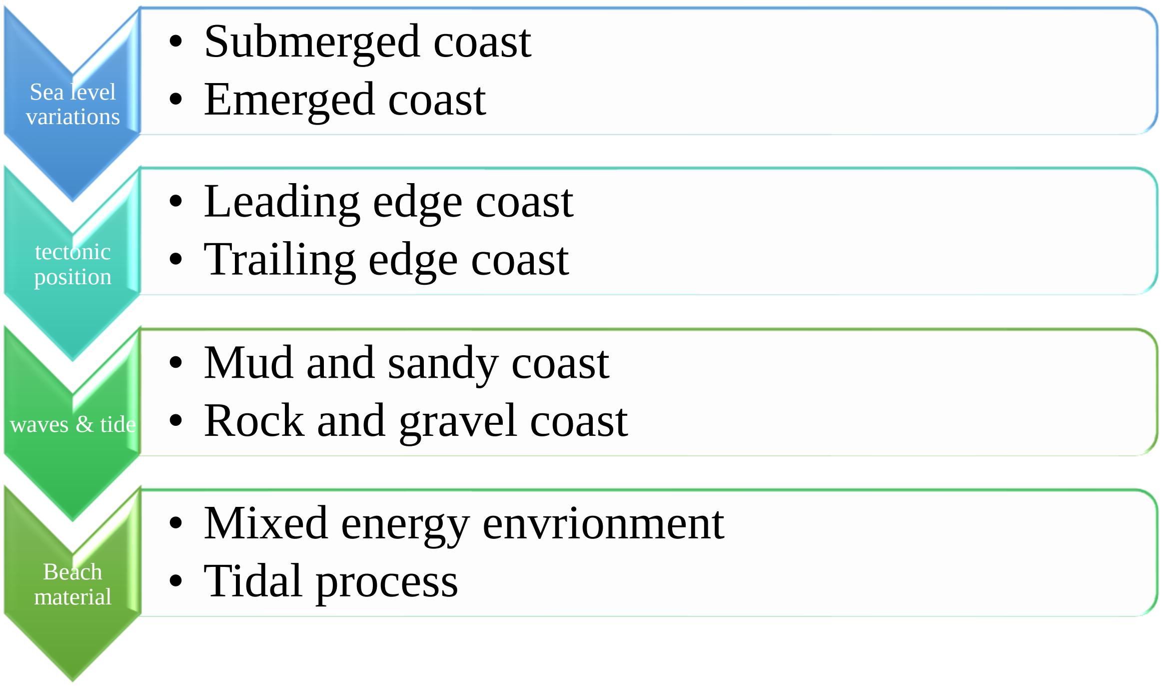

Figure 2. Schematic representation of coastal classification

Since the definition of beaches were given earlier, the stretch of sediments with controlling physical factors forms the beach scenery. Likewise, coasts, the beach also classified into different classes based on the intense characters of waves and tides namely wave- dominated, tide-dominated and tide modified. The characters of each beach zone depend on force of waves and tides leads to formation of various coastal landforms as shown in figure 3. The net transport of coastal sediment includes rolling, sliding and saltation by the flow direction.

The beach area is characterized by particular texture and composition which varies place to place. The material in the beaches and nearshore zone has unlimited range in size, shape and composition. Though, the composition of beach material differs broadly depend on the place, the most beaches are composed of quartz sand with feldspar, sands with volcanic debris and biogenic carbonates. Beach texture tends to reflect the type of material with the intensity of the physical process to which it is subjected to erosion or deposition. The interaction of these processes with one another and with the beach materials produces the various changes that make this environment so dynamic.

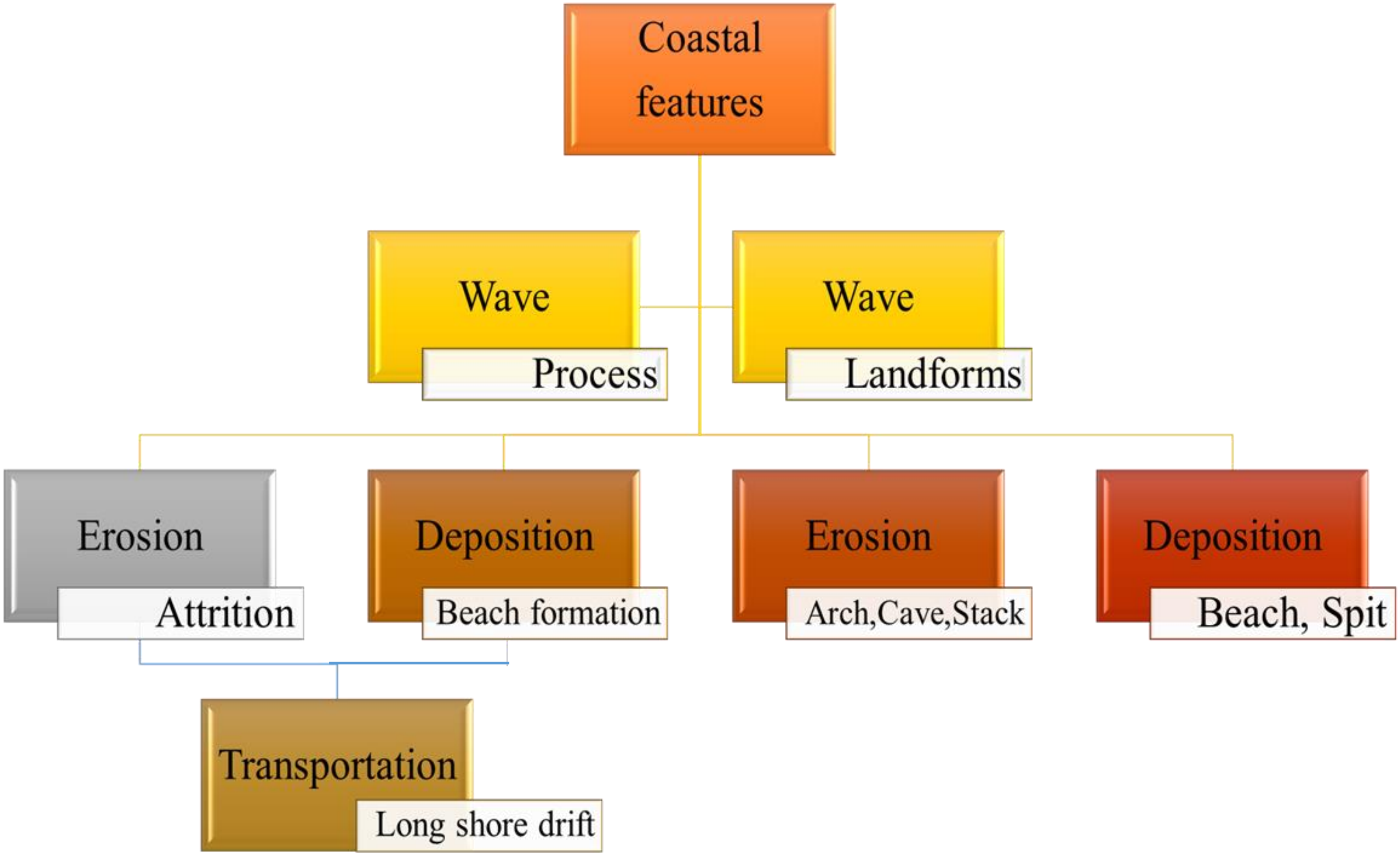

Figure 3. Formation of coastal features

Coastal tourism elements and services

The tremendous geomorphological features became epicenter for the tourism promotion since 21st century, which increased the use of beaches and its resources. The coastal tourism also known as 3S (Sun, Sea and Sand) offers kind of services such as clean water, beaches with scenic beauty, cultural and history heritage, along with installation of infrastructure and providing greater access and various facilities such as security, cleaning and hospitality which leads to intervention and modification of natural areas. The important environmental services of marine ecosystem are presented in figure 4 and the benefits of coastal tourism in table 1.

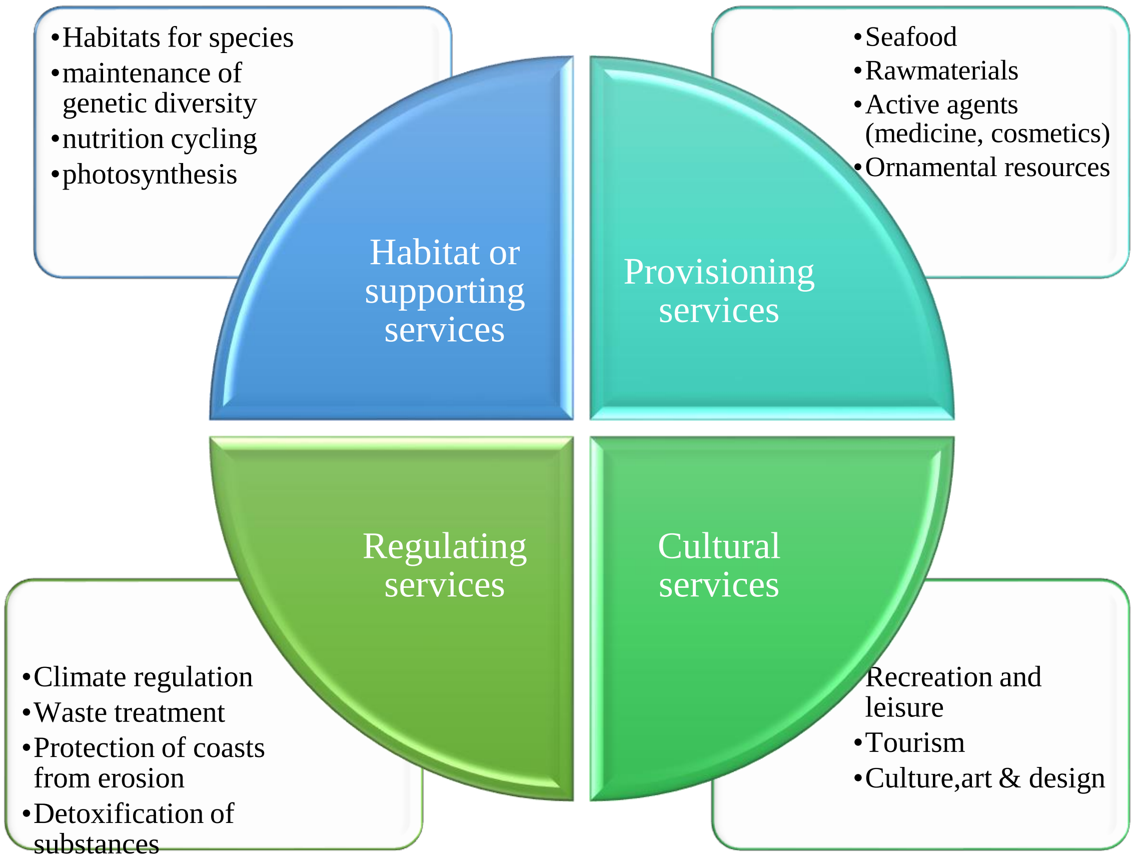

Figure 4. Important marine ecosystem services adopted from Rogers *et al*. (2014)

Table 1. List of benefits generated from coastal tourism

Benefits of coastal tourism
Revenue generation and international receipts
Construction of Infrastructure and community facilities
Generation of new jobs and prosperity
Increasing awareness of the need for conservation
Production of sustainable community livelihoods
Investment in the environment and cultural heritage
Planning for potential end use
(Planning, environment tourism state and municipal authorities and academia)

The over development for coastal tourism for the pursuit of economic benefits has led to intense use of beaches with altered physical and ecological status (McLachlan *et al*., 2013). The purpose and number of visits to coastal areas for recreational purposes has increased drastically, which impose a critic situation to protect and manage the coastal scenery (UNWTO, 2016).

Impacts of coastal tourism

The impacts of coastal tourism on the physical and marine environments have become poorly recognized. The overall understanding of the interaction between tourism and the environment particularly within coastal areas is quite poor, with debates over the impacts of tourism development often dealing in generalities rather than the outcomes of scientific research on tourist impacts in a specific environment or on a specific species. Worldwide, the majority of the coastal

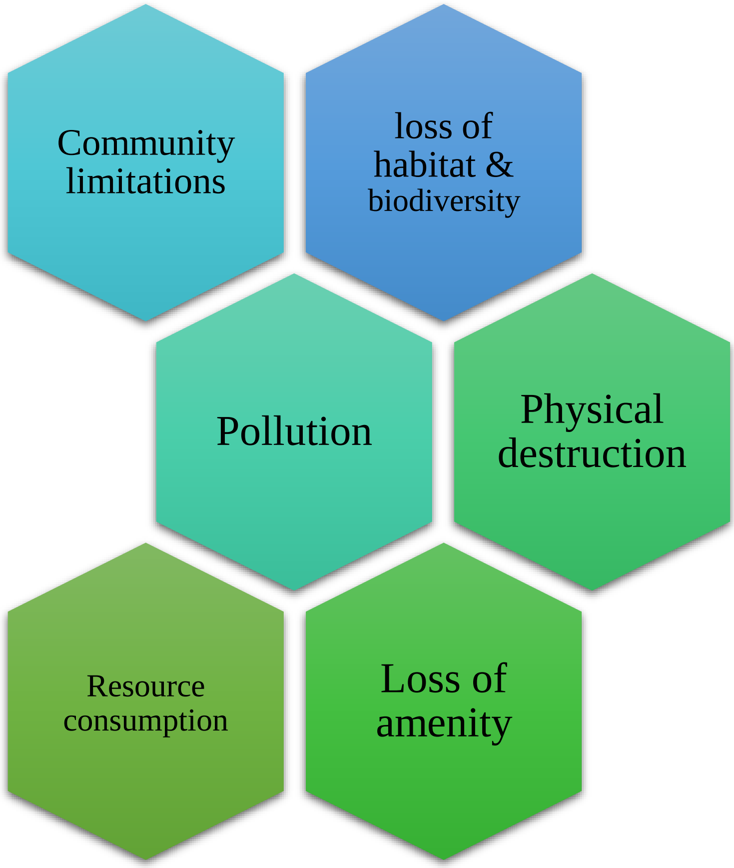

Figure 5. Effects of coastal tourism affecting coastal scenery

regions with the world basic data on tourism and its related problem is extremely poor. In recent years, however, greater concern has been expressed over the condition of the coastal and marine environment which has been resulted from various sources other than tourism. Nevertheless, the increasing economic significance of tourism, the growth of nature-based tourism activities, and the perceived desire of many consumers to experience the pristine environments of the tourist image has contributed to an increase in research on the physical impacts of tourism. Aforementioned, the impact of tourism is clearly notices as an alteration of physical and chemical status such as loss of biodiversity, physical destruction with loss of amenity and resources consumption for development of natural beaches for leisure and recreational area. The other serious is the pollution, so far, the several kinds of beach pollution have been reported derived from tourists and natural impacts. The common observed impacts of coastal tourism are presented in figure 5.

Among the above-mentioned impacts, the beach pollution was alone considered as major threat for the coastal environment, since it's the dynamic area which biologically, ecologically and physically altered during every action. The origin of these pollutants was almost from the anthropogenic origin with some natural background. However, the lack of environmental coordination with an aim to manage coastal and marine areas needs continuous attention and studies to have basic- line data to monitor and mitigate the impacts of tourism on the coastal area. This poses an alarming need to study the coastal environments and its qualities more particularly for the tourist beaches.

LITERATURE REVIEW

The influx of tourism in coastal areas results some inevitably threats to the coastal system which includes liquid and solid in the form of waste. The major problem includes pollution where the pollutants were in the form of physical and chemical and liquid wastes were organic and inorganic form which has become the most worrying marine stressors in recent time. In recent times, many researches have been carried out in order to access the ecological risk which focused on determining the concentration, distribution and behavior of these contaminants which can alter the marine ecosystems. The figure 6 shows the land-based stressors which affects the marine ecosystem.

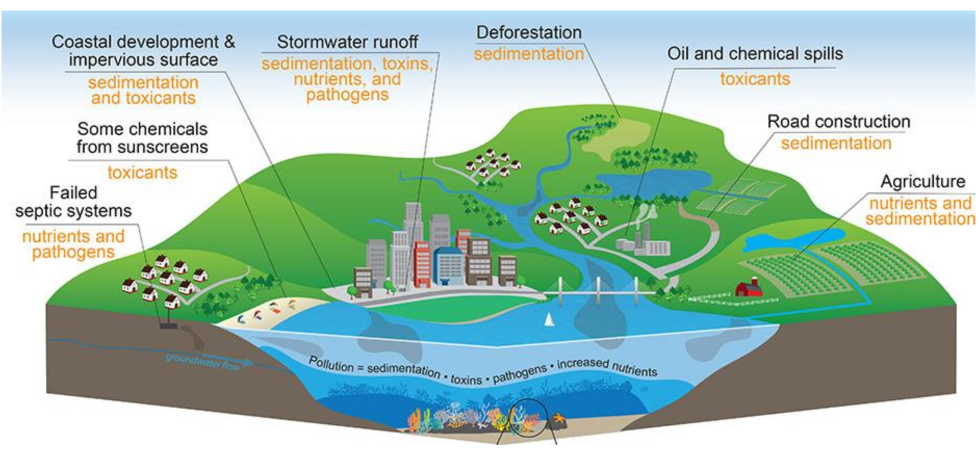

Figure 6. Conceptual model of land- based marine stressors affecting marine ecosystem

The coastal environment was susceptible to different contaminated based on geographic location. The land-based contaminants reach the marine environment through riverine inputs and air-borne deposits. The main chemical inputs from sea-based sources are coming from shipping (e.g.

emissions by operation: exhaust fumes, tank washing, leaching from antifouling paints), offshore industry (oil-, gas-, ore-, sand exploration and exploitation), legacies like dumped munitions and industry waste, as well as dredging of contaminated sediments. Remarkably, even environmentally friendly techniques like offshore wind energy have to be considered for possible inputs of hazardous substances such as lubricating oils and anticorrosion paints. The list of hazardous substances from diverse origin are presented in table 2.

Table 2. Sources of major pollutants found in marine environment (Broeg & Theobald (2018))

Activity	Pollutants affecting marine environment
Shipping	Antifouling, waste and ballast water oil, combustion of gases
Aquaculture	Fertilizers, nutrients, pharmaceuticals, antifouling chemicals
Agriculture	Fertilizers, nutrients, pesticides
Dumping	Industrial chemicals, munition, radioactive wastes
Household	Pharmaceuticals and personal care products, flame retardants, plasticizers and general wastes (solid & liquid)
Offshore industry	Process chemicals, nutrients, combustion gases

Hence, the evaluation of ecological effects involves the combination of chemical stability and physical- chemical properties. Anthropogenic substances can differ very much in their life cycles and these determine to which extend, how fast and under which conditions they enter the environment and their behavior on arrival to the marine environment. Based on geographical differences, the highest impact was measured in coastal areas, close to cities, harbors, marinas, estuaries, followed by shipping lanes and hot-spot areas like offshore oil and gas platforms, and dumping grounds of warfare agents and industrial chemicals. And therefore, the study of contaminants in the beach environment aid to evaluate the beach environmental qualities.

Beach qualities studies

The studies on beaches mainly focus on beach erosion and restoration (Ludka *et al*., 2018), and beach management (Zheng *et al*., 2020; Merino and MaríaPrats, 2020). At present, beach quality evaluation (Botero *et al*., 2014; Blueflag, 2019), beach tourism value evaluation (Zambrano-Monserrate *et al*., 2018; Pascoe, 2019 has attained attention. Generally, the evaluation of beach quality based by evaluating provision of services, facilities and infrastructure to meet environmental quality standards (Mir-Gual *et al*., 2015). Thus, the concept of validating the coastal environmental quality with standards has become efficient across the world. The first-hand studies on the analyzing the beach qualities were depend on physical, biological and sociological parameters with rating indicator of "high quality beaches" and "low quality beaches" (Leatherman, 1997). The estimation of beach quality indices was achieved by analyzing some environmental variables advocated in several works of Morgan, 1999; Williams and Morgan, 1995; Aziana *et al*., 2010 in which beaches are classified by different aspects that are important to beach users. Roig-Munar *et al*. (2005) proposed an alternative system for beach management which is also part of beach qualities. Eco-labelling was introduced in order to try to lessen any negative social and environmental impacts, and to confirm a high level of environmental performance and accountability (Berghoef & Dodds, 2013; Buckley, 2002; Kozak & Nield, 2004; Zielinkski & Botero, 2015). Eco-labels can also be used as a marketing and promotion tool to communicate to consumers and influence their choices (Zielinkski & Botero, 2015). Although there are over 100 different labels in the tourism industry alone (Graci and Dodds, 2015). Among these range of systems created to certify the environmental quality of the beaches; the recognized certification program called as Blue Flags was used in recent times (Fraboni, 2016). They first appeared in 1985, on the beaches of France, to mark places on the coast that not only had excellent waters, but where the environment was cared and respected. The idea was introduced by the European Foundation for Environmental Education (FEE) and developed internationally in 1987. Koutrakisa *et al*. (2001) define that the analysis of beach visitors is an important component in the definition of beach management policies, The analysis of visitor perception is common to meet the need to better understand their behaviors and preferences on different aspects of the beach, as environmental quality, water quality, marine debris, and other issues such as the granting of the Flag blue (Pereira *et al*., 2003; Shivani *et al*., 2003).

So, considering the public perspective during the beach qualities estimation has become important, however, the perception of the visitors regarding erosion, alteration or degradation has been little studied, and has even been used in both his involvement and management (Breton *et al*., 1994; Dahm, 2003; Marzetti, 2007; Marzetti *et al*., 2009 Roig- Munar *et al*., 2009). In addition, the evaluation of geoindicators was considered as an important parameter to evaluate for the environmental management. In recent times, the evaluation of several geoindicators has been increased and among the various environmental matrices of coastal ecosystem, the sediment, water and biota were often focused for the environmental risk assessment studies, since they are become the part of biogeochemical cycles. The components of coastal environmental quality were presented in figure 7. To date, most research on Blue Flag has focused on public awareness and economic impacts, with very little research assessing the effectiveness of Blue Flag as tool for environmental management (Capacci *et al*., 2015).

An investigation of the influence of beach awards based on visitor perception was conducted in Ireland, Wales, Florida United States of America (USA) and Turkey endorses that awareness of the beach awards were ambivalently less among the visitors. In addition, the focus on framing the own criteria with basic research and priorities with the choice of beach visitors (McKenna *et al*., 2011). This paper also agreed on improvisation of water quality for the better achievement of beach awards, an important variable for the evaluation of beach awards. A comprehensive study on blue flag in the beaches of Spain and Islands in Mediterranean Sea and Atlantic Ocean amplifies the idea of giving more services to public than considering the ecological and geomorphological features in the beach system (Mir- Gual *et al*., 2015). However, the real assessment on environmental qualities derived from analyzed environmental matrices makes its more impressive on beach awarding system

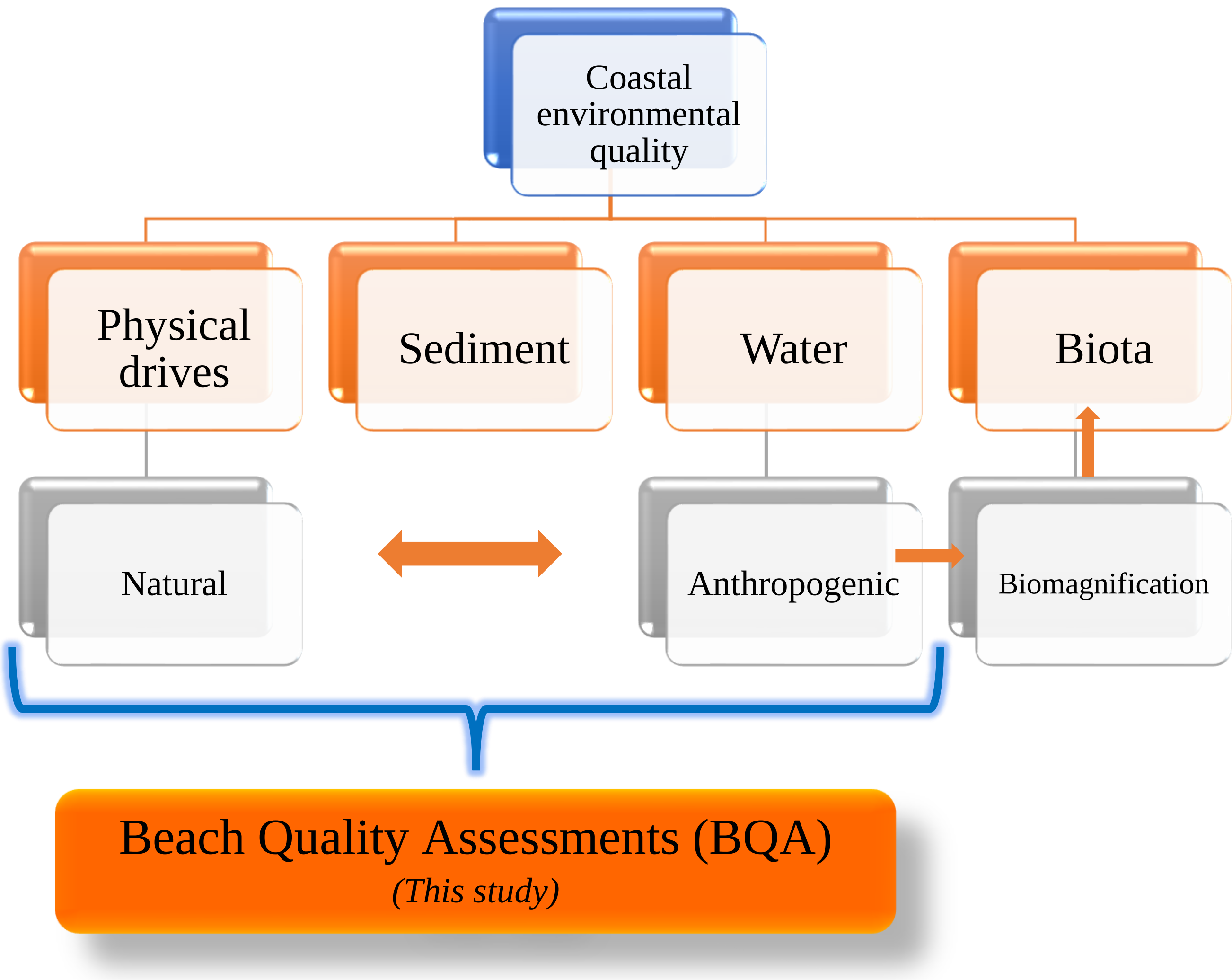

Figure 7. Mind map of Beach quality study components

STUDY AREA

The northeastern coast of the Yucatan Peninsula of Mexico was first part of the North America explored by the Spanish in the early 1500s. After the Caste War (1847- 1855), the dominating Maya communities officially closed the eastern Yucatan to the outsiders nearly for a half a century. During 1950s, the Caribbean coast was opened to tourism and later the 1970s, the Caribbean Coast hosted the international travelers. Owing to tourism, since 1970s, the population was about 88,000 inhabitants, now reaching around 1.5 million inhabitants by 2015 (INEGI, 2017). This exponential growth was majorly related with the leading tourism industry and other economic activity markedly in Riviera Maya, which triggered the extensive urbanization and construction of tourism infrastructures (hotels and recreational centers) that caused important land-use changes, including displacement of coastal vegetation, deforestation and modification of coastal dunes. The initial planning for the development of the region initiated in Cancun as tourist destinations started which during 1968-1970. This attained three stages of development with an average span of 10 years. The initial construction of hotel and the development was during 1970- 1981 with abrupt land use changes. The second stages were initiated during 1982 in order to offer to more tourist and recreational services. This stage also leads to various economic thriving life and activities in Cancun, which lasted about 2000. Now the Cancun is facing its third stage of development since 2000, which includes complete establishment of hotel zone, social centers and some residential area in the center of the city. The photographs on each stage development presented in figure 8 - 11.

Promocional de Cancún, junio-julio de 1975, New York Magazine

Promocional de Cancún, septiembre de 1975, Texas Monthy

Promocional de Cancún, agosto de 1976, Texas Monthy

Figure 8. Primary announcement during tourism development in New York Magazine in 1975 (Source: Uluapa Sr, 2011)

Figure 9. Photographs on first stage of development in Cancun from 1970-1981

(Source: Uluapa Sr, 2011)

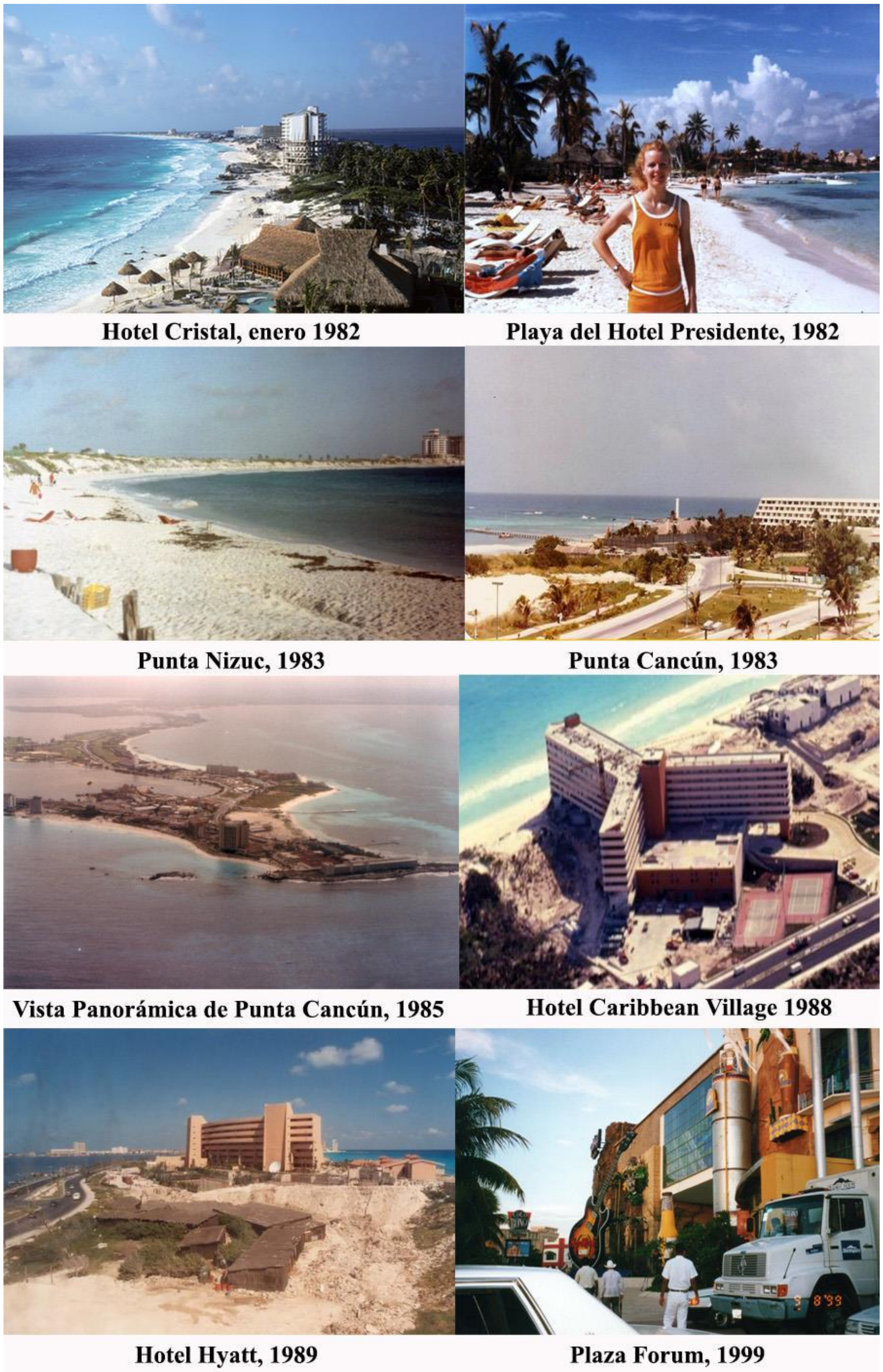

Figure 10. Photographs on second stage of development in Cancun from 1982-2000
(Source: Uluapa Sr, 2011)

Playa Caracol, 2006 | Vista panorámica de Punta Cancún, 2007

Hotel Hyatt, 2007 | Punta Nizuc, 2007

Punta Cancún, 2010 | Playa Chaac Mool, 2010

Figure 11. Photographs on third stage of development from 2001 (Source: Uluapa Sr, 2011)

PHYSIOGRAPHY

The Mexican Caribbean coasts is 210 km long located adjacent to Yucatan basin in the Caribbean Sea with a uniform depth of ~4500 m (Rioja – Nieto *et al*., 2013). The Yucatan basin is bounded to the south by the shallower areas of the Cayman Ridge which is very deep and narrow. Prominent features of karstic landforms are sinkholes and cave systems resulted from mixing zone dissolution. The sinkholes in the easter Yucatan Peninsula consists of bedrock collapse, locally called "cenotes" formed when the roof of a cave passage breaks down to expose the subsurface (Gutierrez *et al*., 2014). The three main islands are located near the continental shelf namely Cozumel, Mujeres and Contoy. The Caribbean coast includes various landforms such as sea cliffs, beach- dune systems, coastal lagoons namely Nichupté, Boca Paila and Chacmuchuc, bay with associated facture system Chetumal, Espiritu Santo and Ascención.

The carbonate topography has distinctive characteristics strongly affected by evapotranspiration, groundwater infiltration and recharge. The Yucatan Peninsula can be divided into six regions based on hydrogeochemical and physiographic characteristics (Perry *et al*., 2002). The hydrogeochemical zonation of the Peninsula is based on differences in tectonic history, rainfall, rock type, and erosion (Perry *et al*., 1995). Cancun, Puerto Morelos (PM), and Sian Ka'an are located in the Holbox Fracture Zone/ Xel Ha Zone, whereas Xcalak is located in the "Evaporite Region" (Perry *et al*., 2002). The Mexican Caribbean coast Mesoamerican Reef System (MAR) spans 1600 km along the coasts of Mexico, Guatemala, Belize and Honduras turns into an important marine ecosystem in the Caribbean coast.

CLIMATE

The Yucatan climate is tropical with cooler dry and warmer wet seasons majorly influenced by the position of Intertropical Convergence Zone (ITCZ), the concentrated band of low pressure located ~ 5- 15 degrees above the equator. The ITCZ position in further south results in cool / dry season from December to April (Hastenrath, 2012), when ITCZ moves north, it brings wet season (May to November) in the Yucatan Peninsula with an average precipitation of 1000-1500mm (Metcalfe *et al*., 2015). During the wet season, from June to October receives the maximum rainfall of 656 mm (Hernández-Terrones *et al*., 2011). The average temperature ranges from 28º C to 30º C from April to August. The winds of the Mexican Caribbean coast are influenced by the Trade Winds, and by mild, cold fronts in the winter, lasting 3–10 days. The prevailing Yucatan Current moves northward along the eastern and western coasts of the island. Cozumel has a subtropical climate with seasonal rainfall, high humidity with constant temperatures. This island is often suspectable to hurricane and tropical storms.

REGIONAL GEOLOGICAL SETTINGS

The Yucatan Peninsula spreads over 300,000 km^2 of entire carbonate platform. The regional geology of the Yucatán Peninsula of Mexico consists of biogenic limestone formed during the Mesozoic- Cenozoic era (Ward *et al*., 1985) ranging from 1500 m to 3000 m (Bauer- Gottwein *et al*., 2011). The peninsular aquifer system has developed mass horizontal, highly permeable rocks dominated by tertiary limestones and dolostones, which were thinly covered by Holocene and Pleistocene epoch carbonate rocks formed during the transgression of the sea (Weidie, 1985) which undergoes cavernous (fracture) and intergranular porous medium (Schönian *et al*. 2005). Regional topography is characterized by low lying limestone with high net permeability, allowing for precipitation to infiltrate through the vadose zone and into the underlying unconfined aquifer (Bauer- Gottwein *et al*., 2011; Beddows *et al*., 2007; Stoessell, 1995). Allende and Quinones (1974) named this calcrete layer as “carapace” leads to formation to recrystallization of aragonite and high magnesium calcite. Beneath this carapace, a low- magnesium calcite called “sascab”. The landscape has been extensively karstified by the interaction of mixing- zone hydrology and littoral processes (Smart *et al*., 2006).

At the end of the Cretaceous period, an asteroid impacted the north of the Yucatan Peninsula producing a 200 km large impact crater known as Chicxulub. Impact breccias related to the Chicxulub impact have been logged at 160 m depth in the north-eastern part of the Peninsula (Ward *et al*. 1995), linked to the impact outcrops in southern Quintana Roo (Bauer-Gottwein *et al*. 2011), and evaporites are found from 1500 to 2000 m depth and become much shallower when going northward (Smart *et al*. 2006).The Chicxulub Impact Crater has high influence on hydrogeology by producing a basin of subsidence resulted from erosion and karstification in the north (Pope *et al*., 1996) paving ways for numerous research studies on geology, geophysical and hydrogeological settings (Rebolledo- Vieyra *et al*., 2011, Zhu *et al*., 20111, Andrade- Gomez *et al*., 2019). The “Ring of Cenotes”, a permeable zone encompassing the Chicxulub sedimentary basin, the Ticul fault zone and the Holbox fracture Zone in the northeastern Quintana Roo. The Ticul Fault Zone originated from a special tectonic event located in the northwest portion of the peninsula, which leads to groundwater channels. The biggest fracture in this region is the fracture of Holbox-Xel Ha, which originates on the northeast coast of the peninsula to the south with a trend N5°E and N10° (SW- NE & SSW-NNE) (Bauer-Gottwein *et al*. 2011). The general geological map of the Yucatan Peninsula is presented in figure 12.

LOCAL GEOLOGY OF QUINTANA ROO (CANCUN- TULUM & COZUMEL ISLAND)

The Quintana Roo includes coastal strata with lagoons and coral reef limestones while the rest of the geological material consists of eolinities, freshwater-lake carbonated and recrystallized carbonates locally termed as caliche. After the sea level rise in Holocene, the Pleistocene dune ridges erodes and formed the island Cancun, Contoy, Mujeres which exposed 2 – 3 m above sea level. Cancun is a modern land hoisting all international hotels and the land is 13 km long and less than 1 km wide elongated platform of Pleistocene and Holocene dune ridges connected by Punta Cancun and Punta Nizuc by Holocene tombolos extend toward the mainland. Depth to the base of the Pleistocene dune rocks is unknown; rock cropping out 3 m below sea level on the Caribbean side of Isla Mujeres appears to be eolianite. The Nichupté Lagoon System (NLS) is an oligotrophic lagoon located in the north-east of the Yucatan Peninsula (Figure 1.13) with number of sub-lagoons connected to the open Caribbean Sea with two inlets namely Cancun and Nizuc inlets. The NLS contains five interconnected water bodies namely Nichupté Lagoon, Bojorquez in the northeast, Rio Ingles in the southwest, Somosaya or Amor at the west in the central; and Caleta at the southwest (De la Lamza and Hernandez., 2011). The depth of the lagoon ranging from 0.3 – 4.5 m with salinity values from 21 – 32 ‰ with a mixed semidiurnal tidal cycle from Caribbean Sea. This NLS also borders the National Park Costa Occidental de Isla Mujeres, Punta Cancun and Punta Nizuc which were being part of Mesoamerican Reef Barrier System (Romero- Sierra 2018). The radiocarbon ages of mollusks show that older Holocene eolianite is younger than 3000 y B.P. In the middle of Island Cancun, the eolianite is overlain by the Blanca eolianite composed of about 90 % ooids with thin coatings.

The Puerto Morelos in the NE coast of the Yucatan Peninsula is an open-ocean connected highly flushed coastal system (Coronado *et al*., 2007). It is situated in the northern part of an extensive barrier- fringing reef complex that extends from Belize to northern Yucatan Peninsula. Inland wetlands are separated from the sea by a 2-3 m high and 100-200m broad sand bar. Puerto Morelos was a small fishing village until the early 1980's, but since it has developed rapidly as tourism has become the main economic activity. Amongst the major attractions are the crystal-clear seas, the white-sanded beaches and the reef ecosystem. The carbonate sand is the leading geological formation aged from Holocene.

Tulum is the southern extension of northern Caribbean coast with unconfined aquifers. Tulum is one of the growing cities in Quintana Roo and Mexico. The only source of freshwater is the freshwater lens from few meters up to 100 m overlying saline water (Gondwe *et al*., 2010). This karstic network provides wetlands and forests with groundwater channels. The Holbox fracture zone with trend of NNE- SSW runs up to 10 km inland of Tulum to Isla Holbox in the north coast of the Peninsula. The other fracture zone called "Rio Hondo" is a normal fault located in the south of Quintana Roo extends up to Belize. Soils in the area of Tulum are very thin and epikarst with high porosity and conductivity outcrops frequently. The quick infiltration through a thin layer of soil, epikarst and fractures, freshwater area of Tulum flows through cave network system going up to 12 km inland forming two main karstic system Sac Aktun and Ox Bel'Ha which is the important among the largest cave in the world. Discharge occurs either at the coast, often as caletas and bays, or within the Mesoamerican coral reef. Coastal outflow rate is estimated at 0.3–0.4 $m^3\ km^{-1}\ s^{-1}$ (Bauer-Gottwein *et al*. 2011). The narrow beach ridge plain is positioned a few kilometers to the west of Puerto Juarez and runs south terminating near Xel Ha.

Cozumel Island, about 20 km off the Caribbean coast from the Yucatan Peninsula, considered as the first cruising tourism destination worldwide (Palafox-Muñoz, 2009). The island is 50 km long and 18 km wide and an area of 540 km^2 with an elevation of 5 m. The passage between the mainland and Cozumel Island become the passage for the transport of Yucatan current later form the loop current into the Gulf of Mexico and continuing as the Gulf stream after passing the Florida current (Carillo *et al*., 2015). The insular shelf of Cozumel Island features water depths up to 35–50 m and extends about 250–500 m from the shoreline. In the northern area, between Punta Norte and Punta Molas, the shelf extends for more than 15 km seaward, where sandy bottoms are found. The nearshore bathymetry comprises two shallow coastal terraces with coral reef lines followed by sandy plains before the steep insular shelf slope along the coastline from Punta Celarain to Punta Norte (APIQOO, 2018). The coral reef systems alongshore the coastal waters of Cozumel Island represent the economic cornerstone in the region with several species mainly found in the east and south coast of the island (Palafox-Muñoz, 2009). In total, three marine protected areas have been established: (a) Reserve of the Biosphere "Caribe Mexicano" (RBCM); (b) National

Park “Arrecifes de Cozumel” (PNAC) (11,988 ha) at the southwest coast of Cozumel Island; and (c) Natural Protected Area of Fauna and Flora “Isla de Cozumel” (APFFIC) at the north and northeast coast of Cozumel (37,829 ha). The low-lying and broad island of Cozumel was the emergent part of a horst block is layered by Pleistocene limestones. The presence of dolines and uvalas with exokarstic forms has been reported, but the majority have been characterized over time, due to the fact that they do not exceed 50 m in diameter. The local geology of the study area from Cancun to Tulum in Quintana Roo is presented in figure 13.

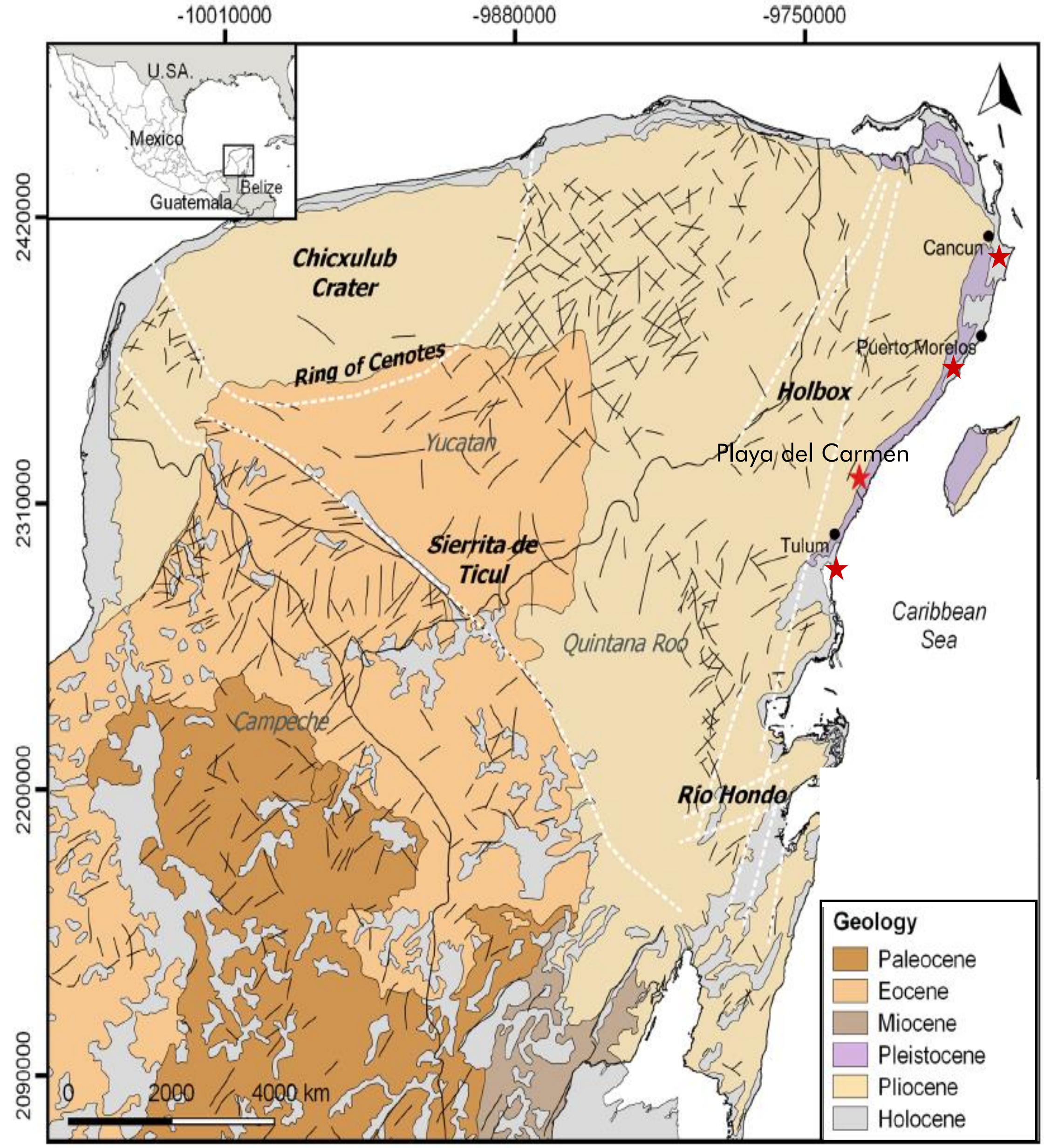

Figure 12. Geological map of the Yucatán Peninsula (adopted & modified from Zamora- Luria et al., 2021)

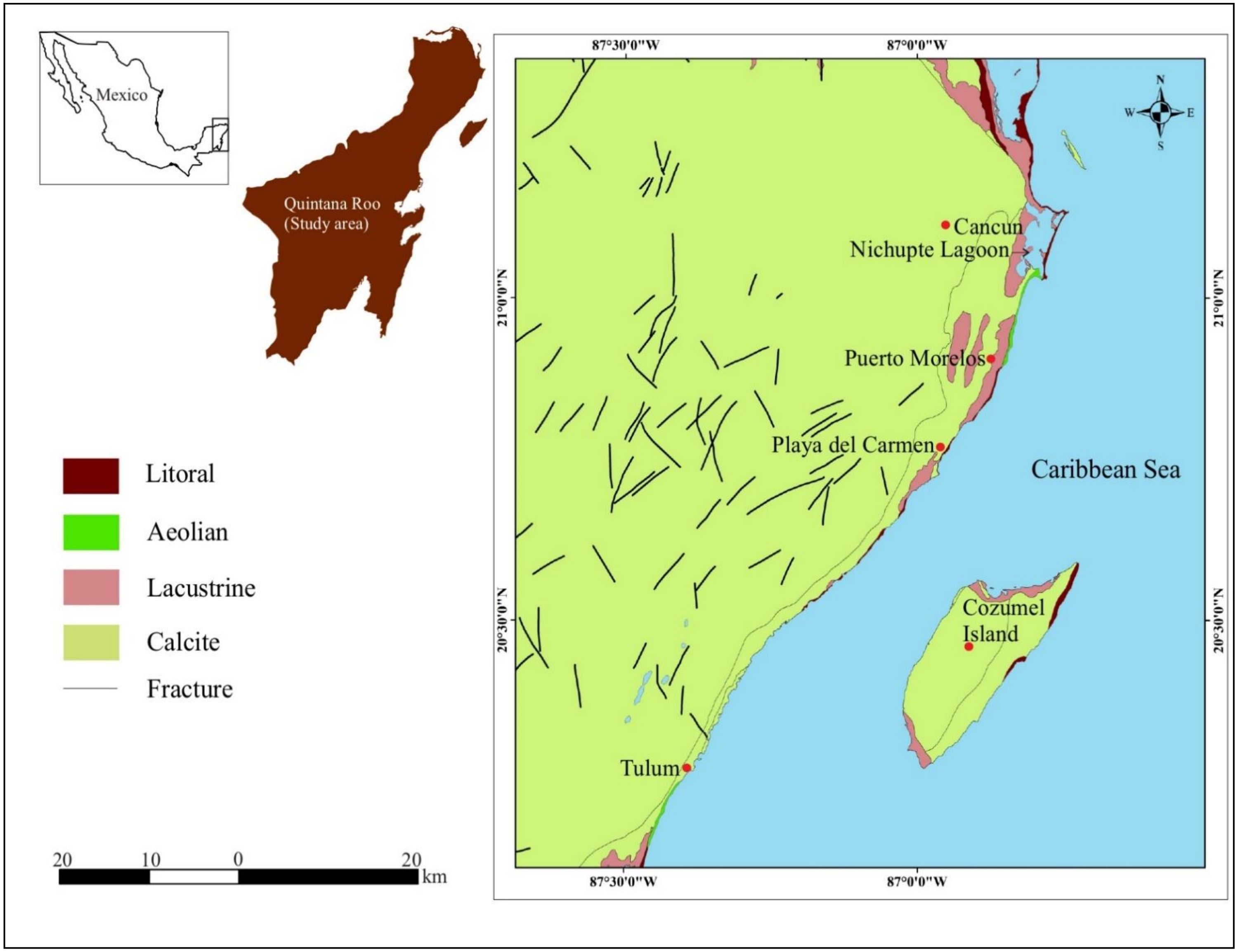

Figure 13. Geology map of the study area (Cancun- Tulum, Quintana Roo)

HYDROGEOLOGICAL SETTING

Due to the nature of the subterranean drainage as well as the low-lying topography, surface water bodies and streams are absent or very limited in the region (Metcalfe *et al*., 2000). For this reason, the main source of freshwater for human consumption in addition to industrial and agricultural usage is supplied from groundwater (Escolero *et al*., 2002). The best-known hydrogeological regional model of the aquifer indicates that coastal areas present the saline intrusion effect, with a freshwater lens floating over greater-density saline water, which gives rise to the formation of a halocline (or mixing zone), and their thickness depends on geological characteristics and underground flow rate. The underground cave system are hydrologically open systems as the flow of the groundwater extremely flow towards the ocean with hydraulic gradients on the scale of 1-10 cm/km (Gondwe *et al*., 2010). Some of the external mechanisms which influences the flow dynamics on a regional scale were due to fluctuations in sea- level and hydraulic head differences (Smart *et al*., 2006). The circulation of the marine and meteoric water mass between the land and coastward direction was controlled by salinity, density and their geochemical composition (Whitaker and Smart, 1990). A mixed layer below the freshwater lens may also present close to the coast within less than 10 km mainly due to tidal mixing between the meteoric and marine water masses (Beddows *et al*., 2011; Null *et al*., 2014).

So far, some the groundwater investigation along the coast has reported higher concentration of dissolved inorganic nutrient (DIN) and Soluble Reactive Phosphorous (SRP) which seems to have a negative impact on coastal communities (Hernández-Terrones *et al*., 2011; Null *et al*., 2014; Camacho- Cruz *et al*., 2019).In Quintana Roo, there are two types of conduits are considered, first is the fissure passages that are 5–10 m high, 0.5–2 m wide and tens of meters long and second is the elliptical tubular passages that are 1.1–5 times wider than higher (from 2 to 30 m wide), the widest part corresponding to the modern mixing zone (Smart *et al*. 2006). Groundwater, in the coastal area flows perpendicular to the coastline nevertheless, due to its particular porosity and permeability, the Holbox fracture zone represents a preferential flow path. A general conceptual diagram of hydrogeology of Quintana Roo is presented in figure 14.

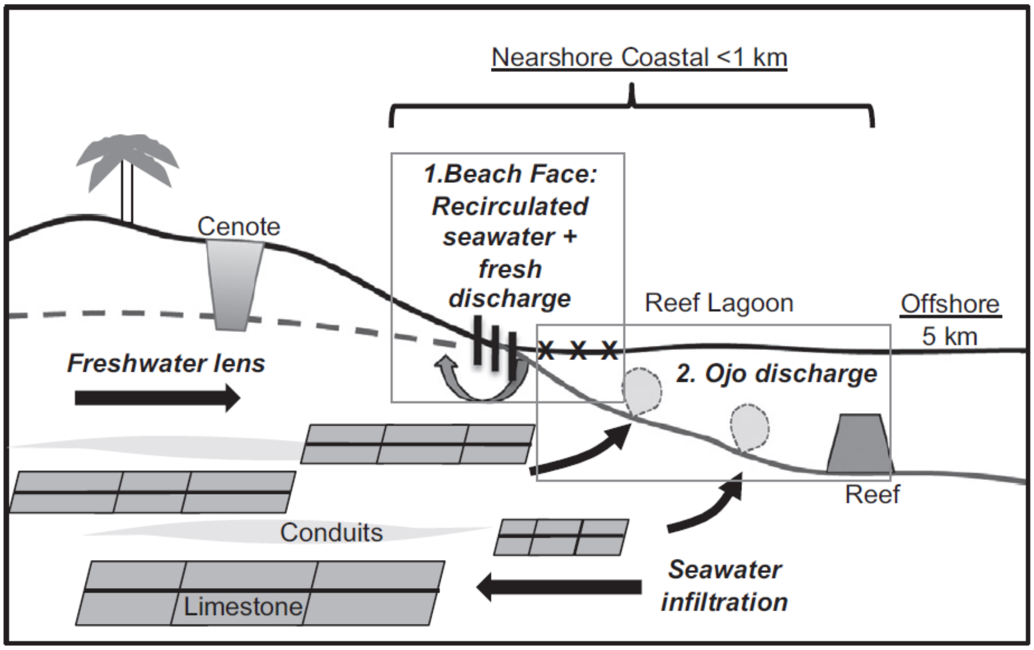

Figure 14. Conceptual diagram representing various hydrogeological settings near the coastal zone in Quintana Roo

COASTAL DUNE VEGETATION & CORAL REEFS

The coastal vegetation of the Yucatan Peninsula is classified by Flores & Espejel (1994) as coastal dunes vegetation. According to these authors, this type of vegetation extends along the entire coast of the Peninsula and is only interrupted by strip mangroves and lime cliffs located at specific points on the coastline. In general, it grows on sandy soils and, on the coast of Quintana Roo; it may be adjacent to rocky areas where pioneer herbaceous and creeping species, as well as other shrubs are developed (Flores & Espejel 1994).

In the Mexican Caribbean, the pioneer species that colonize the beach, also during the initial stages of dune formation and the first frontal cord of sand dunes are *Sesuvium portulacastrum*, *T. gnaphalodes*, *C. uvifera*, *S. maritima* y *Euphorbia buxifolia*; and the characteristic species of shrub strata in this region are *Thrinax radiata*, *Coccothrinax readii*, *Bravaisia berlandieriana*, *Pithecellobium keyense*, *Cascabela gaumeri*, *Cordia sebestena*, *Sideroxylon americanum*, *B.*

macrocarpa, *Erithalis fruticosa*, *Agave angustifolia*, *Leucaena leucocephala*, *C. uvifera*, *Metopium brownei*, *Bursera simaruba*, *Coccoloba barbadensis*, *Piscidia piscipula* y *Diospyros salicifolia* (Moreno-Casasola *et al*. 2014).

The NLS is a Flora and Fauna Protected Area (Área de Protección Manglares de Nichupté) declared as Ramsar Site by Mexican National Commission of Protected Areas (CONANP in spanish) (RAMSAR, 2007). Mangrove species like *Rhizophora mangle, Avicennia germinans, Laguncularia racemosa* and *Conocarpus erectus* are present in the Nichupté lagoon system, listed under "threatened" category according to Mexican Norm NOM-059-SEMARNAT-20102 (SEMERNAT,2010).

In Cozumel Island, Téllez *et al*. (1989) recognize the presence of coastal vegetation, which is classified for them as halophilous vegetation or coastal dunes vegetation. They describe their development in sandy and gravelly soils, and report the eight plant associations: (1) *Ambrosia hispida – Opuntia stricta – I. pes-caprae*; (2) *Canavalia rosea – Tephrosia cinerea – Sophora tomentosa*; (3) *Thournefortia gnaphalodes – S. maritima – C. uvifera*; (4) *Thrinax radiata – Hymenocallis littoralis– I. pes-caprae*; (5) *Thrinax radiata – Caesalpinia bonduc*; (6) *Rachicallis americana – E. fruticosa – Ernodea littoralis*; (7) *Salicornia bigelovii – Batis maritima*; (8) *Vallesia antillana –Quadrellaincana – Enriquebeltrania crenatifolia*. Although, at the island level some research has been carried out to evaluate the general characteristics of the vegetation in coastal dunes.

MESOAMERICAN CORAL REEF SYSTEM (MAR)

Coral reefs in the Mexican portion extend from Isla Contoy (the northernmost island of the MAR) south to Xcalak, including the submerged bank of Arrowsmith, Cozumel Island, and Banco Chinchorro. Extended fringing reefs border most of the continental and a commonly wide (typically hundreds of meters) shallow lagoon separates the reefs from the shoreline (Jordán-Dahlgren & Rodríguez-Martínez, 2003). The lagoon floor is usually sandy, harboring extensive beds of seagrasses, and sporadic coral heads (Figure 15). Usually considered a continuous system, coral reefs in the region have different geomorphological structures. The continental northern reefs are small in area and have an identifiable reef lagoon, back reef and fore reef. The reef crest and shallow fore reefs were, until recently, dominated by *Acropora palmata*. Deep fore reefs (>10 m) are mostly coral grounds colonized by multispecies assemblages with low relief and a gentle slope (Rodriguez-Martinez *et al*., 2014), suggesting that modern accretion has been minimal, and features of geological structures determine reef morphology (Jordán-Dahlgren & Rodríguez-Martínez, 2003).

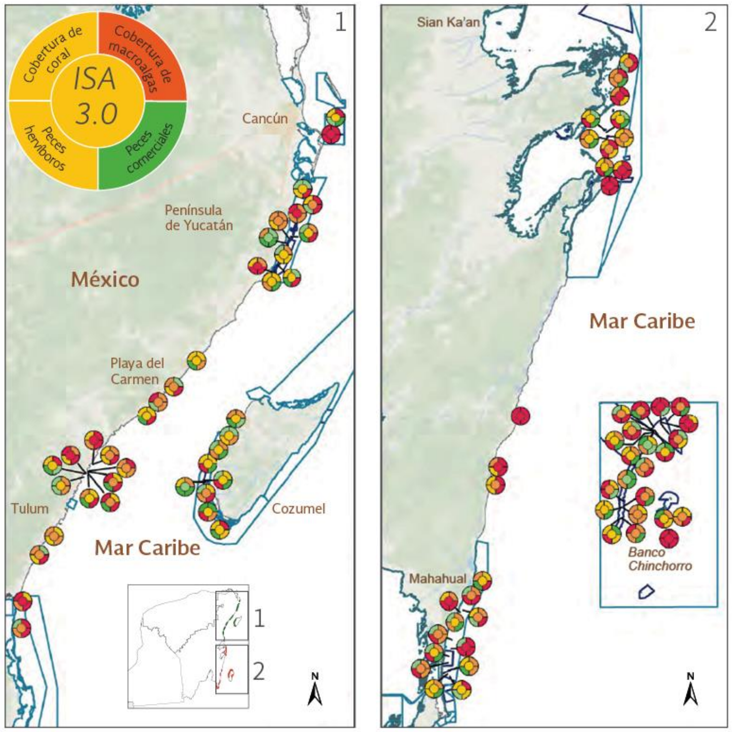

Figure 15. Mesoamerican reef system of Mexico. (Source: Kramer et al., 2015).

In Cozumel Island, located ~22 km off the eastern coast of Quintana Roo, fringing reefs, patch reefs, and coral colonies on hard substrate are distributed around the island, with well-defined structures on the west coast (Rioja-Nieto & Sheppard, 2008). Reefs can be observed fringing the coast (<5 m depth), at the edges of the steps forming linear patch reefs (5–15 m depth), and bordering the edge of the shelf (10–20 m depth) with large reef structures that can rise up to 5 m above the sand-covered shelf. The most developed reefs are present in the South-western area, which are bordered by a narrow shelf formed by a succession of terraces stepping at increasing depths. On the windward side of Cozumel, there are no extended fringing reefs. However, in some areas, large coral colonies form a distinct reef wall (Jordán-Dahlgren & Rodríguez-Martínez, 2003; Reyes-Bonilla, Milletencalada, & Alvarez-Filip, 2014). Also, in this area of the Island, the

Caribbean's western-most algal ridges are found. These form structures up to 5 m high (Steneck, Kramer, & Loreto, 2003).

ANTHROPOCENE EVENTS IN QUINTANA ROO

Hurricane events

One after the development of tourism in Cancun after 1970, from 2005-2007, Cancun faced a high cyclonic activity which caused a drastic lang in the coastal landscapes. Hurricane Emily on July 2005 exposed rock outcrops in several sections of the subaerial beach (Silva *et al*., 2006); while the successive Hurricane Wilma on October 2005 caused the total destruction of the beach (Silva *et al*., 2006) leaving the hotels being hit by waves. Hurricane Dean (August 2007) induced the movement of considerable sediment volume towards the submerged beach profile (Martell *et al*., 2012). In the past, the natural sediment balance of the dune enabled the beach to maintain a dynamic metastable equilibrium (Mendoza *et al*., 2015) but since after the construction of the hotels on the dunes, the natural response of the beach to storm events was altered and affected in which the suspended sediment is deposited on submerged bars offshore the wave breaking zone, Besides, the actual response of the beach of Cancun to hurricanes is the permanent loss of sediment with a very slight and slow capacity of recovery manifesting an additional external practices.

The two hurricanes namely Manuel and Ingrid originated in the Pacific Ocean during 2013 caused flooding events in the cave systems in the area from Tulum to Puerto Aventuras and the effects of the hurricane on sedimentation in the Yax Chen Cave system. In 2014, tropical storm Hanna caused landfall in the eastern and southern portion of Yucatan Peninsula and northern Belize. The photographs on beach nourishment in Playa Marlin after the hurricane Ida during 2009 is presented in figure 16.

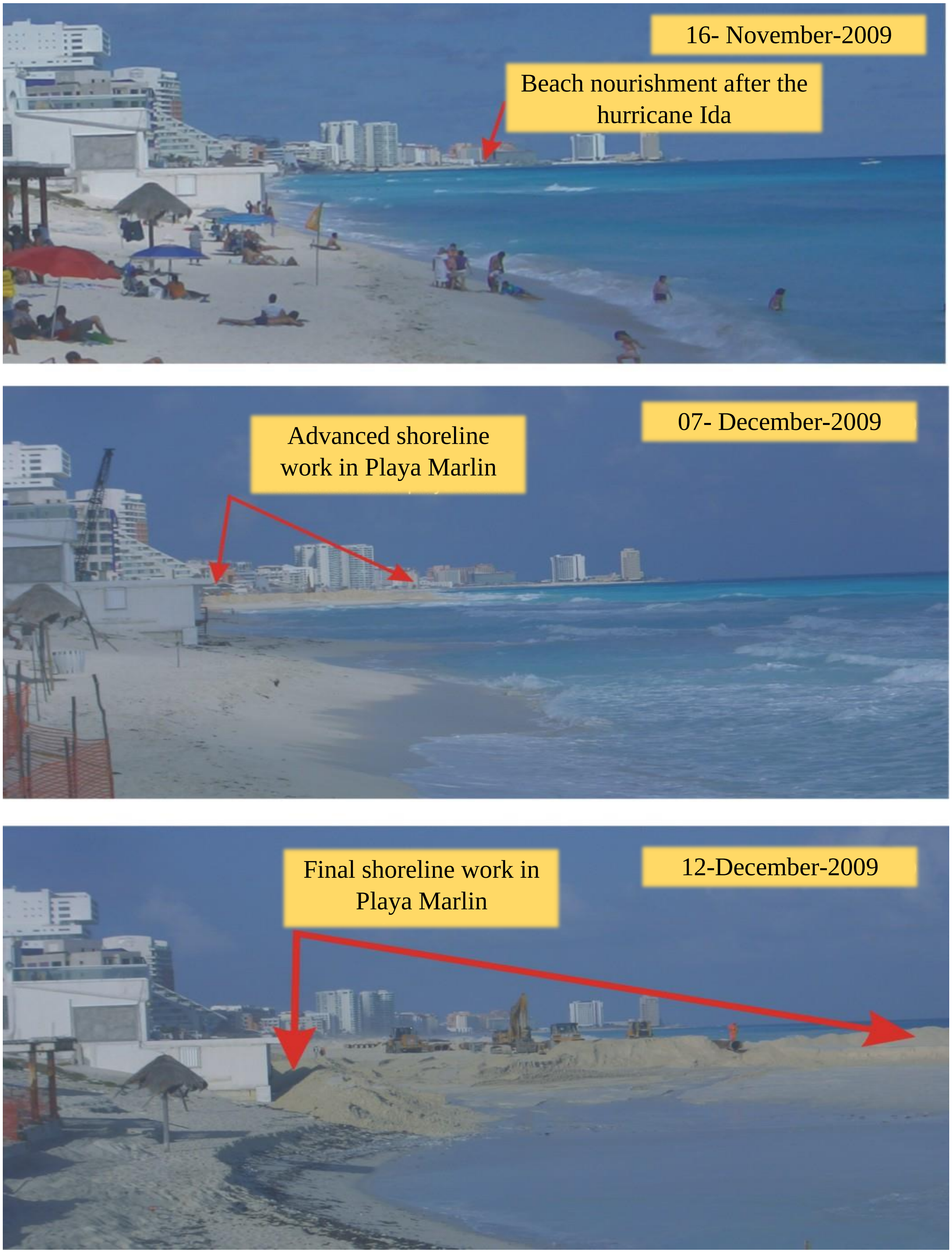

Figure 16. Beach nourishment after the hurricane Ida in 2009 (Soure: Uluapa Sr, 2011)

Sargasso- golden tides

The Caribbean Sea experiences an invasive arrival of *Sargassum* Spp. Consisting of *Sargassum fluitans* and *S. natans*. During 2011, the first report on ocean scale accumulation of drifting Sargassum spp has reported from the North Atlantic Recirculation Region (NARR) (Oyesiku and Egunyomi, 2014). Smetacek and Zingone (2013) used the term “golden tides” for drifting masses of Sargassum spp., due to their brown-yellow color that resembles gold. In the open ocean, this seaweed provides habitat for fish, invertebrates, sea turtles and seabirds, and it serves as spawning and nursery areas for many organisms (Pendleton *et al*., 2014). However, beaching of this massive quantities of drifting Sargassum spp. resulted in piling of decaying beach-cast material that colored the clear near-shore waters murky brown, due to production of leachates and organic particles. During the decay of this algal mass, the generated organic matter on the beaches affected human health and the tourist industry (Rodriguez-Martínez *et al*., 2016), economic and health hazards also posed an environmental threat to the coastal ecosystems. The Sargassum-brown tides caused acute high loads of organic material and increased turbidity, but the degree of impact varied among the sites (Tussenbroek *et al*., 2017). The general practice of removing this dried sargasso or the decay algal mass was the direct dumping in the landsites. The Yucatan Peninsula being highly porous karst aquifer have higher probable to get polluted by the pollutants from near surface deposits which infilters directly into the groundwater system causing accumulation of As and other potentially toxic metals in the groundwater. Later, the groundwater discharge due to the porous rock bed, transport the toxic metals and other indigenous nutrient from the freshwater sites to the marine environment, posing a long-term impact in the marine environment. The conceptual diagram for the impacts of Sargasso is presented in figure 17.

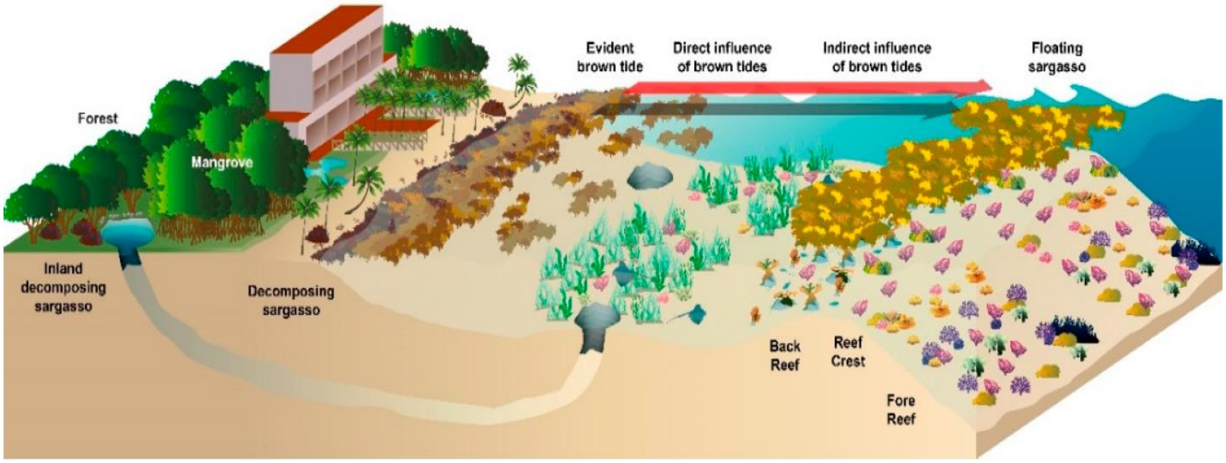

Figure 17. Conceptual representation of the Mexican Caribbean coast profile with impacts of Sargasso (Adopted from Chavez *et al*., 2020)

Coral reef communities

In Cozumel and the northern part of Quintana Roo, the 2005 bleaching event and subsequent hurricane impacts affected more than 50% of coral colonies (Jackson *et al*., 2014). In 2007, hurricane Dean (category 5) hit the Southern Quintana Roo reefs affecting Mahahual and Chinchorro Bank. In the following years, i.e., 2009–2011 and 2014–2017, Mexican Caribbean (MC) coral reefs were less affected by increasing sea surface temperatures (SST) (NOAA, 2018) and hurricane impacts (NOAA,2019). Nonetheless, the rapid increases in macroalgae and the growing local threats diminish the capacity of the coral reefs to recover (Suchley *et al*., 2016). On the onset of tourism in late 1970s has impacted reefs and other ecosystems through the constructions of piers to receive massive tourist cruise ships (Martínez-Rendis *et al*., 2016), the clearing of vegetation to construct roads, houses, restaurants and hotels (Hirales-Cota *et al*., 2010; Figueroa-Zavala., 2015), and recreational activities. However, they also pose potential threats to reef communities, e.g., breakage of corals by divers and snorkelers, trampling, taking fishes for aquaria, oil contamination due to shipping, among others (Gil *et al*., 2015). Indeed, there are additional threats of the Mexican Caribbean coral communities such as invading species (e.g. lionfish [*Pterois volitans*]) (Schofield, 2009) and the massive arrival of Atlantic Sargassum species reaching Western Caribbean coasts (Putman, 2018). The disintegration of these Sargassum not only releases nutrients and consumes oxygen, but also decreases light availability at the seafloor, thereby affecting ecosystem functions such as benthic photosynthesis (Wang *et al.*, 2018). All these threats impacted the Mexican Caribbean coral communities are left investigated.

JUSTIFICATION

Beaches are unique and important coastal ecosystem connected with multi- element activities. This complex environment was easily disrupted by beach development for tourism purposes and other social- economic standpoint, thus producing an altered scenario by exploiting natural resources with serious impact in the ecosystem. The eastern coastal corridor of Quintana Roo recognized as famous tourist destination for the white sand and tortoise blue water. With the increase of tourism in Quintana Roo, several studies have reported in other aspects of the environmental impacts. The karstic terrain of Quintana Roo made this place as a unique ambient forming cenotes and with the absence of surface freshwater sources. The urbanization and tourism development have contaminated the groundwater with high dissolved inorganic nutrient resulted from improper drainage system. The massive arrival of Sargasso has created vigorous environmental impacts including public health. These kinds of problem were investigated using quality assessment studies in the coastal environment. Hence, this comprehensive study in coastal environmental qualities in the Caribbean coast derived from detailed analysis of environmental components and paving a way to improvise the existing quality criteria and practices to manage the beach quality management.

RESEARCH QUESTIONS

This study on evaluation of beach qualities will be effective if the following research questions are answered through the investigation

- What is the present condition on beach water qualities?
- How do the environmental conditions affect the status of inorganic nutrients (nitrites, nitrates and phosphates)?
- Does the arrival of sargasso contributes more nutrient input in to the marine ecosystem?

- Does the anthropization events shows any changes in coastal landscape?
- What is perception of beach awards by the beach visitors? Do they encourage more beach awards?
- Does the arrival of sargasso affects the beach awarding criteria?
- What is the most noticed marine stressors affecting beach environmental qualities?

HYPOTHESIS

The principal factor which affects the coastal landscape and the environment in the Mexican Caribbean coast is due to the anthropogenic activity for the intense growing tourism in the region.

GENERAL OBJECTIVE

The principal aim of this study to identify the present environmental status and evaluate the beach qualities in the Mexican Caribbean coast of Quintana Roo, Mexico

Special Objectives

- Evaluate spatial and temporal variation in the physico-chemical characters, inorganic nutrients and dissolved trace metals in the surface water from several beaches.
- Evaluate the water quality by measuring the bacteriological concentration in the water
- Evaluate the qualities of beaches by analyzing environmental indicators based on physical, biological, natural and social condition of the beach.
- Verify the effectiveness of existing blue flag award systems and the visitor’s perspective over beach certification systems.
- Assessment of anthropization impact in the coastal area over four decadal period resulted during tourist development.

SAMPLING PLAN

This study is an integral approach to evaluate the coastal environmental qualities in the coastal corridor of Quintana Roo. A large-scale sampling was done in 2019 and 2020 from private and public beaches from Cancun to Tulum in the coastal corridor and Cozumel Island as illustrated in figure 18. In 2019, 56 surface water were collected and 23 samples were collected separately. But in 2020, due to the existing pandemic restriction, only 48 water samples were collected and 22 nutrient samples were collected due to accessibility restrictions. The questionnaire survey was carried on all the samples beaches during the field work. The local and international beach visitors were considered for responding the questions in order to obtain the perspective on present beach qualities and beach awards.

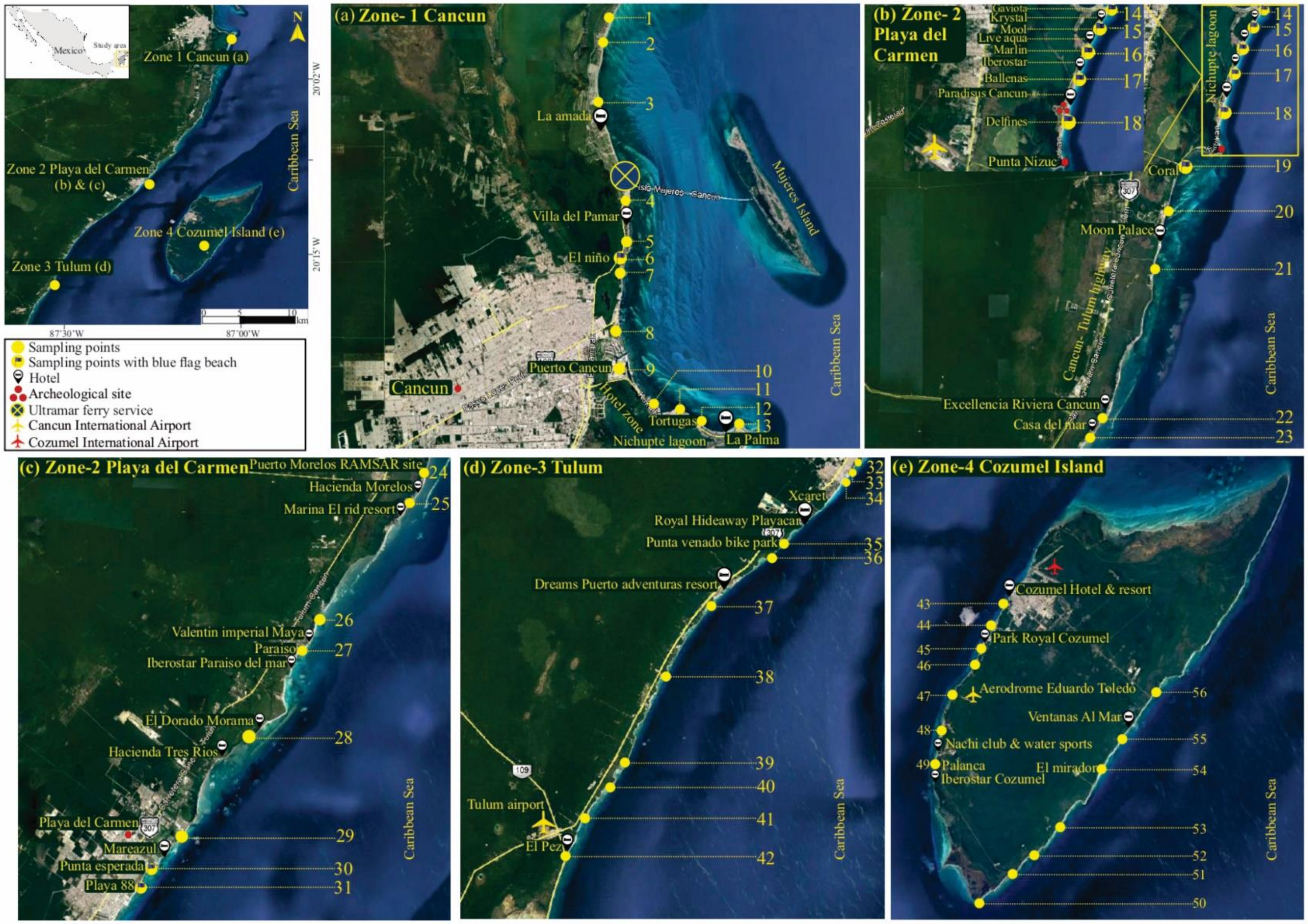

Figure 18. Map indicating the sampling spots in eastern corridor of Quintana Roo for the beach quality studies, Quintana Roo, Mexico

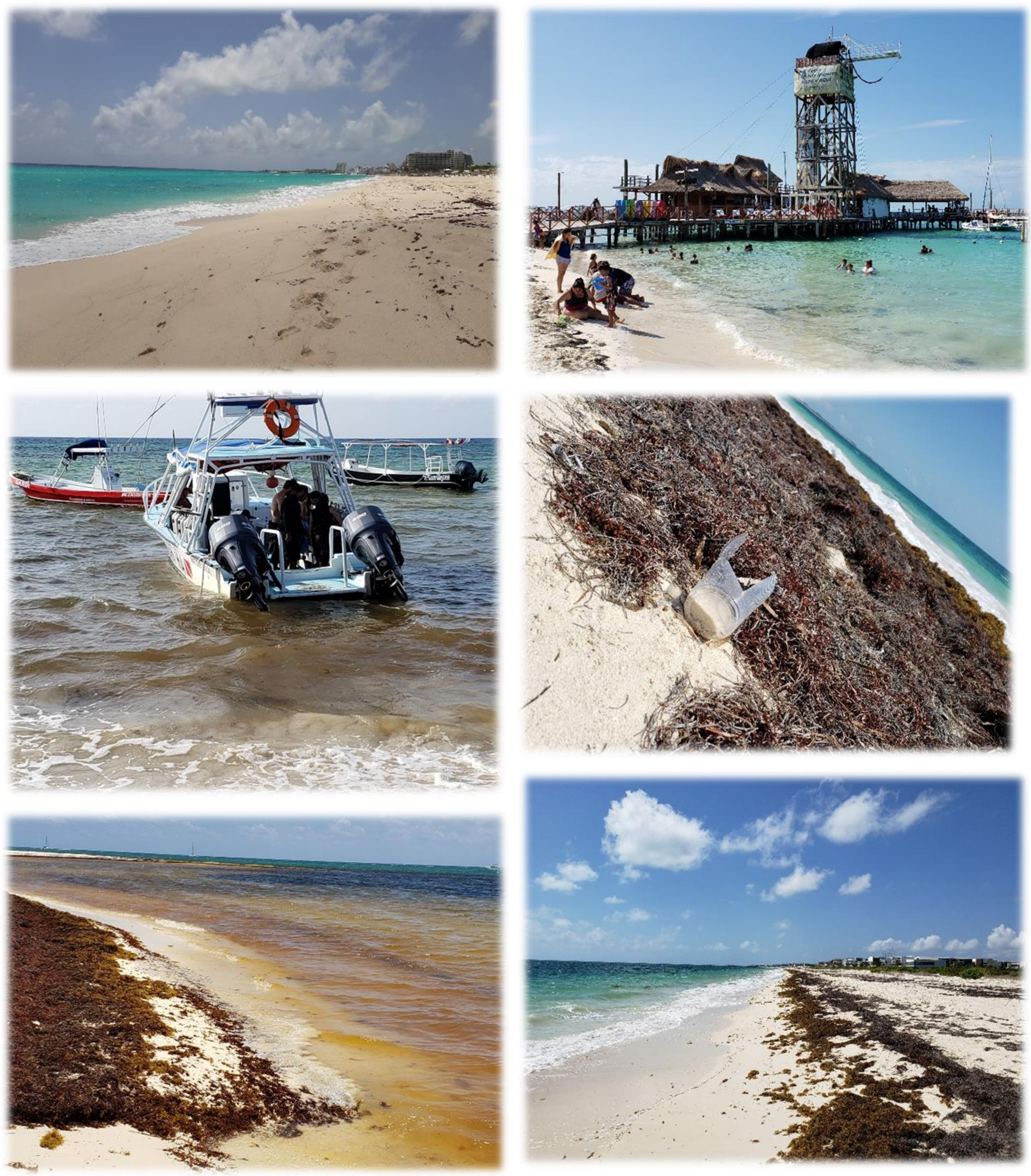

Figure 19. Photographs showing the present environmental status of beaches in eastern corridor of Quintana Roo

Figure 20. Photographs of field sampling (2019 & 2020); (a) & (b)measuring in-situ parameters (c) water sampling for nutrients & trace metal analysis

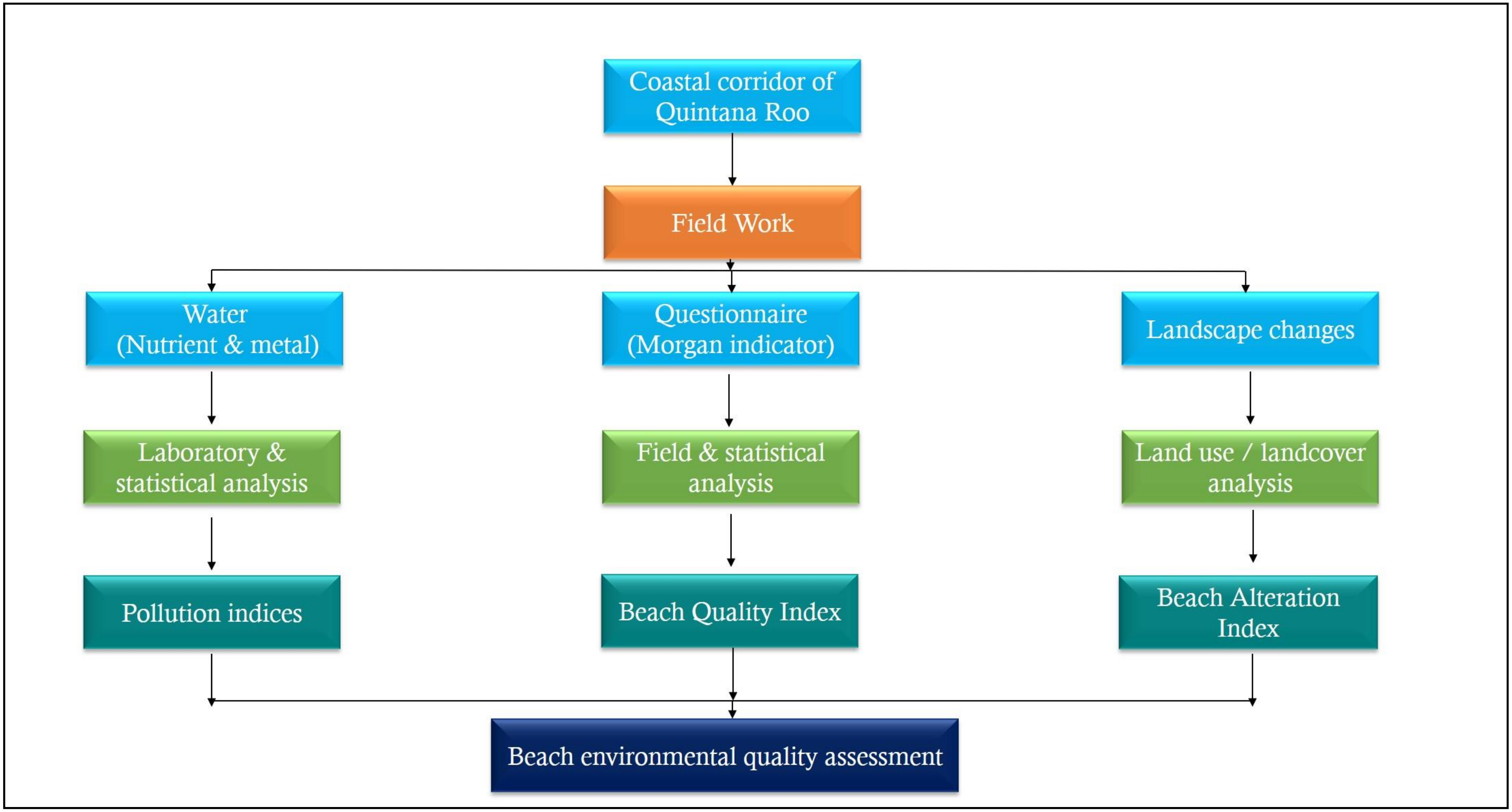

Figure 21. Schematic presentation of this study applied on coastal corridor of Quintana Roo, Mexico

CHAPTER I

BEACH WATER QUALITY ANALYSIS BY GEO ENVIRONMENTAL PARAMETERS AND APPLICATION OF COASTAL WATER QUALITY INDICES

I.1. INTRODUCTION

The coastal area is a zone of transition between the purely terrestrial and marine components on Earth's surface. It is widely recognized as being an important element of the biosphere – as a place of diverse natural systems and resources. The importance of coastal areas as a study object has emerged in recent times due the development of complex activities the coastal region. So, coastal processes and natural ecosystems are subject to changes that vary greatly in geographic scale, timing and duration that combine to create changes in biologically productivity of coastal systems which is vulnerable to additional pressures resulting from human activities (Vivian and Schlacher, 2015). In turn, the sustainability of human economic and social development in the costal region that is vulnerable to natural and human-induced hazards as a result of our poor understanding of the dynamics of land-ocean interactions, coastal processes and the influence of poorly planned and managed human interventions. Numerous natural and human-induced forces influence coastal ecosystems thus modifying various aspects of societal interest, including marine services, natural hazards and public safety, public health, ecosystem health and living resources.

Coastal monitoring through satellite map works has included a diversity of settings, such as individual beaches, dunes, mangroves, local communities, tourism sites, coastlines, and islands (Gould and Arnone, 1997; Stockdon *et al*., 2002). The coastal transformation is not only limited to specific events, but several environmental elements with their altered status resulted mostly from tourism activities and their persisting impacts on the coastal environment have been documented ideally (Lai *et al*., 2017). However, the impact of anthropization and their approaches were least studied and evidenced (Lima Magalhães *et al*., 2015) specifically in coastal zone. The anthropization concepts can vary and based on the intensity of existing problems on a particular environment, the relation between every anthropization factors should be addressed during a study (García-Ayllón, 2018). The general attributes for the assessment of anthropization impacts were considered on urban transformation of natural soil, the creation of artificial port infrastructures thus altering the sedimentary movements of the beach, the waste water influent from the terrestrial environment, the alteration of beach environment for the recreational purposes, thus in whole affecting the marine environment (Dias *et al*., 2013, Mata- Lara *et al*., 2020). So far, the study on estimating anthropization impacts were reported with various approaches. Among the analytical methods, the analysis of ecosystem indicators were the commonly used methods by the considering physical, biological, chemical and geological indicators (Mercier *et al*., 2011). Henceforth, the present study assesses the anthropization impact through the spatial analysis of particular environment by the evaluation of land- use and land-cover change (Guetté, *et al*., 2018; Da Silva *et al*., 2015) and their respective changes over specific time period.

I.2. LITERATURE REVIEW

Generally, the effects of change in land use on global level are still little known, but the factors behind those processes, are not fully understood. There are difficulties in defining methods of intervention in the regions and in obtaining support instruments for decision making which are fundamental to managing, understanding, monitoring and assessing the (environmental and social) changes resulting from modifications in land use. Land- cover changes results from the modification of the landscape character without affecting the existing overall classifications to extreme case, where one land- cover type completely replaces another, which is referred to as land conversion (LC). The Land-cover modification refers to anthropogenic resulted from deforestation for urban and agricultural expansion or naturally caused resulted from flooding, wildfire, disease or epidemics causing Land-cover Changes (LCC). Since Holocene, the earth's landscapes experienced natural caused and anthropogenic LCC as well as LC.

There are three main concepts that guide vulnerability assessments: (1) Physical Vulnerability, which is closely related to susceptibility; (2) Social Vulnerability, which is related to how prepared society or individuals are to deal with or adapt to a hazard; (3) Social and Physical Vulnerability, which is related to the susceptibility and sensitivity of the environment to a particular hazard, and results from the social context. The detection of long-term changes of beaches is challenging as a consequence due to limited availability of data, particularly for remote island settings and the highly dynamic nature of coastal environments that may be strongly influenced by seasonality as well as episodic changes caused by transitional processes, such as storm surges, tectonics, and land use/land cover change. As a consequence, the morphological analysis of a remotely sensed image time-series is a useful approach to identify and classify beach morphologies (Pais-Barbosa *et al*., 2011). The space–time characteristics of such surveillance systems are important factors in defining the beach conditions that can be assessed and the changes that can be determined. Mann and Westphal (2014) report that remote imagery with a low sampling frequency may be sufficient to characterize prominent morphological changes in platform beach configuration of reef islands, but the timing of those images relative to the nature of beach dynamics is critical in ascertaining change patterns and trajectories. Satellite imagery has been used to examine coastal forms and patterns and to classify beaches and their hydro-morphological stage. Advances in the spatial and spectral resolution of remote sensing systems have revolutionized our ability to characterize beaches and their configurations by directly mapping geomorphic features, landforms, species assemblages, and even identifying species of individual trees and shrubs that populate beaches and dunes (Turner *et al*. 2006).

Cancun had its first hotel construction since 1974 supported by Fondo de Fomento a la Infraestructura Turística (INFRATUR) and the Banco Mexicano SOMEX for the construction. A year later, Cancun counted with 1322 rooms with 99500 tourists annually. Later 1976, the construction of hotel continued on large and international hotels were established. The 1990's represented the adjoining of Spanish chains to Cancun's hotel business, although the national and international chains also grew. Hence, in that year there were 17,470 available rooms due to the incorporation of hotels from the Melia, Oasis, Westin and Marriot chains. Nine years later 7,140 rooms had been added to the site and the Ritz Carlton, Royal Islander, Caesar Park, Hilton Cancun Beach, Gran Caribe Real, Le Meridian and Moon Palace hotels had been built. The abrupt changes in the construction reveals the increasing demand and tourism in Cancun. The list of tourist arrivals from 1970 to 2009 were given in figure 2.1. This expanding tourism accounts reaches around 7.8 million for 2016 and 8.1 for 2017 (SECTUR, 2017). By the end of the 2019 and 2020, the tourists arrival accounts for 25 and 12 million respectively and the variation of -51. 89% between 2019 and 2020 were due pandemic covid restrictions (SEDETUR, 2020).

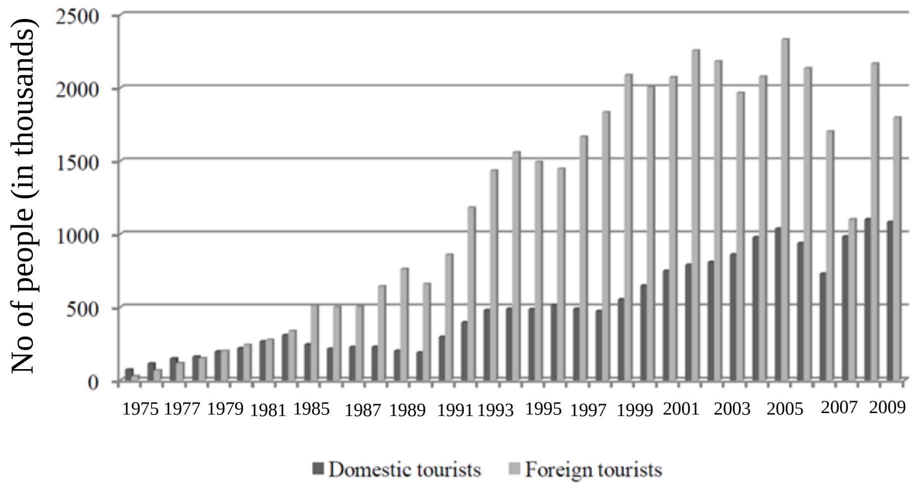

Figure I.1. Evolution of arrivals of tourists into Cancun from 1975 to 2009 (Adopted from FONATUR, 2010)

Thus, intense tourism causing several environmental impacts including land use and land cover changes. Even, with advanced development on land use and land cover changes studies, the anthropization impact approaches are still remained difficult due to their complexity. Hence, the GIS was used as important diagnostic tools to evaluate the anthropogenic impacts on the coastal environment. Recently, the application of GIS for the environmental assessment studies has gained attention through the implementation of integrated indicators. So far, these novel methodologies have been implemented for diverse environments such as sandy beaches, coastal lagoons, flood risk areas (Pagan *et al*., 2017; Garcia- Ayllon., 2017). Henceforth, the recent methodology based on GIS indicators were used for the evaluation of coastal environments which were subjected to high anthropization.

I.3. OBEJECTIVE

The aim of this work to estimate the anthropization impact on the beach environment of Quintana Roo coastal corridor.

I.3.1. SPECIFIC OBJECTIVE

- Advocate the land uses – land cover changes associated with urban development in the coastal corridor of Quintana Roo for three decades.
- Elucidate the land cover transformation for each zonal region with a decadal interval.
- Estimate the tourist's urbanization index (I_{TU}) by identifying the urban development near the coastal environment.
- Estimate the Beach Alteration Index (I_{BA}) by identifying the transformation of beach area over a specific period of time.
- Understand the anthropogenic inertia on the GIS indicators on the coastal environment over a certain period of time.

I.4. METHODOLOGY

I.4.1 LAND USE AND LAND COVER CHANGE ANALYSIS

An open methodology was framed to analysis the GIS indicators to determine the anthropization impacts on coastal environment. The initial stage of the analysis involves the land use and land cover change analysis over a period of three decades. The Land use/Land cover (Lu/Lc) change analysis was carried out from 1990 to 2020 with five years interval. These maps are prepared from Landsat satellite images downloaded from earth explorer website (USGS). The 1990, 1995 and 2000 Lu/Lc maps were prepared from Landsat - Thematic Mapper (TM), 2005 and 2010 Lu/Lc maps were prepared from Landsat - Enhanced Thematic mapper plus (ETM+) and finally, Landsat - Operational Land Imager (OLI) was used to prepared the 2015 and 2020 land use/land cover map. This data was geometrically rectified to a common map projection system of UTM Zone 16 North, WGS84 geodetic datum.

The image enhancement techniques like histogram equalization, Principal Component Analysis (PCA) and filtering was applied to enhance the satellite images for better interpretation (Abdi and Williams, 2010). The false color composite of satellite images was prepared and manual on-screen digitization method was applied for visual image interpretation of satellite images to prepare the land use/land cover map by using Arc GIS software. Visual interpretation can give an idea concerning land cover variation over a particular time period. The Lu/Lc classes are demarcated based on National Remote Sensing Centre (NRSC, India) classification. The data products used for this study is listed in the following table I.1. Finally, the obtained land use and land cover maps were used to determine the drastic changes in the coastal environment and later considered for the calculation of aforementioned indices for anthropization impacts.

Table I.1. Specifications of satellite data used in the study

Satellite/ Sensor	Acquisition Date	Resolution
Landsat 5 (TM)	22/12/1990	30 m
Landsat 5 (TM)	21/12/1995	30 m
Landsat 5 (TM)	09/12/2000	30 m
Landsat 7 (ETM+)	24/12/2005	30 m
Landsat 7 (ETM+)	22/12/2010	30 m
Landsat 8 (OLI)	12/12/2015	30 m
Landsat 8 (OLI)	09/12/2020	30 m

I.4.2. CHANGE DETECTION ANALYSIS

The land use map obtained from the earlier process were analyzed further change detection map in the coastal environment. Change detection has been defined as a "process of identifying differences in the state of an object or phenomenon by observing it in different times" (Singh 1989, Al- doski *et al*., 2013). This is considered an important process in monitoring LULCC because it provides quantitative analysis of the spatial distribution of the population of interest and this makes LULC study a topic of interest in remote sensing applications (Song *et al*. 2001, Gallego 2004).The change detection was carried out by selecting the initial data from 1990 and the final data from 2020 in order to detect the estimated changes and a buffer of 5 km range were prepared using the land use and land cover map. Since, the study area have more anthropogenic pressures in and near the coastal zone due to demanding recreational activities, the buffer zone of 5 km was considered sufficient for clear visual interpretation and to evaluate the pressuring factors on coastal environments. The change detection procedure was done by considering the following land types such as forest area (FA), mangrove forest (MF), marshy land (ML), swampy land (SL), lagoon

(L), water logged area (WLA), sandy area (SA), build-up land (BL). All the categories were selected for change detection from the year 1990 as original feature status and the final detection wad calculated for 2020 using filed calculator, thus obtaining the decadal changes of each land cover/ land use types and their corresponding changes in the recent times. The same procedure was repeated by considering one the land categorized as initial features and their respective changes in 2020 and the respective changed were recorded. The entire procedure was conducted in QGIS software version 3.16.3. The final output was classified according to the zone for better interpretation.

I.4.3. INDICES FOR BEACH ANTHROPIZATION IMPACT

Since natural areas are suspectable to dynamic changes, the coastal areas are never exceptional for the land cover changes. So, based on the land use and land cover changes results, an application of indices to evaluate the anthropization impact were applied in this study. Such an approach was valid, since the study area has an increasing tourism demand day by day from the development of the study zone. Due to many complexities and sensitivity of the environment which is subjected to severe anthropization, there was a limitation on considering various scientific disciplines. Henceforth, the coastal sandy area changes were considered as major drive which undergoes a large-scale alteration due to hotel construction and for the recreational activities over long period of time. Thus, the total changes in the sandy are coverage resulted from land use / land cover analysis was used to calculate the following indices according to a pilot study proposed by Garcia-Ayllón (2018). As, this study infers the freedom on choosing indicators and further modification on the indicators analysis, the following land cover characteristics were chosen for this study based on study area.

I.4.3.1. Tourists Urbanization Index (I_{TU})

This index was based on the phenomena of land transformation related to tourist activity which is markedly hotel or resort construction and some practiced recreational activities in the study area. Aforementioned, though the land use/ land cover categories were used to determine the change detection, for the application of the indices, only the land cover of sandy areas which includes dune areas and other vegetation which has converted into urban spaces were considered. Due to mass tourism and the gradual development of tourism in the study area, the pre-existing coastal settlements were also taken into account for the index application. Hence, the urban areas other type of vegetation located up to 2 km from the beach have been considered to determine the changes. The formula for the tourist urbanization index as follows as,

$$I_{TU} = \frac{S_{T1} + S_{T2}}{S_U}$$

where S_T being the sum of surface area (in sq.km) transformed by urbanization (S_{T1}) and coastal resources use for recreational activities (S_{T2}) since 1990 with a coastal buffer of 2 km, where the S_U was the reference surface area of the beach.

I.4.3.2. Beach Alteration Index (T_{BA})

Beaches are very dynamic environment often affected by several factors derived from tourism with corresponding anthropogenic activities and coastal events. Generally, the results of this serious actions result affects the sediment movement and their dynamics, thus modifying the nature of the beach. Hence, it is important to evaluate the phenomenon of sediment accumulation or erosion in the beaches in order to obtain the beach alteration index over a particular period of time. The Beach Alteration Index (I_{BA}) is the quotient between the beach surface area transformed by the alteration of the beach area by the non-natural causes and the total beach area. Non- natural causes are understood as the main anthropogenic factors than natural causes such as wind storms, water floods, waves etc. The proposed formula for the beach alteration index is follow as

$$I_{BA} = \frac{\Sigma_i \, \Delta S_{TBA}}{\Sigma_i \, S_{UBA}}$$

Where $\Sigma_i \, \Delta S_{TBA}$ is the sum of absolute value for deposition or erosion in beach areas due to non – natural causes between 1990 and 2020 and $\Sigma_i \, S_{UBA}$ is the total surface area of the existing beach area of the selected zone.

I.5. RESULTS & DISCUSSION

I.5.1. LAND COVER PATTERN OF QUINTANA ROO

The preplanned methodology has been applied to the beach area which includes zone 1- Cancun (a), zone 2- Playa del Carmen (b), zone 3 – Tulum (c) and zone 4 – Cozumel (d) and studied for land use and land cover changes. The long- time spatial analysis for the land- use and land cover analysis carried out through GIS from 1990 till 2020 has been presented in figure I.2 and I.3 respectively. The multi-decadal analysis between 1990 and 2020 showed a large-scale variation in the land cover patterns influenced by several anthropogenic environmental variables. The land use changes near the coastal zone includes urban area like Built up land, water logged areas and Lagoon, natural land such as ML, SA, SL and forest such as EF, MF, FA. The accelerated tourist development since 1980 has altered the natural landscape into built up land which was clearly manifested in the figure I.2 and I.3 zone (a) that showed a change in beach cover by 65- 75% (Escudero-Castillo *et al*., 2017). The main anthropogenic alteration in the Cancun coast includes the construction of very crowded infrastructure such as hotels, roads, several recreational courses etc. near the beaches. The changes in the water-logged area markedly the area fronting Nichupté Lagoon has undergone severe landcover uses since 1990 due to construction of the hotel, which is now locally termed as "Hotel Zone". The Nichupté lagoon facing the Caribbean Sea has undergone several changes due to expansion of hotel area from 1990 which attained complete changes during 2005. These mentioned changes have been clearly noticed in Cancun zone. Among the studied zone, Cancun and playa del carmen had faced severed land use changes when compared to Tulum and Cozumel Island. This intense in the beach cover results on deduction on natural sediment availability due to intense erosion and the corresponding loss was estimated at an annual rate of 1.8. for 1967- 2005 (Martell *et al*., 2010). The marshy and swampy land were noticed with subtle changes from 2005. The marshy land near the Nichupté lagoon has changed into swampy land during 2010- 2015. However, Cancun has faced severe land use changes since 1980, due to severe development of tourism and urbanization.

Secondly, Playa del carmen, the next up leading area under development in Quintana Roo. The figure I.2 and I.3 clearly shows the landcover change in the zone (b) playa del carmen. It shows a gradual land cover changes from evergreen forest, swampy land and marshy land into built -up land. The intense land cover changes were noticed since 2000 and the severity of land use changes were high since 2005 which resulted from urbanization due to increased tourism demand. The swampy land coverage in 2020 are expected further for intense change due to human demand.

The zonal region Tulum has affected by the human intervention since after the complete development of tourism in Cancun and Playa del Carmen. The land cover changes for Tulum which is zone (c) are presented in figure I.2 and I.3. The land use changes are highly vulnerable in this zone due to urbanization which observed as emergence of built-up land along the coast since 2000 and drastic changes was noticed since 2005 which is on increasing trend. The forest area is the major land cover pattern encountered in this zone was altered near the coast due to development of the built-up land. This abrupt changes in the forest cover were excepted for intensive alteration due to increasing tourism development in this region (Rodriguez Martinez, 2008). However, the increase of built-up land in this region resulted from change forest cover from 2005. The overall alteration shows the upcoming negative impacts on the Tulum region resulting from deforestation and sequential urbanization.

Finally, the Cozumel Island has showed a distinctive alteration over decades as shown in figure I.2 and I.3 (d). The eastern island showed no urbanization when compared to the west of the island. The western island which has intact with the mainland through water- based transport have gone through severe urbanization due to development of ports, airports and docks for cruises and other ferries from 1990 till 2020. Also, the western side of the island hoist several multi-star hotel resorts for the demanding tourism. The north of the island has unaltered land cover such as water-logged area and swampy land due to remote access and less or no human activities from 1990. Some of the forest cover has changed into built up land since 2005 markedly in west of the island. Though, west of the island noticed with no drastic changes from 2005, an expected changes in land cover were expected for upcoming years in Cozumel Island.

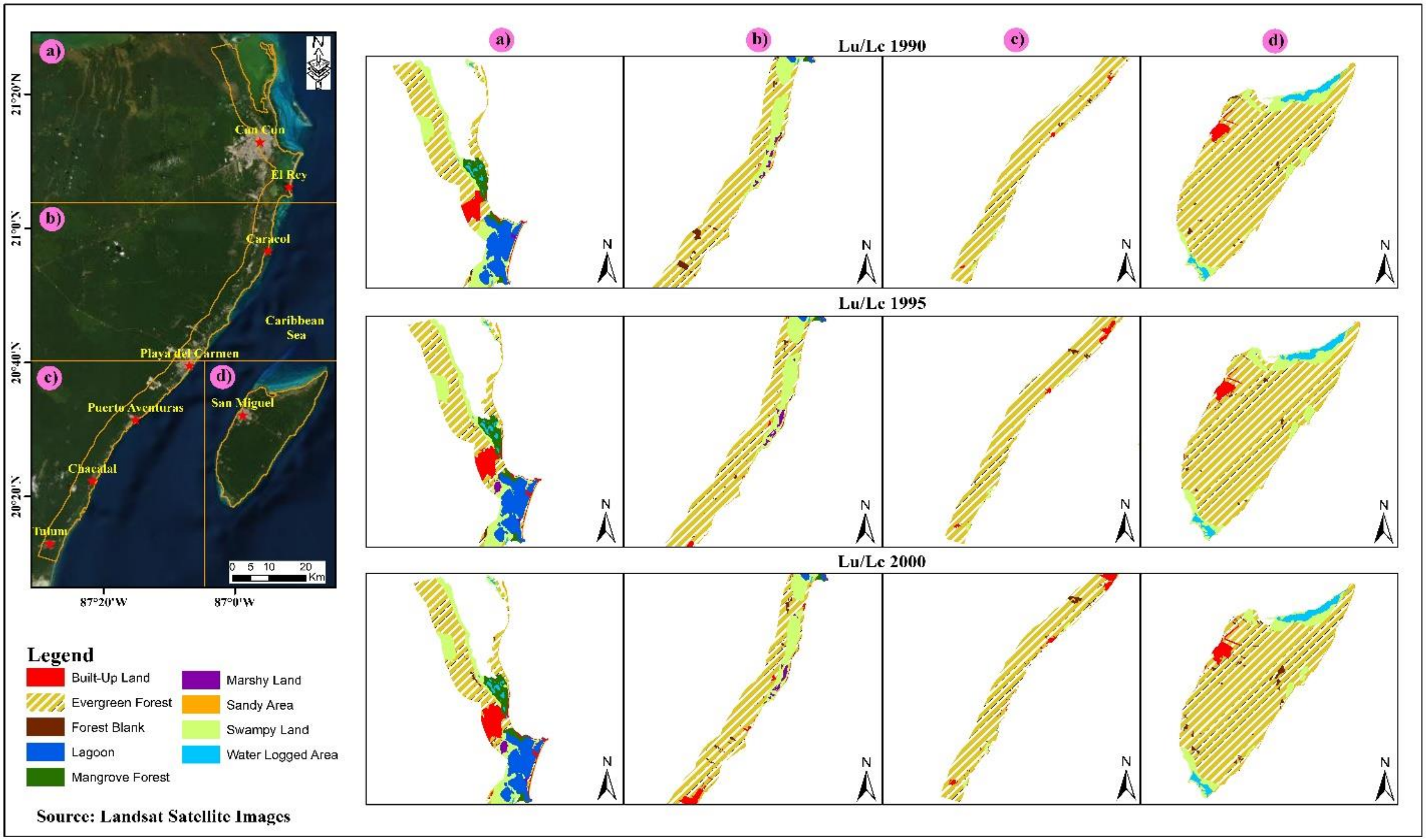

Figure I.2. Decadal - spatial analysis of land use/ land cover changes for zones Cancun(a); Playa del Carmen (b); Tulum (c); Cozumel Island (d) from 1990-2000

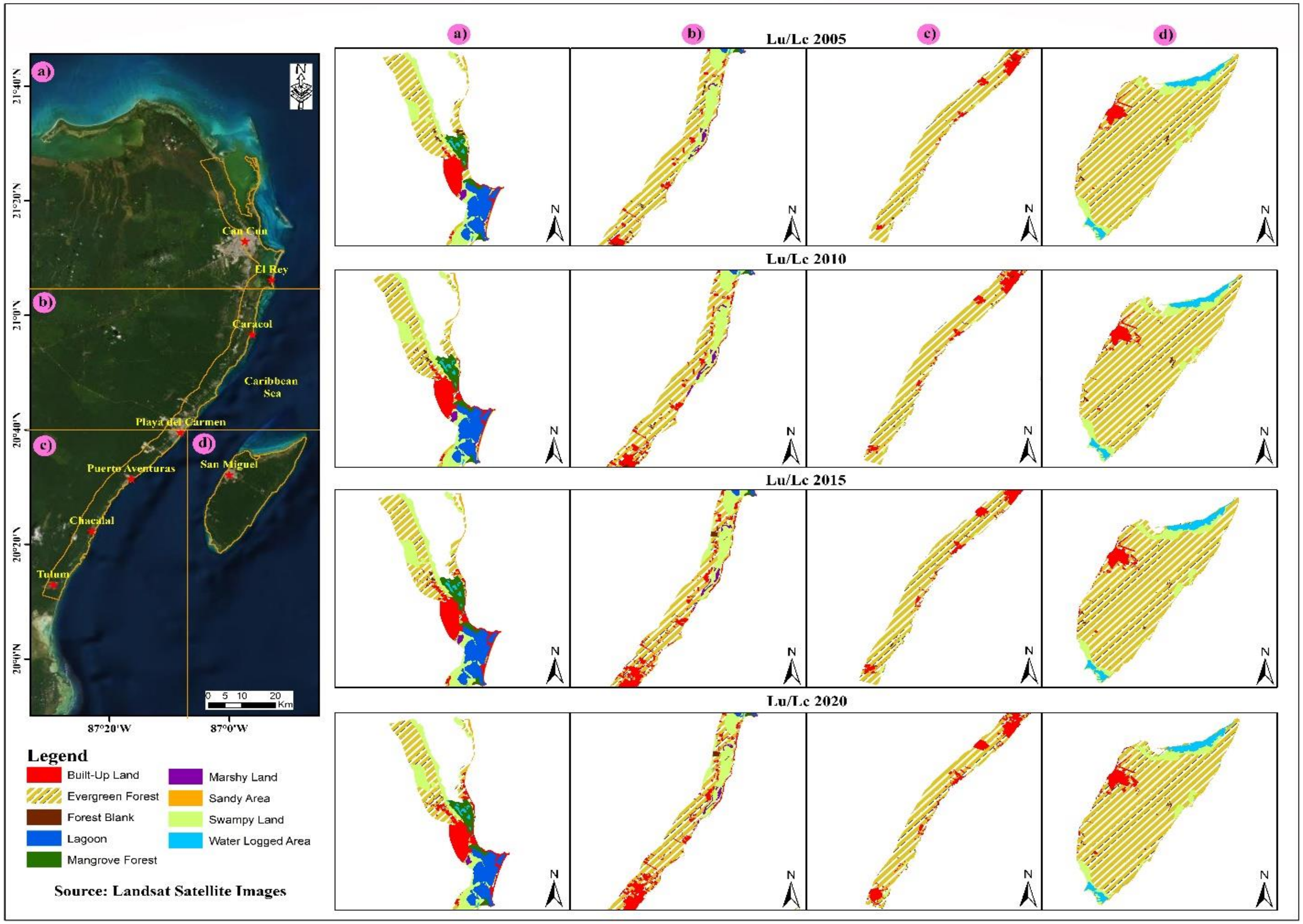

Figure I.3. Decadal - spatial analysis of land use/ land cover changes for zones Cancun(a); Playa del Carmen (b); Tulum (c); Cozumel Island (d) from 2005-2020

Since, the satellite imagery studies manifest the land cover changes their alteration characteristics were identified mainly through changes surface area. Table I.2 represents the land cover changes in overall Caribbean coast from 1990 to 2020 presented in sq.km. The major land type which undergone severe changes by the area was evergreen forest. There was a gradual decrease in the evergreen forest area by 40% every demi-decade, from 1125.16 sq.km with a final surface area of 984.90 sq.km. This drastic forest changes infers the destruction of forest area for the urban construction near the coastal zone. The next leading land type was swampy land which has an 12% decrease for every demi-decade. The mangrove forest area also was reduced in area by 15% from the total area since 1990 due to high need for human use (Calderon and Orozco,2009). The sandy area has shown a severe change in their surface area by 30% all over the study period. Besides, anthropogenic causes, some of the natural factors such as waves, storm events causing severe coastal erosion changing the coastal orientation (Del Rio *et al*., 2013).

The water-logged area, lagoon and swampy land showed an increase since 1990 accounting for 10% thus inferring a land cover change under the external pressures and change in original landcover of carbonate terrain. Since the beaches has undergone several beach nourishments due to some natural factors, the input of external sediment sources from nearby sandbank caused this alteration in the original landcover. Astonishingly, the built- up land showed a multi- fold increase by 8 times since 1990, which mainly manifest the persistency of anthropization in the coastal area. Unlike other land cover types, the built-up land has always on increasing tends which resulted from increasing tourism demand and consequential creation of urban buildings. Overall, the surface area changes show the vegetation cover has been highly reduced due to external land occupation for human use and constant increase of built-up land due to severe anthropization.

Table I.2. Land cover changes in the Caribbean coast from 1990 to 2020 (area in sq.km)

Land cover type	1990	1995	2000	2005	2010	2015	2020
Built-up Land (BL)	28.42	42.79	57.78	98.02	125.12	147.98	172.31
Evergreen Forest (EF)	1125.16	1109.12	1090.24	1067.40	1039.47	1004.93	984.90
Forest Area (FA)	14.30	10.17	19.50	9.64	8.08	5.80	5.02
Lagoon (L)	48.42	48.48	48.69	48.83	48.83	48.84	49.13
Mangrove Forest (MF)	20.28	18.61	20.86	20.86	20.94	22.79	22.76
Marshy Land (ML)	4.76	7.57	7.96	7.78	9.44	8.45	7.66
Sandy Area (SA)	13.65	12.45	10.84	10.43	10.62	10.08	8.24
Swampy Land (SL)	150.83	156.21	149.30	142.15	143.19	155.42	152.79
Water Logged Area (WLA)	17.95	20.87	21.46	21.55	21.41	22.82	24.30

I.5.2. CHANGE DETECTION ANALYSIS

The new approach on change detection approaches become more important for consideration, since it provides accurate information about change areas for better understanding. Since, the scale of accuracy is dependent upon the quality of the dataset, data complexity and opted method to perform the change detection. The present study achieved the essential quality and resulted with distinctive changes in each zone. Based on the procured results, the change detection for multi-decadal from 1990 to 2020 infers the major transformation of land cover due to creation and expansion of the built area. The overall results show the intense urbanization in these periods and the zonal wise change detection has been discussed for better interpretation.

In the Caribbean region, the zone 1 Cancun has been identified with intense changes from 1990 to 2020. The change detection for the zone 1 Cancun were presented figure I.4 and the results showed that nearly 50% of the land were encountered with no changes since 1990, while the other 50% of the land were changed drastically over this period. The green color indicates the changes resulted from water logged area. Sandy land, marshy and swampy land, forest area, mangrove forest and lagoon into built- up land. Thus, the change endorses the complete change of major land cover into built-up land for human use by 30% from the original landcover. The north side of the Cancun coast were the Isla Blanca, Nichupté lagoon and some inner land near north of Cancun city. The yellow cover indicates the change of forest, lagoon, water logged area, marshy land and mangrove forest into swampy land which accounts for 12%. The blue land cover shows the change detection from water logged area, swampy land, forest area and built-up land into mangrove forest by 6%. The elusive presence of mangrove cover among the urban construction and near the sea shore has left undisturbed over a long period of time. The yellow indicates the change detected from forest, lagoon, mangrove forest, marshy land, water logged area and sandy area into swampy land by 2% which was detected in the north of Cancun adjacent to the coast and deep north of Isla Blanca. The lateral area of the Nichupté lagoon have detected with a change from forest area with mangroves, marshy and swampy land, sandy area into lagoon which infers the morphological changes of the lagoon over a long of period. Since the lagoon also hoist several recreational activities which least to alteration of the pre-existing land cover. Among the studied zone, the Cancun showed a diverse change from the original land cover, due to severe anthropization and high human demand for this zone.

Secondly, the Playa del Carmen (zone 2) showed a major change towards the built-up land. The change detection analysis for Playa del Carmen was presented in figure I.5. Among the changes detected, nearly 50% of the land were detected with no change over multi-decades. However, the rest of the land were encountered with built- up resulted from changes in water logged area, lagoons, swampy and marshy land, sandy area, forest cover. Though, Cancun zone have multi-star hotels since the creation of Cancun and during the three-stage development of tourism, the Playa del Carmen located next to Cancun have faced the anthropization which manifested from the partial change of this zone from various land cover into built up area. The water-logged area, swampy and marshy land, sandy area, forest cover with mangroves were ultimately into built up land which accounts for 42%. Furthermore, forest with mangroves, lagoon and water-logged area, sandy area, marshal land was converted into sandy land near the coast which is nearly 3 % and these changes were found among the built-up land. The private resorts with beaches have caused the created the sandy area by altering aforementioned land covers for tourism and recreational activities. Nearly 3% of the land was marshy which resulted from swampy area and sandy area present very adjacent to the coast. Then 2% of the land cover were forest which changed from all the major pre-existed landcover in the zone.

Subsequently, the proceeding zone -3 which is Tulum represented in figure I.6 has showed nearly 30% changes which ended in built-up land from water logged area, swampy and marshy land, sandy area, forest with mangroves. Since, Tulum being protected areas hold up densely vegetated forest, which remains nearly 75% without any changes since 1990 till 2020. However, Tulum is now facing a rapid built-up expansion by new constructions of hotels and resorts, but the constraining policies on protected areas such as Sian Kan Biosphere aiding more forest conservation in this area despite emerging tourism demand (Rodriguez-Martinez, 2008).

Finally, the change detection analysis on Cozumel islands clearly infers the change of land covers markedly in the west of the Island which faces the mainland. The change detection for the zone 4 Cozumel Island is presented in figure I.7. As aforementioned, the west side of the island which faces the main land has undergone severe change into built-up and urban land. Since majority of the hotel, ports and docks are located in the westside of the island which showed 15% of the land cover alteration from water logged area, swampy and marshy land, sandy area, forest with mangrove covers. Due to densely vegetated area in center of the island, about 75% of the land were remained unaltered till 2020. Since, the Caribbean region now facing severe anthropization due to increased tourism, the unaltered landcover were expected for gradual changes in the upcoming years. Almost 10% of the land were changed into water logged area in the north and south border of the land. The water-logged area was resulted from the change of swampy land, forest with mangrove cover, sandy area, which infers the excavation of sand from this region for development and feasible transportation. The change of forest with mangrove cover, lagoon and water-logged area, marshy land into swampy land. As, the pre-existing land covers has altered into swampy and water-logged land identified in the north and south of the island, the tidal and wave actions majorly control the geomorphology of this area, besides permitted sand excavation for beach nourishment in the mainland (Varillas, 2010).

Henceforth, the change detection analysis which aimed to identify the overall change from the preexisting land cover mainly infers the massive emergence of built-up land for human use since 1990 (Vargas Martinez *et al*., 2013). Cancun and Playa del Carmen has already attained complete landcover changes into built up land near the coastal zone, but Tulum and Cozumel Island were showing gradual built land up changes which posing a drastic loss of biodiversity in the Caribbean region in future scenarios (Perez-Hernandez *et al*., 2020).

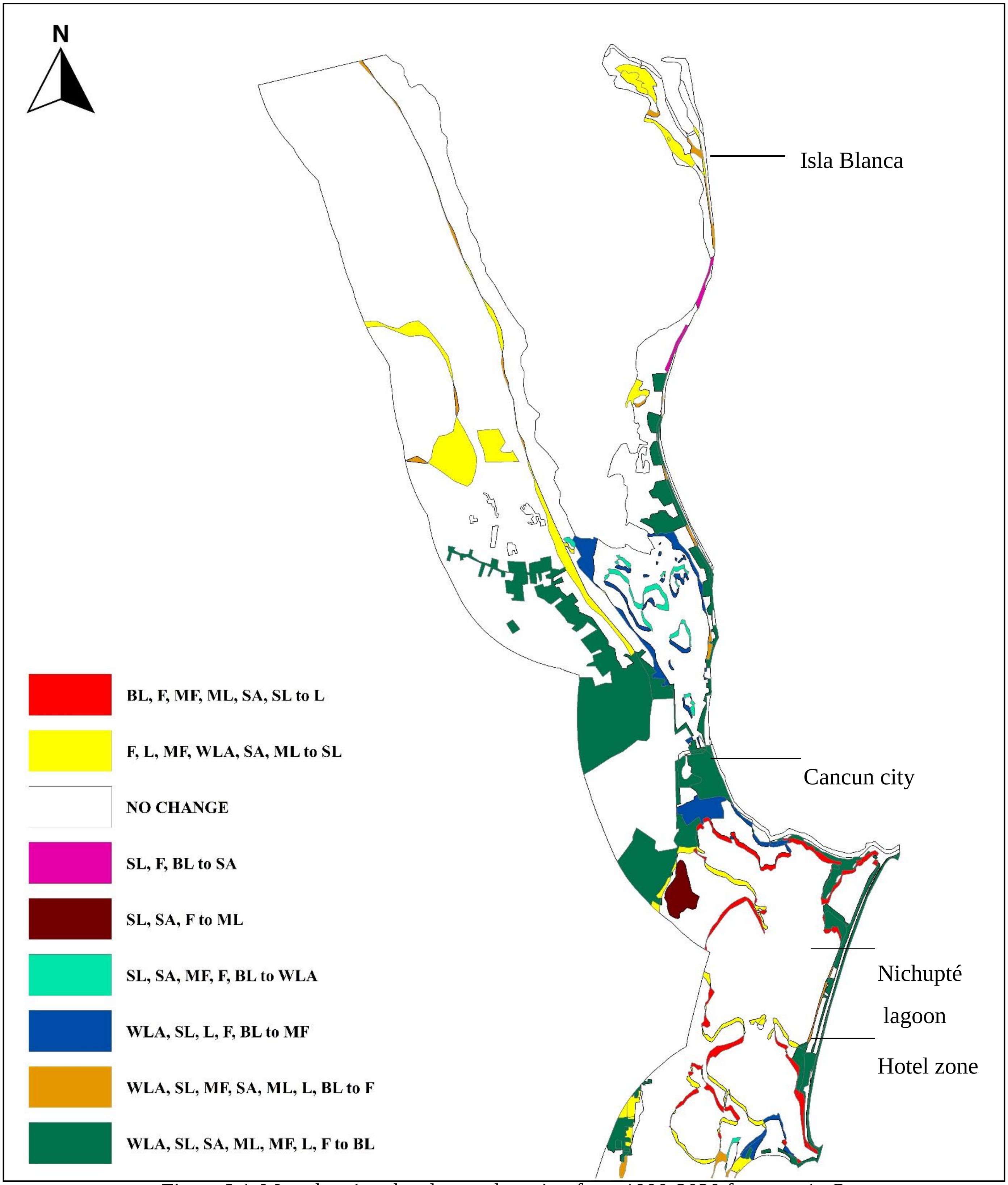

Figure I.4. Map showing the change detection from 1990-2020 for zone 1- Cancun

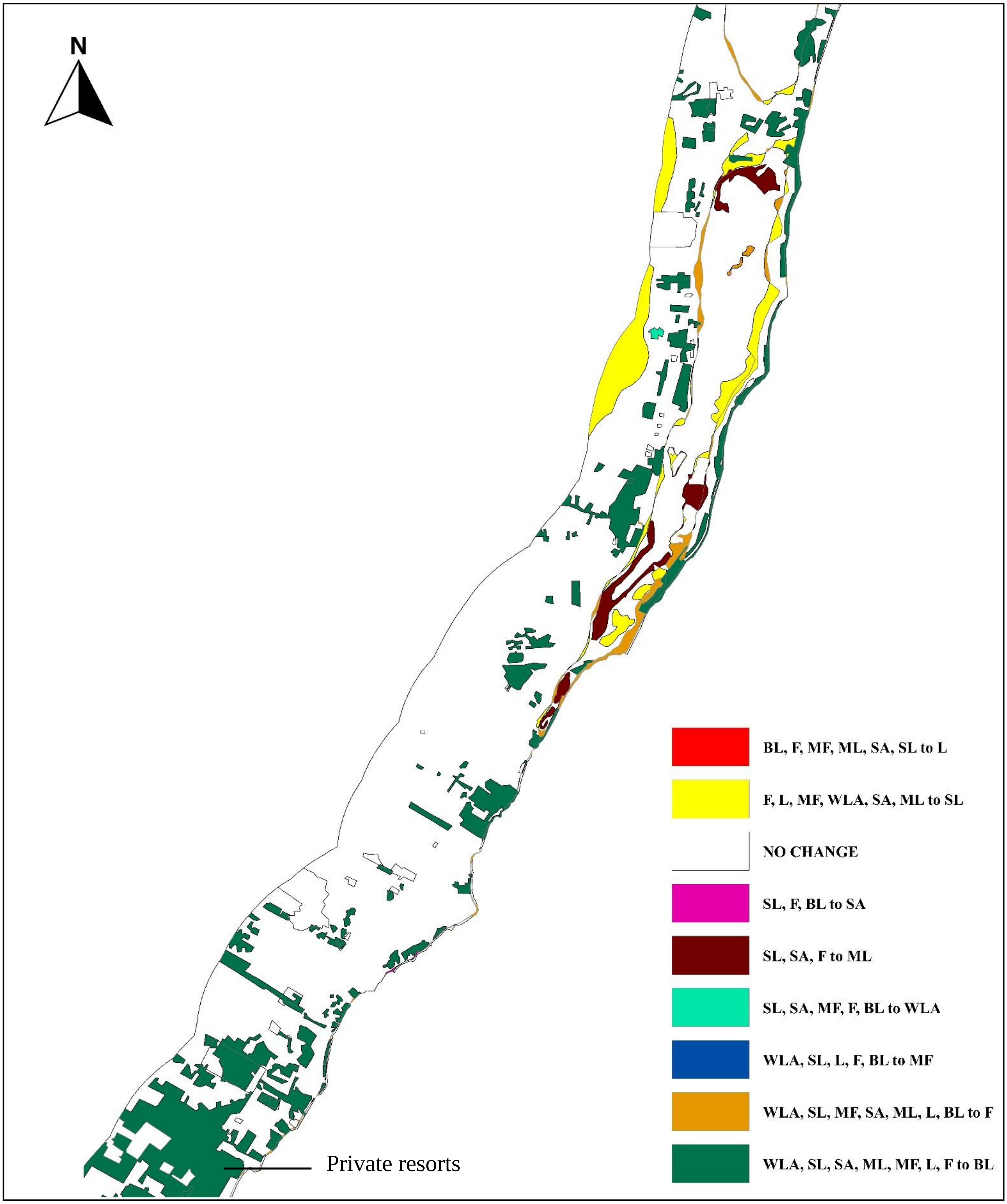

Figure I.5. Map showing the change detection from 1990-2020 for zone 2- Playa del Carmen

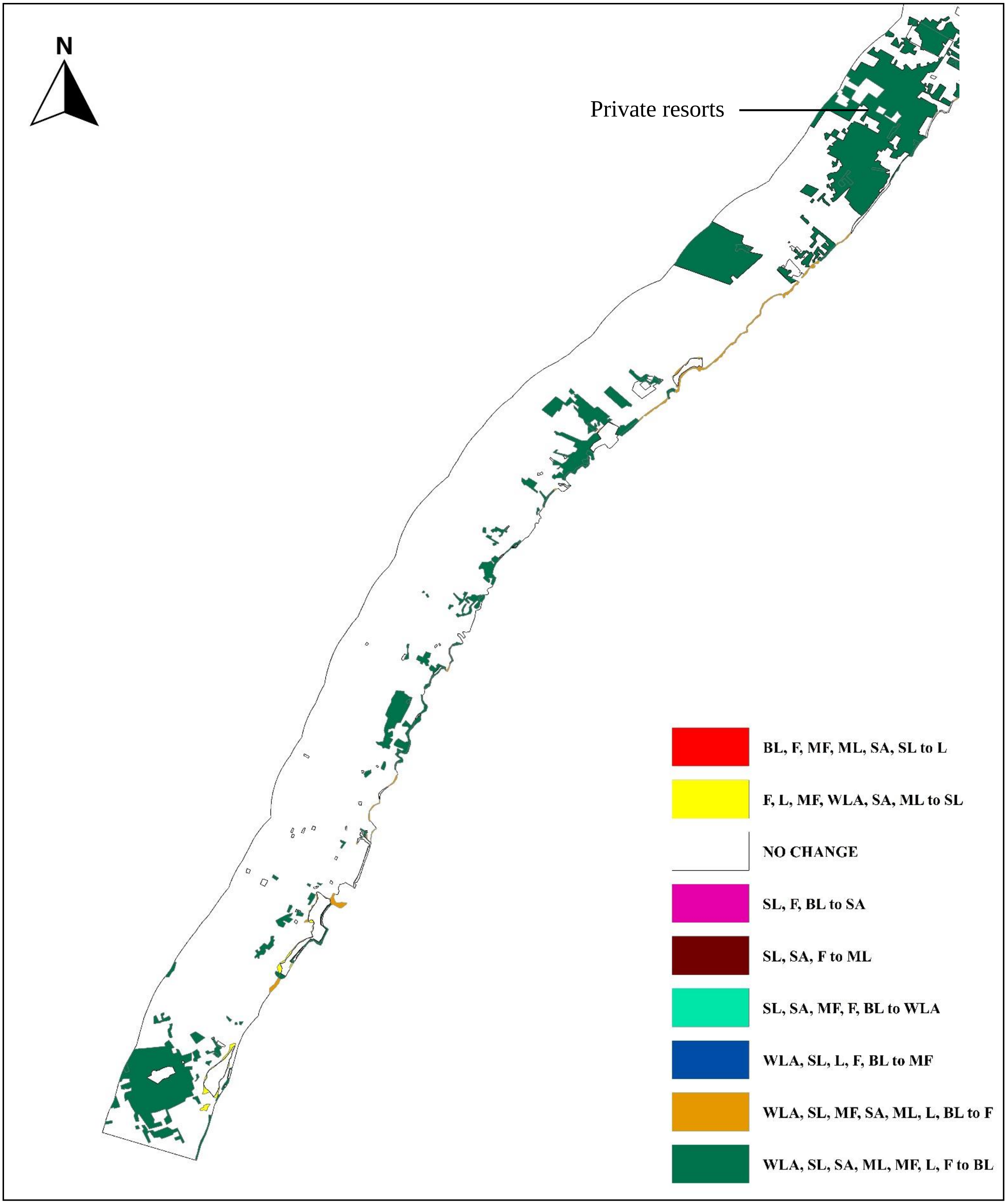

Figure I.6. Map showing the change detection from 1990-2020 for zone 3- Tulum

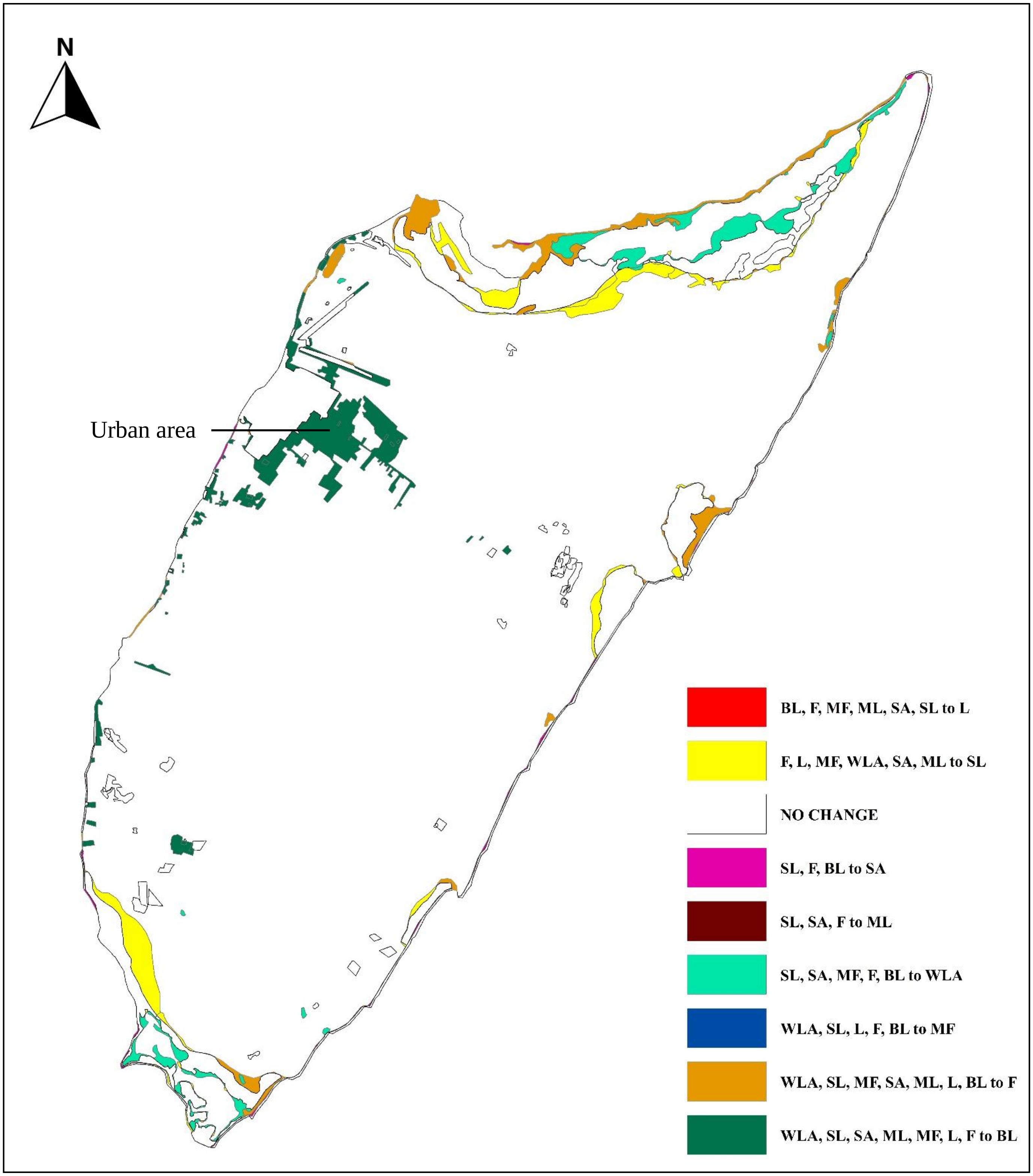

Figure I.7. Map showing the change detection from 1990-2020 for zone 4- Cozumel Island

I.5.3. TOURISTS URBANIZATION INDEX

Quintana Roo was a space of exile, isolation and refuge over many centuries. The isolated barrier island of Cancun, became the initial site for the nation's first master-planned resort named as "Tourist Integral Center" in 1970s. After the onset of this establishment in Cancun, the production space of Rivera Maya and the Costa Maya and Mayan world of Central America caused an abrupt change for massive tourism. The application of tourists urbanization index shows an increasing trend of the index quotient. Aforementioned, the creation of Rivera Maya, the Costa Maya and the Mayan world of Central America (Vargas Martinez *et al*., 2013). This region had gone through three stages of tourism development from 1970, the initial stage with less tourism and construction of hotels and resorts, the second stage from 1998- 2000 with moderate tourism and increases urban use and the final stage was after 2001 with complete tourism. The results also infer the weightage of this stage development with an increasing trend of index by 12%, 13% and 30% for every three decades

The obtained index for tourist urbanization from 1990 to 2020 is presented in table I.3. The intensity of tourists urbanization from 1990-2000 manifest a low index value such as 0.1155, which showed two-fold increase like 0.1321 for the second decadal changes of 2000-2010, which resulted from the increase in inhabitants (Fernandez de Lara, 2009). Finally, the last stage of urbanization showed a multi-fold increase of three times than the previous. The final stage of urbanization has 0.3046, however, the overall index variables showed an increasing trend from 1990, that infers the intensity of urbanization in the Caribbean region. Since, landcover and change and change detection were discussed detailly in the previous session, which advocated the major changes notices was the creation and expansion of built-up land near the coastal zone. This was further elucidated by the increasing index for every decade; besides hotel zone the population increase from 1983 has caused many inland urban expansions markedly in Cancun zone (Romero, 2009; Vargas Martinez *et al*., 2013).

Table I.3. Index values for beach anthropization impacts from 1990- 2020

Index	1990-2000	2000-2010	2010-2020
Tourists Urbanization Index (I_{TU})	0.1155	0.1321	0.3046
Beach Alteration Index (I_{BA})	1.3700	1.1561	1.1686

I.5.4. BEACH ALTERATION INDEX

Beaches are prone to morphological changes due to persisting natural and anthropogenic pressures. The application of beach alteration index aids in identify the intensity of the beach alteration over long period of time. The index of beach alteration showed an insensitive alteration during the first stage of transition in Caribbean coast. During 1990-2000, the beaches were morphology altered contributed more erosion and deposition along the coast. The construction of hotels and the subsequent hurricane events have caused severe sediment movement along the coasts which gives the higher index value of 1.37 during this period. Later, during the second stage of development from 2000 – 2010, the index value indicated a moderate beach alteration of 1.15, which is two-fold decrease from previous decade. This period faced a historical main hurricane event named Emily and Wilma in 2005, which caused severe erosion in the beach which exposed deeply near the coastal zone. Meanwhile, the complete transition of Caribbean region into tourists destination has happened in this period caused the beach alteration. Astoundingly, the recent decadal period from 2010-2020 showed a low index value of 1.16 which is slightly varied from previous study period. The index of beach alteration for every decadal period was presented in table I.3.

The beach alteration was found more intense by more than 100% during three decades which was encountered by the anthropization on the coast by hotel construction and also some of the natural events should be taken into consideration for the beach alteration. Though this natural events like hurricanes have caused severe erosion along the Caribbean coast, some of the beach practices such as beach nourishment have taken place in these regions in order to uphold the touristic pressure on the coastal zone.

Since, the Quintana Roo are exposed to many cyclonic activities over decadal periods causing natural alteration of the beach by transporting large quantity of sediments from the shore. During 1988, Cancun received the full impact of hurricane Gilbert, where the waves and storm surge transported massive quantities of sand which was never considered to recover. Later in 2005, the hurricane Emily and Wilma hit the Caribbean coast removing 8 million m^3 of sand leaving the coast with no sand (CFE., 2009). As the tourism demand and several natural calamities has caused beach erosion on a marked period over a decade, the first beach nourishment was held in Cancun from January to April 2006, 2.7 million cubic meters of sands were places on the beach with a coast of USD 19 million. The sediment was borrowed from two nearby sand banks of La Ollita and Megarrizaduras. La Ollita sand bank is 12 km north-east of Cancun, o the northern end of Isla Mujeres. Around 1.7 million cubic meters of sand were extracted from here, from an average depth of 25 m. The Megarrizaduras sand bank is 15 km north of Punta Cancun, in shallow waters (7–10 m depth) between Cancun and Isla Mujeres. Around one million cubic meters of sand were extracted from this bank. (CFE, 2009, Varillas, 2010). Immediately after the sand nourishment, the recovered beach shore was again damaged by hurricane Dean in August 2007. Also, by 2007 the level of anthropization of the Cancun was over 95%, with creation of commercial centers, hotels, houses, gardens, and a wide boulevard covering almost all the areas that had originally been dunes, coastal vegetation, and mangrove (Felix, 2007, Martell *et al*., 2020). A second stage of beach nourishment were performed from December 2009 to January 2010, but this time the amount of sand used to beach replenishment were twice the amount of sand that of 2006 (5.2 million cubic meters) that used in first beach recovery stage. For the second nourishment project, 2.5 million cubic meters of sand were extracted from La Ollita II sand bank, next to the sand bank used in 2006. The sand was extracted from an average depth of 25 m. The remaining 2.8 million cubic meters of sediment were taken from the sandbank at Punta Norte, in the shallow waters north of the island of Cozumel, 48 km away, at a depth of 12–29 m. While all the borrowed sand was of marine biogenic origin, the sand used had different mechanical, physical and chemical characteristics from the sand native to Cancun beach. The differences in the sand characteristics may explain the unpredictable behavior of sand transport on the beach and therefore the beach evolution after the second nourishment (CFE, 2009; Martell *et al*., 2020). After the second nourishment, the Cancun beaches has managed to conserve a stable beach environment with a stable width of 30 m since 2013 (Martell *et al*., 2020). Thus, the sediment imbalance prevents the natural self-regulation of the coastal system; causes very low sediment input into the system; and leads to large amounts of sediment being transported out of the system by hurricane-induced high wave energy. These conclusions have been very important in understanding the beach behavior at Caribbean coast.

Finally, an estimation of the anthropogenic impacts on the Caribbean corridor reveals the grave changes in the coastal environment from anthropogenic and natural stressors. The landcover and land use changes accompanied with decadal change detection techniques divulges the long-term changes ended up in the urbanization along with lost of vegetation and forest cover present in the Caribbean region jeopardizing the coastal biodiversity.

CHAPTER -II

BEACH WATER QUALITY ANALYSIS BY GEO ENVIRONMENTAL PARAMETERS AND APPLICATION OF COASTAL WATER QUALITY INDICES

II.1. INTRODUCTION

Coastal marine ecosystems integrate the dynamic area between land and ocean which are highly productive and biogeochemically dominant zone of the biosphere. This coastal ecosystem has been profoundly modified by human inventions with simultaneous negative effects on the coastal environment (Tscharntke *et al*., 2012). Among those inventions, urbanization is the most ubiquitous factor that leads to alteration of natural assemblages and terrestrial, marine and freshwater ecosystems by engineered structures and impervious surfaces (McPhearson *et al*., 2016). So, the approach of geoindicators was a valuable tools used for vulnerability assessments because, by definition, they derive from intrinsic and natural characteristics of the environment, and imply sensitive response to environmental changes. Geoindicator is a coined term for a class of geologic environmental indicator recently developed as a tool to assess rapid change in the environment and provide some measure of ecological health by examining the abiotic component of ecosystems. Thus, they have been developed for use in integrated environmental monitoring in order to assess changes important for the attainment of sustainability and have utility for ecosystem management, environmental auditing, and environmental impact and risk/hazard assessments.

As a result of this alteration, water quality of coastal and nearshore environments such as watersheds, coastal lagoons, coral reefs, estuaries, mangroves and coral reefs. The foreshadowing impact leads to costal eutrophication, global problem caused by excess nutrients (Markogianni *et al*., 2017) from the terrestrial inputs. In most of the marine ecosystems, the biological available forms of nitrogen and phosphorous are related to eutrophication with simultaneous ecological disturbances such as harmful algal blooms along with hypoxia conditions (Wu *et al*., 2017). The sediment – water interface was the chief boundary and storage of several contaminants in the form of reactive substances due to their prolonged existence by constant circulation. Under specific in-situ, these substances are released into water column by particle re-suspension, bioturbance, turbulent and molecular diffusion which enhances the nutrient concentration in the water column

(Mu *et al*., 2017). Although, the origin of these toxic pollutants was considered as terrestrial along with anthropogenic activities, in some specific coastal regions submarine groundwater discharge (SGD) were considered as an important source of trace element conveyance from land to ocean. (Santos *et al*., 2011; Beck *et al*., 2013).

So, in order to determine the coastal water quality by the in- situ physical properties, trace metal analysis and nutrients concentration. The documentation of the impacts of SGD in the coastal environment have increased to understand the salinity gradient, redox state which is responsible for the biogeochemical cycling of trace elements (Santos *et al*., 2011). This SGD also imposed an impact on global ocean element budgets and transport of dissolved species to the ocean (Gonneea *et al*., 2014). Globally, 12% of the SGD flows through karst subterranean environment and some of the geo- tracers were used identify the environmental process. Hence, it is noteworthy to have geochemical approach to determine the coastal water quality using geo- indicators available in the environment.

This study based on the analysis of geo indicators such as, heavy metals, nutrients and bacteriological factors to assess the environmental status in the east Caribbean region. Despite, the current stressing scenario of Caribbean region, the geochemical analysis of trace metals and nutrient concentration aids to determine the coastal water quality owing to increasing tourism demand.

II.2. LITERATURE REVIEW

II.2.1. BEACH WATER QUALITY

Coastal waters have long been recognized for their recreational activities, but one of the greatest challenges in the coastal tourism was maintaining the coastal water quality due to fecal pollution (González- Fernández *et al*, 2021). Globally, the beach management tools adopted the beach water quality classification mainly to assess the public health risk associated with bathing waters. To quantify the beach water quality, one of the most important parameters used for analysis was the presence of specific pathogens of concerns (Ashbolt *et al*., 2010). The overall detection of pathogens was impractical, hence the human enteric viruses from sewage was considered as quality indicator for bather health (Sinclair *et al*., 2009). The fecal indicator bacteria (FIB) such as

Escherichia coli (E. coli) and enterococci are usually found in feacally-polluted water, hence to understand the influence of sewage water in to the coastal water, the analysis of these bacteria helps to determine the coastal water quality.

The coastal water quality estimation for the fecal pollution conducted in two recreational beaches of Thailand showed the intense contamination of fecal bacteria which exists the marine water quality standards. In this case, the human sewage was considered as source of contamination (Kongprajug *et al*., 2021). A long-term coastal water quality monitoring study in Hongkong showed a less fecal pollution than E. coli which indicates human pollution sources in the local context. Nearly, 24 beaches were classified for good water quality out of 37 studied beaches as per the WHO guidelines and EU scheme on "Guidelines for Safe Recreational Water Environments" (Thoe *et al*., 2018). The study in the beaches of Spanish coast showed the dependance of external factors such as water temperature for the survival of E. coli, nevertheless the concentration of nutrient should take into account for the growth of bacteria in the coastal water (Aragonés *et al*., 2016).

When E. coli bacteria from the pollution source enters the aquatic system their concentrations and their survival rate depend on the environmental conditions within the system like the interaction between physical actions, biological and biogeochemical process (Pommepuy *et al*., 2005) and high amounts of the organic matter and turbidity favor the fecal bacteria survival in the marine environment (Tymensen *et al*., 2015; Perkins *et al*., 2016). Additionally, dissolved organic materials (DOM) can also be an important trigger of enhanced microbial pollution, to suspended solids (Andersson *et al*., 2015). Schippmann *et al* (2013) identified the fecal pollution in the south-eastern part of Baltic Sea were mainly due to the industrial and domestic wastewater and agricultural run-off into the freshwater environment later into the marine environment. The major in-situ properties like pH, dissolved oxygen, suspended particulate matter and chlorophyll concentrations enhance the growth of E. coli which was verified during the study of water quality in Curonian Lagoon (Kataržytė *et al*., 2018). Henceforward, the detailed study about the macro nutrient concentration with chlorophyll and other physical parameters such as pH, dissolved oxygen, temperature, biological oxygen demand helps in understanding the intensity of fecal indicator bacteria and their respective coastal water quality.

II.2.2. NUTRIENT AND DISSOLVED TRACE METALS (DTM)

Nutrients and heavy metals are usually concentrated in coastal waters relative to open sea water due to river and groundwater inputs. Coastal eutrophication is really concerning marine stressors derived from natural and anthropogenic input of nutrients into the marine environment. Submarine groundwater discharge (SGD), driven by both terrestrial and marine forcing components, comprises fresh groundwater and re-circulated seawater. Submarine groundwater discharge has been recognized as an important pathway for delivering water and chemicals (nutrients, heavy metals, carbon and tracers) from land to sea (Cardenas *et al*., 2010; El- Gamal *et al*., 2012). It plays a significant role in coastal environments such as bays, lagoon, estuaries and open sea and because a variety of chemical materials tend to be enriched in groundwater compared to surface water (Peterson *et al*., 2009; Hwang *et al*., 2010).

Many studies have demonstrated the potential importance of submarine groundwater discharge in marine geochemistry and ecosystem (Santos *et al*., 2012; Stewart *et al*., 2015). Fresh groundwater may directly discharge into the ocean either as diffuse seepage along the shoreline or offshore, or as point-source springs (Slomp and Van Cappellen, 2004), which directly release nutrients, heavy metals, carbon and organic pollutants from aquifers into coastal waters (Wang *et al*., 2018). On a global scale, Submarine groundwater discharge derived DIN and DIP fluxes were 1.4 and 1.6 times the riverine inputs to the global ocean, respectively (Cho *et al*., 2018). Large quantities of nutrients and heavy metals via submarine groundwater discharge can influence their budgets and biogeochemical cycles, and drive the deterioration of water quality and coastal eutrophication (Pavlidou *et al*., 2014; Wang *et al*., 2018; Adolf *et al*., 2019). Zhang *et al* (2020) reported the high Dissolved Inorganic Nutrient (DIN) / Dissolved Inorganic Phosphorous (DIP) ratio in submarine groundwater discharge which change nutrient structure, lead to potential phosphorus and limitation in different ecosystems.

In Hong Kong, a study conducted by Liu *et al* (2017) statistically proved the relationship between the DIN and DIP which resulted from the remineralization of organic matter. Gonneea *et al* (2014) studied the conservative behavior of Mn, Ca, Sr, U, Ra from karst subterranean estuaries through the sub-groundwater discharge. The submarine groundwater discharge -derived nutrient fluxes generally face water interactions in the aquifer such as mineral dissolution and reduction-oxidation reactions and surface process, making it more complex to understand (Wang *et al*., 2014). While, the chemical composition of submarine groundwater discharge is influenced by several factors, such as the geological matrix and the geochemical conditions of the coastal aquifers (Mcallister *et al*., 2015; Santos *et al*., 2012).

Trezzi *et al* (2016) explained the comparable concentrations of dissolved Fe between karstic and detrital submarine groundwater discharge that resulted due to the oxygenated conditions of karstic submarine groundwater discharge and to the precipitation of Fe, with the formation of Fe oxides, when recirculated seawater mixes with groundwater in detrital systems (Windom*et al*., 2006). Finally, for Cd, Pb and Zn, the generally comparable ranges of concentrations in karstic and detrital SGD were due to their lower redox sensitivity (for Pb and Zn) (Santos-Echeandia *et al*., 2009), to their lower association with the organic matter (for Cd, Pb and Zn) (Santos-Echeandia *et al*., 2009) or to their removal from the solution due to the presence of the so-called Fe-curtain (for Cd and Zn) (Trezzi *et al*., 2016) causing these metals (Cd, Fe, Pb and Zn) distinctly more enriched in karstic SGD. Zhang *et al* (2018) ascribed the behavior of heavy metals (Fe, Mn, Cr, Ni, Cu, Zn, Cd and Pb) according to the seasonal variation. The dissolved Zn, Ni and Cd were found in water phase and Fe, Mn, Ni, Zn, Pb, Cu and Cd were found in dissolved phase influenced by biological processes. The distribution and transport of heavy metals mainly controlled by physicochemical processes in Laoshan Bay, China. This study endorses the metal behavior of Cd with Dissolved Oxygen and Suspended Particulate Matter (SPM) and inverse behavior with pH, salinity and total inorganic nutrients and Soluble Reactive Phosphorous (SRP) indicates its conservative behavior (Wang *et al*., 2019). In the Gulf of Suez, the heavy metal (Fe, Mn, Cd, Cu, Pb and Cd) indicates its similar geochemical behavior derived from multiple anthropogenic sources prevailed in the study area (Nour & El- Sorogy, 2020). In Vigo estuary, the Cu and Zn concentrations were highly correlated indicating their similar origin from the boats and yachts in the coast, also Fe and Mn were influenced by riverine origin (Cid *et al*., 2021).

II.3. OBJECTIVE

The principal aim of this determines the coastal water quality using available geo-indicators.

II.3.1. SPECIFIC OBJECTIVES

- To determine the basic physio-chemical variables in the coastal water.

- To estimate the concentration of nutrients and bacteriological parameters.
- To estimate the dissolved trace metals concentration and to understand their inter-elemental relationship.
- To estimate the "Water Quality Index" using environmental variables.
- To determine the trophic status (TRIX) to understand the ecological status of the Caribbean region.

II.4. METHODOLODY

II.4.1. PHYSIO-CHEMICAL & DISSOLVED TRACE METALS

The study area is divided into four zones namely: 1) Zone 1 (Z1 - Cancun: samples 1-13); 2) Zone 2 (Z2 - Playa del Carmen: 14 – 31); 3) Zone 3 (Z3 - Tulum: 32 – 42) and 4) Zone 4 (Z4 - Cozumel Island: 43 – 56). The samples were collected in the inter-tidal region of selected tourist beaches which is occupied by luxurious resorts/ hotels and certified as "*Blue Flag*" beaches.

Field parameters pH, conductivity, dissolved oxygen was done directly using the multiparameter Hannah instrument (Model No. HI 9828-25) and the calibration was done using known calibration standards. Likewise, Ca and Mg was determined by prescribed standard procedure according to Strickland and Parsons, 1972 in the Eutrophication Laboratory in IPN – CIIDIR Sinaloa, Mexico using Jenway 6715 UV/Visible Spectrometer device. Samples were collected for dissolved trace metals (1L) and nutrients (4 L) in pre-cleaned polyethylene bottles. Later the samples were preserved separately for nutrient and trace metals analysis. For the dissolved trace metals, the samples were acidified using high purity HNO_3 to a pH of 2 and stored in refrigeration until analysis. Dissolved trace metals Fe, Mn, Cr, Cu, Co, Ni, Pb, Zn, Cd, Sr, V, As were determined in IPN – CIIEMAD, Mexico using Atomic Absorption Spectrometer (Perkin Elmer Model AAnalyst 100) following the method (EPA, 2007; Navarrete- Lopez *et al*., 2012). Estimation of As was done using cold vapor technique with hydride generation was utilized. Additionally, known sample solutions were added to all samples to know the recovery percentage of the dissolved metals in seawater. Certified reference material (CRM) (WatR^{TM} Pollution trace metal Lote: P213-500) was used after every 10th sample during the analysis and lanthanum oxides were added to each sample to avoid spectral and non-spectral interferences. The overall precision in the present analysis of dissolved trace metals varied from 93.18 to 107.43% for the analyzed metals.

II.4.2. NUTRIENT & BACTERIOLOGICAL ANALYSIS

The environmental variables temperature, pH, dissolved oxygen and% oxygen saturation was determined using a YSI ProODo sonda multiparameter. The quantification of Cl-a concentration was carried out according to Venrick & Hayward (1984) and active chlorophyll was calculated using the equations of Jeffrey & Humphrey (1975).

Of the samples obtained, a part was filtered through fiberglass filters grade GF / F (pore size 0.7 µm) for the analysis of dissolved inorganic nutrients. For the ammonium analysis, the samples were conserved according to what was proposed in APHA (1989), while the rest of the sample was frozen for later analysis. Additionally, an unfiltered portion was preserved for the analysis of total nitrogen and phosphorus (TN and TP). The determination of inorganic nutrients was carried out using the spectrophotometric techniques described in Strickland and Parsons (1972), while the analysis of total nitrogen (TN) and total phosphorus (TP) will be carried out according to the digestion method proposed by Valderrama (1981) and finalized as recommended in PROY-NMX-AA-029-SCFI-2008 and NMX-AA-079-SCFI-2001, while the total suspended solids and particulate organic matter were performed according to the gravimetric method (APHA, 1989).

 

Figure II.1. Analysis of inorganic nutrients in the eutrophication lab from CIIDIR - IPN, Sinaloa

II.4.2.1. Nitrites

Among the analytical methods for the estimation of nitrite in water, the Griess reaction was considered this analysis using colored “azo” dye. The nitrite in the sea water is allowed to react with sulphanilamide in an acid solution. The resulting diazo compound reacts with N- (1-naphthyl)-ethylenediamine and forms a highly colored azo dye, the extinction of which is measured using 10-cm cells (Strickland and Parsons, 1972). Limit of detection: 0.01 μg-at/L.

II.4.2.2. Nitrates

The nitrate in sea water is reduced almost quantitatively to nitrite when a sample is run through a column containing cadmium filings loosely coated with metallic copper. The nitrite thus produced is determined by diazotizing with sulphanilamide and coupling with N-(1-napthyl)-ethylenediamine to form a highly colored azo dye the extinction of which is measured. A correction may be made for any nitrite initially present in the sample. Reduction of nitrate to nitrite is nearly complete and the method described above is probably as sensitive as is practicable by a routine spectrophotometric procedure. (Strickland & Parsons, 1972). Limit of detection: 0.05 μg-at/L.

II.4.2.3. Phosphates

Phosphate in sea water relies on the formation of a phosphomolybdate complex and its subsequent reduction to highly colored blue compounds. Methods using stannous chloride as a reductant at room temperature have been favored as they are most sensitive and give less interference from easily hydrolysable organic compounds than do other techniques. Method: The seawater sample is allowed to react with a composite reagent containing molybdic acid, ascorbic acid, and trivalent antimony. The resulting complex heteropoly acid is reduced in situ to give a blue solution the extinction of which is measured at 8850 Å. (Strickland & Parsons, 1972). Limit of detection: The smallest amount of phosphate that can be detected with certainty is about 0.03μg-at P/L.

II.4.2.4. Bacterial Parameter

The collected water samples were stored at 5º C and without any delay the analysis was carried out no more than one day once after collection. The micro bacteriological analysis was carried using the standard protocols mentioned in “criterios ecologicos: CE-CCA-001/89” framed for ecological water quality in 1989. Along with the norms used for the analysis of individual microorganisms such as Escherichia coli, Estreptococos fecalis, Vibrio y Paravibrios, Coliformes totals and Coliformes fecales as mentioned in table II.1.

Table II.1: List of methods used for micro bacteriological analysis in seawater

Microorganisms	Methods	Units
Estreptococos fecalis	Métodos Normalizados 9230 C: Agar m STF y Medio Cromogénico	UFC/100ml agua
Vibrio	Métodos Normalizados 9260 TCBS	UFC/100ml agua
Coliformes totales	Métodos Normalizados 9221B	NMP100/ml agua
Coliformes fecales	Métodos Normalizados 9221B	NMP/100ml agua

II.4.3. WATER QUALITY INDICES

Generally, water quality monitoring will provide a large and complex database comprising of physical, chemical and biological variables (El- Mezayen *et al*., 2018). Thus, the Water Quality Indices (WQI) has been widely used to convert a whole set of water date base into single number along with a range of water quality from very good to poor (Abtahi *et al*., 2015). Despite some of the limitations towards the random selection of variables, some efforts are made to classify the water quality depends on specific variables. In this study, several quality indices were applied for different set of data variables. To evaluate the contamination degree of trace metal, Heavy metal Evaluation Index (HEI) and the trophic status index (TRIX) to evaluate the ecological status for the nutrients were used. The bacteriological parameters were used to determine the water quality by the bathing water directives and Mexican norms for beach water quality. Finally, by computing these variables, the coastal water quality indices were carried out. Hence, these indices were used in this study to obtain a clear framework for the beach water quality.

II.4.3.1. Heavy metal Evaluation Index (HEI)

Determination of water quality in terms of metal concentration was done using the Heavy metal evaluation index (HEI) (Edet., 2002) using the formula:

$$\mathrm{HEI}= \Sigma_{\mathrm{i=1}}^{\mathrm{n}} \frac{H_c}{H_{mac}}$$

Where H_c is the monitored value of the i^{th} parameter and H_{mac} is the maximum allowable concentration of the i^{th} parameter. The HEI values are classified into three categories: HEI < 400 (Less contamination); 400 – 800 (Medium concentration) and > 800 (High concentration) respectively.

II.4.3.2. Tropical status Indices

The index used in the present work has been given by the following formulation (Vollenweider *et al*., 1998)

TRIX = [Log_{10} (PO_4 ∗DIN∗ Chl α ∗DO_2 %) + a] /b

Where:

Chl-α Chlorophyll-α concentration as micrograms per liter

DO_2% The % of the oxygen concentration from saturation conditions

DIN Dissolved inorganic nitrogen (DIN) = $NO_3 + NO_2 + NH_4$ (micrograms per liter)

[PO_4] Total inorganic phosphorus as P–PO_4 (micrograms per liter)

The parameters a = 1.5 and b = 1.2 are scale coefficients, proposed by Giovanardi and Vollenweider (2004) to fix the lower limit value of the index and also to fix the scale range from 0 to 10. Thus, this scale ranges helps to determine the trophic level status of the present study area.

II.4.3.3 Coastal Water Quality Indices (CWQI)

The overall water quality was assessed by an important tool called coastal water quality indices by selection nine important water quality indicators. Among the analyzed parameters, this study used selected variables such as pH, DO, BOD, TSS, NH_3, NO_2, Total Phosphorous (TP), Chl – a, and fecal coliforms. The CWQI calculation comprises od derivation of unit index (W_i) and subindex (Q_i). The initial step has assessment of unit index for the above mention based on the following equation (1) adopted from Gupta *et al* (2003) and Jha *et al* (2015).

$$Wi = \frac{k}{Si} \text{ .... (1)}$$

where "*k*" is constant of proportionality, "Si" is recommended permissible limits of the *i*th parameter. Also, the value of *k* was calculated by the following equation (2):

$$k = \frac{1}{\Sigma Si} \text{ .... (2)}$$

Then the consecutive step for the calculation of subindex (Q*i*) which is ratio of monitored value of *i*th parameter (V*i*) and recommended standard for *i*th parameter (S*i*) given in equation (3):

$$Qi = 100 \left[\frac{Vi}{Si} \right] \text{ .... (3)}$$

The final step is the cumulative sum of unit indices and sub-indices gives the CWQI as showed in equation 4 and the individual ranking of water quality provided in the table II.2.

$$CWQI = \Sigma\, Wi \times Qi \text{ .... (4)}$$

Table II.2. Ranking scores for Coastal Water Quality Indices

CWQI- range	Rank- category
0 - 25	Very bad
26 - 50	Bad
51 - 70	Moderate
71 - 90	Good
90 - 100	Very Good

II.4.4. STATISTICS

Spearman correlation analysis (R-mode, p = 0.05) was done for each zone separately using STATISTICA (version 12.0) to understand the geochemical relationship of the physio-chemical parameters and dissolved trace metals in the region. Likewise, the data set of nutrients were statistically analyzed by hierarchical agglomerative cluster analysis after normalizing the data set by generating the dendrogram to identify the inter-elemental relationship of the nutrients and their behavior in the coastal environment (Yang *et al*., 2010; Jha *et al*., 2014).

II.5. RESULTS & DISCUSSION

II.5.1. PHYSICO-CHEMICAL VARIABLES

The results of pH, conductivity and dissolved oxygen showed a similar trend in both monitoring seasons, with a clear influence of the rainy season on conductivity in 2020 (Figure II.2 a-b). The concentrations and distribution of pH in the region during both years did not indicate any important change, and the lowest values observed in Playa del Carmen (Z2) and Tulum (Z3) are directly related to groundwater discharges through the region which was corroborated by the high association with the other environmental variables mainly during 2019, in addition to the zonal advection and the changes in the surface wind force (Wu *et al*., 2018). The conductivity of both years showed a significant variation (2019: Z4 > Z1 > Z2 > Z3; 2020: Z1 > Z2 > Z4 > Z3) with average values of 54.57 and 40.2 mS cm^{-1} in 2019 and 2020 respectively. The relationship between the environmental variables pH and conductivity did not show significance between them except for the Playa del Carmen region in both years, and the abrupt changes in the conductivity values during both seasons together with the observed values, suggest the control of oxygen in water over the redox potential of seawater (Yang *et al*., 2014). The three-fold increase in conductivity values in 2020 than 2019 infers that rainfall episodic events are all specific features of shallow coastline and freshwater discharge influencing this parameter (Robinson & Prommer, 2007; O'Connor *et al*., 2015).

Dissolved oxygen indicates a variation from 3.91 to 10.51 mg L^{-1} in 2019 (avg. 7.79) and 2.72 to 9.82 mg L^{-1} in 2020 (avg. 6.94) (Figure II.2 c). Zone wise calculated values indicates that Z2 > Z3 > Z1 > Z4 respectively. The low distribution of DO is directly related to the organic matter degradation/ remineralization in the coastal region as well the terrestrial ground water which is recirculated in sea water (Guo *et al.*, 2020). Moreover, the low-oxygen ground water discharges due to the karst topography features present in the region will directly contribute to low oxygen level diluting the DO in coastal bottom waters (Cai *et al.*, 2014). The very low value (> 5 mg L^{-1}) in Z2, Z3 is characterized by intermittent discharge of effluents/ runoff and moreover heavy presence of the degrading Sargassum species in the coastal regions especially in low tidal areas (Zhang, 2011; Wang *et al*., 2017).

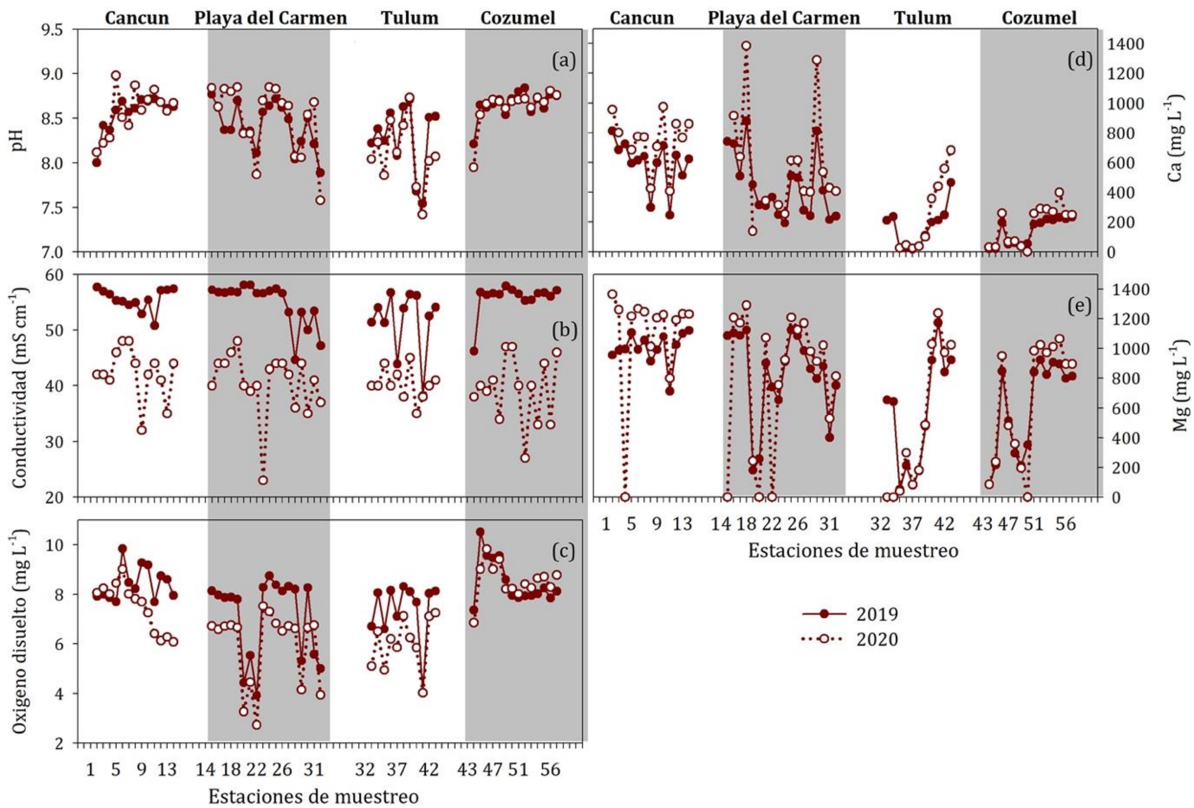

Figure II.2. Spatial and temporal variation of a) pH b) Conductivity c) Dissolved Oxygen 4) Calcium 5) Magnesium during 2019 and 2020 from the region Cancun, Playa del Carmen, Tulum and Cozumel, Quintana Roo

The distribution of Ca and Mg were similar in both seasons (figure II.2 d-e), and their concentrations in 2019 (averages Ca: 346 mg L-1, Mg: 761 mg L-1) and 2020 (average Ca: 400 mg L-1 and Mg: 771 mg L-1) indicate a geogenic origin associated with the dissolution of the carbonate mineral (calcite and magnesite), which is the predominant rural rock in this region and reaches the coast through of groundwater enriched by treated or untreated wastewater (Sanchez-Ahuactzin *et al*., 2018). The slightly higher average of Ca observed in 2020 was associated with a higher entry of groundwater and surface water from the runoff during the rainy season and that enriched the coast despite the decrease in the contributions of tourist activity due to the effect of the pandemic. Additionally, the large amount of organic matter contributed by Sargassum in both seasons, facilitated the dissolution of these minerals on the coast (Gödde & Conrad, 1999; Liu *et al*., 2021).

II.5.2. DISSOLVED TRACE METAL CONCENTRATIONS

The concentration pattern of dissolved trace metals in seawater in the present study is in the following descending order (based on zonal avg.): 2019 Zone 1: Sr > Pb > Ni > Co > Fe > Zn > Cu > V > Cd > Mn > Cr > As; Zone 2: Sr > Pb > Ni > Co > Fe > Zn > Cu > Cd > V > Mn > Cr > As; Zone 3: Pb > Sr > Ni > Co > Fe > Zn > Cu > Cd > Mn > Cr > V and Zone 4: Pb > Ni > Co > Sr > Fe > Cu > Zn > Cd > Mn > Cr > V. Likewise, during 2020 in Zone 1: Sr > Pb > As > Cu > Fe > Ni > Zn > Cd > V > Mn > Co > Cr; Zone 2: Sr > Pb > As > Cu > Fe > Ni > Zn > Co > Cd > V > Mn > Cr; Zone 3: Sr > Pb > Cu > As > Zn Fe > Ni > Mn > Co > Cd > V > Mn > Cr; Zone 3: Sr > Pb > Cu > As > Zn > Fe > Ni > Mn > Co > Cd > V > Cr and Zone 4: Sr > Ni > Pb > Cu > Zn > As > Fe > Co > V > Cd > Mn > Cr respectively (figure II.3- II.4).

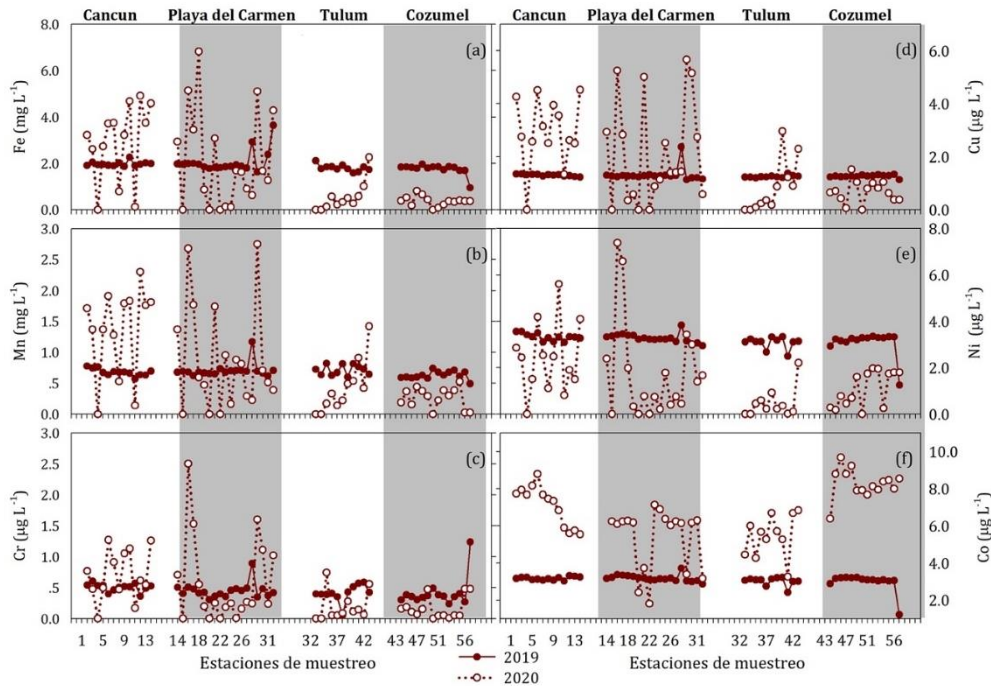

Figure II.3. Spatial and temporal variation of a) Fe b) Mn c) Cr d) Cu e) Ni f) Co during 2019 and 2020 from the region Cancun, Playa del Carmen, Tulum and Cozumel, Quintana Roo

The concentration pattern of dissolved Sr in the region is high compared to other metals, indicating that they are strongly influenced by variations in composition based on the rocks of the continental bed (Peucker-Ehrenbrink, 2019). The high concentrations of Sr in Z1 and Z2 in both periods (1.980 – 16.610 µg L^{-1}) suggest dissolution of the young carbonate rocks, where complex geochemical interactions are generated from the evaporites. This is also supported by the variable mix of groundwater, where carbonates from the oldest Cretaceous or Cenozoic (Cancun and Puerto Morelos) dissolve to release Sr, and in the presence of fracture zone (near Tulum) and sinks closer to the coastal section where entry of submarine groundwater has already been reported (Hodell *et al*., 2004; Hernández-Terrones *et al*., 2021).

Fe and Mn concentrations during 2019 showed a similar distribution pattern and values in all zones (Fe ranges: 0.95-3.64 mg L^{-1}, Mn: 51-1174 mg L^{-1}), while in 2020 it was observed greater variability with higher concentrations in Cancun and Playa del Carmen and lower in Tulum and Cozumel compared to the previous year (figure II.3 a-b). The main source of Fe and Mn in this region is enrichment in groundwater inflow (Avelar *et al*., 2013). In 2019, the concentration of these elements had its origin mainly in the use of water from tourist and urban activities (Padhi *et al*., 2013), which maintained very similar values throughout the region expect some sampling sites

(S. No: 14,16,17,18,21,27). During 2020, although there was a reduction in tourism in the region (46%) with simultaneous decrease in anthropogenic sources of Fe and Mn, only in Tulum and Cozumel where this effect was clearly observed. This evident the fact that Cancun and Playa del Carmen have an important residing population (911,503 and 333,800 inhabitants respectively) (INEGI, 2020) that endure the anthropogenic contribution of these metals. Additionally, during 2020, the intense rain (62 mm) by tropical storm Marco in August (Ciclones Tropicales, 2020) which contributes high influx of terrigenous material and enriched groundwater towards the coastal zone.

The dissolved chromium concentrations in the present study indicate a different pattern compared to other metals analyzed (Fig. II.3 c). The Cr distribution presents a higher average in Z1 (0.704 and 0.502) and Z2 (0.560 and 0.444) for 2020 and 2019 respectively. The concentrations obtained in both stations remained high for normal karstic environment, suggesting an enrichment due to anthropogenic activity (Padhi *et al*., 2013). In addition, the large amount of organic matter produced by the decomposition of Sargassum accumulated on the coast, especially the ligands result in higher concentration of Cr in solution (James, 1983; Van Aken, 2007). In 2020, the obtained pattern for Cr indicates that the greater variability of Cr in that year was associated with rainfall in Z1 and Z2.

Ni showed higher concentrations in 2019, associated with its anthropogenic use as a component of paint on fishing boats in the tourist area (Padhi *et al*., 2013) and others human activities. In 2020, confinement conditions in areas with a lower population result in lower concentrations, while high runoff impose a greater variability in Cancun and Playa del Carmen (figure II.3 e). Unlike the other dissolved metals, Co concentrations were higher during 2020, which was related to the redox sensitive nature of this element often released in the dissolved phase by decomposed organic material near the interface sediment-water (Huynh-Ngoc, 1989; Tappin *et al*., 1995). In the area the accumulation of large amounts of Sargassum stimulated this mechanism, in addition, increasing the leaching of these materials due to the effect of runoff and the more intense waves during the "Marco" storm.

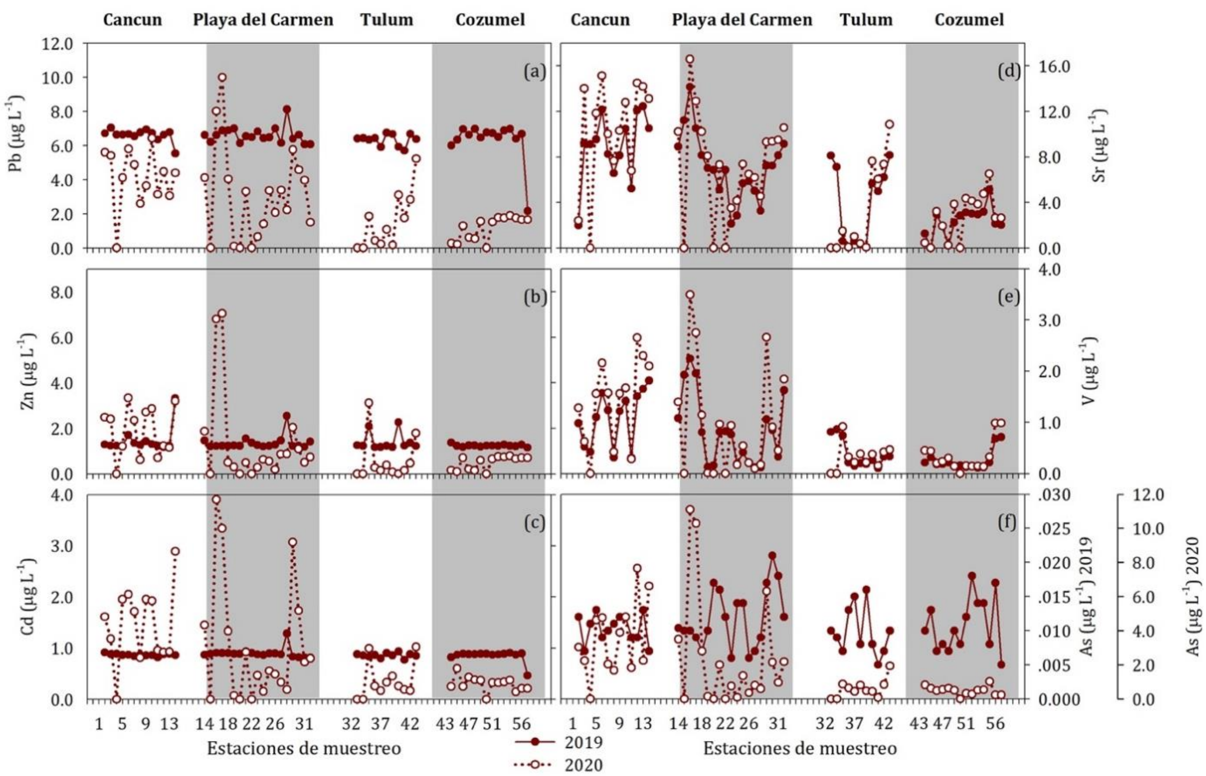

Figure II.4. Spatial and temporal variation of a) Pb b) Zn c) Cd d) Sr e) V f) As during 2019 and 2020 from the region Cancun, Playa del Carmen, Tulum and Cozumel, Quintana Roo

The highest values of Cu, Ni, Pb in 2019 in zones 1 and 2 are mainly due to the high movement of ferry services, construction and development activities in the region (Padhi *et al*., 2013). During 2019, higher concentrations of Pb detected in coastal waters which mainly due to high tourist activity, the use of fuels for local transport (boats, ferries, jet skis, automobiles). The pattern observed during 2020 was determined by runoff events along with decrease in tourist activity and urban activities mainly in Z1 and Z2 (figure II.3, II.4). The Zn values in the study region result from enrichment provoked by the use of construction materials. The seasonal variation showed slightly low concentrations in 2020 (averages 2019: 1.36, 2020: 1.09 mg L-1; figure II.3 b) caused by low anthropogenic activity related with confinement, and the higher variation in Cancun and Playa del Carmen was related to runoff events. The seasonal distribution of V for both stations show a similar pattern, where the presence of V is commonly noted in the karst groundwater environment (Arcega-Cabrera *et al*., 2021). The obtained results infer the slight variation in 2020 that the V source acquired from the runoff and its pathway from the local construction sites that they noticed with the use of steel alloys for construction (Arcega-Cabrera *et al*., 2021). The V in dissolved phase is generally scavenged by the oxidation of Fe- Mn markedly in the sediment-water through advective process (Kowalski *et al*., 2009). Hence, it is evident for higher values in 2020 indicates resuspension during the storm events in the coastal region which increases in the dissolved V phase (Hobson *et al*., 2018). Sequential order of Zn in the present study suggest that it is behind Pb and Cu in both the years, indicating that it is due to the resuspension from the sediments high volume of suspended particulate matter in the dynamic region (Li *et al*., 2015). The concentrations of As obtained in the present work were found below the contamination levels, but the values during 2020 infers the influence of runoff which is enriched with higher concentration of As due to huge dumping and subsequent decomposition of Sargassum in the local land and near the beaches. Since, the decomposition of Sargassum mainly results with the discharge of leachates as their major byproduct which has major impact in the coastal environment (Chavez *et al*., 2020).

In general, the results obtained showed differences in the intensity of anthropogenic activities between the sampling periods, which had a strong influence on the concentrations of dissolved metals during 2019 and 2020. The reduction of tourist activities by 47.5% during the COVID 19 pandemic had the greatest impact in areas with the smallest resident population (Tulum and Cozumel) (INEGI, 2020). On the other hand, in Cancun and Playa del Carmen, dissolved metals associated with anthropogenic activities showed greater variability and higher concentrations during 2020, which inferred the high influx of metals due to land-based rainfall and the intense mixing processes in the coast due to the effect of the tropical storm "Marco" registered during the month of August in the region (Ciclones Tropicales, 2020).

II.5.3. STATISTICAL ANALYSIS

The zonal wise correlation matrices for both years are presented separately in tables II.3 and II.4. The results of environmental variables (pH, DO and conductivity) with metals indicate that terrestrial, anthropogenic sources, the biogenic process, and hydrography play a significant role in the pattern of dissolved metals in the region between seasons. A clear difference was observed in the correlations of the physicochemical parameters and the concentration and variability of the metals in the area. In 2019, positive correlations were obtained with Cr, Ni, Co and Cd (table II.3), which suggests the entry of groundwater enriched with these metals that originate in urban, tourist and construction activities (Table II.3) (Padhi *et al*., 2013). During 2020, a strong correlation was observed between trace metals and the main elements (Ca, Mg) (table II.4), associated with the effect of metal carryover by rainwater from urban areas during the rainy season in the coastal zone (Padhi *et al*., 2013), that increased the concentrations of all metals, mainly those associated with anthropogenic activities in Cancun and Playa del Carmen, which due to being urban areas and having a high resident population (911,503 and 333,800 inhabitants respectively). In the case of Tulum and Cozumel, the concentrations of metals in 2020 were lower, due to the reduction of the tourist influx, except for the case of metals from natural sources such as Sr and V which maintained similar patterns between samplings (figure II.3, table II.4).

The results of the correlation analysis of Ca and Mg ions with some trace metals showed a strong association for 2019, especially with Sr and V due to their natural origin. The correlation of Mn with dissolved trace metals in the 2020 season especially infers that in sub oxic conditions the reduction of Mn occurs and also acts as a scavenger for other metals with a high content of organic matter along the coast (Pavoni *et al*., 2020). During this year, a strong correlation was obtained between all metals, mainly in Cancun and Playa del Carmen, which suggests that their concentrations were determined by common processes (table II.4), such as high urban activity. Dissolved Vanadium is almost last in the sequential order which correlates with high Fe values where high organic materials affect the flux of V leading to removal from seawater under high pH values (Riedel *et al*., 2011).

II.5.4. HEAVY METAL EVALUATION INDEX (HEI)

Calculated HEI values for all the four zones were done for 2019 and 2020 separately. All the trace metals (except Ni & Cd) were lower than the <400 indicating that the region is not contaminated with reference to beach water. However, Ni (1598, 735) and Cd (4355, 4050) were higher in both years 2019 & 2020 respectively. Higher values of Cd in both the seasons indicate strong active remineralization due to regular presence of high organic matter from in the study area dominant with coral sandy nature (Riedel *et al*., 2011; Achary *et al*., 2016). Likewise, Ni is also high in the present study enriched due to the various sub-oxic or anoxic regions in the coastal beaches, where mobilization of Ni takes place (Huynh-Ngoc *et al*., 1989). Moreover, higher dissolved Ni is often released into higher saline regions in the coast and minimum desorption takes place at freshwater seawater interface (Chaminda *et al*., 2013; Kikuchi *et al*., 2017). Overall, various coastal management practices are implemented by the local government, nevertheless natural geochemical process is disturbed due to excessive presence of organic materials which aids in enriching this metal well above the permissible limits.

Table II.3. Correlation matrix values of physico-chemical variables and dissolved trace metals in tourist beach waters off Cancun during 2019, Caribbean Sea, Mexico

	pH	Cond.	DO	Ca	Mg	Fe	Mn	Cr	Cu	Ni	Co	Pb	Zn	Cd	Sr	V	As
Zone 1 (Cancun)																	
pH	1.00																
Cond.	-	1.00															
DO	-	-	1.00														
Ca	-	-	-	1.00													
Mg	-	-	-	-	1.00												
Fe	-	-	-	-	-	1.00											
Mn	-0.73	-	-	0.66	-	-	1.00										
Cr	-	-	-0.74	-	-	-	-	1.00									
Cu	-	-	-	-	-	-	-	-	1.00								
Ni	-	0.61	-	0.62	-	0.65	-	-	0.77	1.00							
Co	-	0.83	-	-	-	-	-	-	-	-	1.00						
Pb	-	-	-	-	-	-	-	-	-	-	-	1.00					
Zn	-	-	-	-	-	-	-	-	-	-	-	-	1.00				
Cd	-0.64	0.74	-	-	-	-	-	-	-	0.87	0.65	-	-	1.00			
Sr	-	-	-	-	0.70	-	-	-	-	-	0.59	-	-	-	1.00		
V	-	-	0.58	-	0.75	-	-	-0.60	-	-	-	-	-	-	0.81	1.00	
As	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1.00
Zone 2 (Playa del Carmen)																	
pH	1.00																
Cond.	-	1.00															
DO	0.62	-	1.00														
Ca	-	-	-	1.00													
Mg	-	-	-	-	1.00												
Fe	-	-	-	-	-	1.00											
Mn	-	-	-	-	-	-	1.00										
Cr	-	-	0.63	-	0.56	-	-	1.00									
Cu	-	-	-	-	-	-	-	-	1.00								
Ni	-	-	-	-	-	0.56	-	-	-	1.00							
Co	-	-	-	-	-	0.62	-	-	-	-	1.00						
Pb	-	-	-	-	-	-	-	-	-	-	-	1.00					
Zn	-	-	-	-	-	-	-	-	0.70	-	-	-	1.00				
Cd	-	-	-	-	-	-	-	-	0.58	0.83	0.77	0.53	0.51	1.00			
Sr	-	-	-	0.66	-	-	-	-	-0.52	-	-	-	-0.53	-	1.00		
V	-	-	-	0.57	-	-	-	-	-	-	-	-	-	-	0.60	1.00	
As	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1.00
Zone 3 (Tulum)																	
pH	1.00																
Cond.	0.64	1.00															
DO	0.81	0.76	1.00														
Ca	-	-	-	1.00													
Mg	-	-	-	0.84	1.00												
Fe	-	-	-	-	-	1.00											
Mn	-	-	-	-	-	-	1.00										
Cr	-	-	-	-	0.78	-	-	1.00									
Cu	-	-	-	-	-	-	-	-	1.00								
Ni	-	0.70	-	-	-	-	-	-	-	1.00							
Co	-	0.73	-	-	-	-	-	-	-	0.91	1.00						
Pb	0.86	-	0.74	-	-	0.63	-	-	-	-	-	1.00					
Zn	-	-	-	-	-	-	0.79	-	-	-	-	-	1.00				
Cd	-	-	-	-	-	-	-	-	-	0.61	0.62	-	-	1.00			
Sr	-	-	-	0.75	0.61	-	-	-	-	-	-	-	-	-	1.00		
V	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1.00	
As	-	-	-	-	-	-	-	-	-	-	-	-	-0.75	-	-	-	1.00
Zone 4 (Cozumel Island)																	
pH	1.00																
Cond.	-	1.00															
DO	-	-	1.00														
Ca	-	-	-	1.00													
Mg	-	-	-	0.71	1.00												
Fe	-	-	-	-	-	1.00											
Mn	-	-	-	-	-	-	1.00										
Cr	-	0.73	-	-	-	-	-	1.00									
Cu	-	-	-	-	-	-	0.89	-	1.00								
Ni	-	-	-	-	0.57	-	0.71	-	0.87	1.00							
Co	-	-	0.63	-	-	-	-	-	-	-	1.00						
Pb	-	-	-	-	-	-	0.61	-	-	-	-	1.00					
Zn	-	-0.57	-	-	-	-	-	-0.74	-	-	-	-	1.00				
Cd	-	-	-	-	-	-	0.56	-	0.61	-	-	0.70	-	1.00			
Sr	-	-	-	0.54	0.82	-	-	-	-	0.63	-	-	-	-	1.00		
V	-	-	-	-	-	-	-	-	-	-	-	-0.54	-	-	-0.58	1.00	
As	-	-	-	-	-	-	-	-	0.67	0.64	-	-	-	-	-	-	1.00

Table II.4. Correlation matrix values of physico-chemical variables and dissolved trace metals in tourist beach waters off Cancun during 2020, Caribbean Sea, Mexico

	pH	Cond.	DO	Ca	Mg	Fe	Mn	Cr	Cu	Ni	Co	Pb	Zn	Cd	Sr	V	As
Zone 1 (Cancun)																	
pH	1.00																
Cond.	-	1.00															
DO	-	-	1.00														
Ca	-	-	-	1.00													
Mg	-0.57	-	-	0.66	1.00												
Fe	-	-	-	0.76	-	1.00											
Mn	-	-	-	0.73	-	0.84	1.00										
Cr	-	-	-	0.70	0.58	0.75	0.80	1.00									
Cu	-	-	-	0.74	0.67	-	0.66	0.90	1.00								
Ni	-	-	-	0.84	0.70	0.67	0.70	0.92	0.92	1.00							
Co	-	-	-	0.58	-	0.62	0.68	0.93	0.90	0.86	1.00						
Pb	-	-	-	0.84	0.73	-	0.60	0.68	0.73	0.87	0.59	1.00					
Zn	-	-	-	0.76	0.66	0.59	0.75	0.92	0.95	0.95	0.90	0.80	1.00				
Cd	-	-	-	-	-	-	-	0.80	0.81	0.76	0.91	0.55	0.84	1.00			
Sr	-	-	-	-	-	0.64	0.78	-	-	-	-	-	-	-	1.00		
V	-	-	-	0.58	-	0.91	0.86	0.70	-	-	0.56	-	-	-	0.82	1.00	
As	-	-	-	0.71	-	0.81	0.92	0.74	0.65	0.68	0.73	0.58	0.71	0.61	0.68	0.79	1.00
Zone 2 (Playa del Carmen)																	
pH	1.00																
Cond.	0.48	1.00															
DO	0.79	-	1.00														
Ca	-	-	-	1.00													
Mg	-	-	-	0.79	1.00												
Fe	-	-	-	0.88	0.72	1.00											
Mn	-	-	-	0.74	0.58	0.76	1.00										
Cr	-	-	-	0.70	0.55	0.78	0.61	1.00									
Cu	-	-	-	0.64	0.52	0.60	0.78	0.69	1.00								
Ni	-	-	-	0.88	0.69	0.90	0.81	0.84	0.76	1.00							
Co	-	-	-	0.82	0.57	0.88	0.81	0.84	0.71	0.98	1.00						
Pb	-	-	-	0.89	0.74	0.81	0.74	0.83	0.83	0.93	0.87	1.00					
Zn	-	-	-	0.66	0.57	0.63	0.53	0.88	0.77	0.81	0.76	0.84	1.00				
Cd	-	-	-	0.87	0.67	0.92	0.85	0.85	0.78	0.97	0.95	0.91	0.74	1.00			
Sr	-	-	-	0.79	0.57	0.89	0.64	0.79	0.57	0.88	0.91	0.80	0.70	0.87	1.00		
V	-	-	-	0.79	0.61	0.89	0.85	0.81	0.66	0.90	0.92	0.78	0.68	0.90	0.81	1.00	
As	-	-	-	0.85	0.68	0.94	0.80	0.87	0.71	0.98	0.97	0.90	0.78	0.97	0.89	0.94	1.00
Zone 3 (Tulum)																	
pH	1.00																
Cond.	-	1.00															
DO	-	-	1.00														
Ca	-	-	-	1.00													
Mg	-	-	-	0.92	1.00												
Fe	-	-	-	0.93	0.81	1.00											
Mn	-	-	-	0.95	0.95	0.85	1.00										
Cr	-	-	-	-		-	0.66	1.00									
Cu	-	-	-	0.88	0.95	0.74	0.91	-	1.00								
Ni	-	-	-	-		-	-	-	-	1.00							
Co	-	-	-	-		-	-	0.79	-	0.88	1.00						
Pb	-	-	-	0.80	0.71	0.64	0.74	0.65	0.75	-	-	1.00					
Zn	-	-	-	-	-	-	-	0.61	-	0.69	0.70	0.67	1.00				
Cd	-	-	-	-	-	-	-	0.84	-	0.85	0.95	-	0.66	1.00			
Sr	-	-	-	0.80	0.75	0.64	0.75	0.62	0.83	-	-	0.96	-	-	1.00		
V	-	-	-	-	-	-	-	0.68	-	0.77	0.84	0.80	0.88	0.73	0.67	1.00	
As	-	-	-	-	-	-	-	0.65	-	0.80	0.83	0.72	0.92	0.77	-	0.96	1.00
Zone 4 (Cozumel Island)																	
pH	1.00																
Cond.	-	1.00															
DO	-	-	1.00														
Ca	-	-	-	1.00													
Mg	-	-	-	0.97	1.00												
Fe	-	-	-	-	-	1.00											
Mn	-	-	-	-	-	-	1.00										
Cr	-	-	-	-	-	-	-	1.00									
Cu	-	-	-	-	-	-	-	-	1.00								
Ni	-	-	-	0.67	0.59	-	-	-	-	1.00							
Co	-	-	-	-	-	-	-	-	-	-	1.00						
Pb	-	-	-	0.86	0.83	-	-	-	-	0.67	-	1.00					
Zn	-	-	-	0.83	0.79	-	-	-	-	0.63	-	0.90	1.00				
Cd	-	-	-	-	-	0.58	-	-	0.55	-	-	-	-	1.00			
Sr	-	-	-	0.84	0.86	-	-	-	-	0.54	-	0.85	0.75	-	1.00		
V	-	-	-	-	-	-	-	0.67	-	-	0.72	-	-	-	-	1.00	
As	-	-	-	-	-	0.71	0.67	-	-	-	-	-	-	-	-	-	1.00

II.5.5. Bacterial indicator

The coastal water is influenced by several kinds of stressors. Many developing countries, high organic matter rich sewage directly affects the coastal water results in bacterial decomposition and consequent degrading water quality (Franklin *et al*., 2018). Among them, viral, bacterial and protozoan pathogens are considering as water quality indicators which enters the coastal environment mainly through sewage discharges (Wear and Thurber, 2015). This study estimates the presence and their abundance of fecal bacteria indicator in the 23 selected beaches from Cancun (1-9), Puerto Morelos (10-15) and Playa del Carmen (16- 23) for 2019 and 2020 respectively. The abundance of this fecal bacteria is presented in figure II.5 and II.6.

Based on the abundance of the fecal bacteria, the bathing water quality were evaluated by comparing with the bathing water directive as given in table 3.5. During 2019, most of the beaches from Cancun, Puerto Morelos and Playa del Carmen have excellent and good water quality as per the directive used in this study. Markedly, station 3 and 4 from Cancun and Station 15 from Puerto Morelos showed a higher abundance for the presence of Streptococcus faecalis, Total Coliforms and fecal coliforms but remains constrained within the directive. In the aspect of total coliform, majority of the beaches from Cancun have good water quality. However, over all abundance of bacteria stays within limits and the Cancun has more abundance of total coliforms and fecal coliforms and the Vibrio remains least count signifying almost no presence of this bacteria in the zone. However, the presence of pathogenic bacteria Vibrio spp were found in marine environments in Thailand (Siriphap *et al*., 2017). But these bacteria were also contributed from the nutrient contents and some abiotic conditions such as temperature and salinity (Dickinson *et al*., 2013). In addition, the intense anthropogenic activities resulted from tourism and urban lifestyle leads to fecal pollution through sewage influencing the coastal environment (Borbolla- Vazquez *et al*., 2020). Overall, the water quality remains between excellent and good based on bathing water directive and below the Mexican standard values Mexican standard values (CE-CCA-001/89: E. coli < 200MPN/ 100ml; NMX-AA-120-SCFI-2006: Enterococci -100MPN/100ml)

Table II.5: Categories for the evaluation of coastal and transitional bathing waters according to the directives

Directive	Indicator (per 100 ml)	Excellent	Good	Insufficient
76/160/EEC	Total coliforms	<500	500–10,000	>10,000
76/160/EEC	Fecal coliforms	<100	100–2000	>2000
2006/7/EC	E. coli	<250	250–500	>500

During 2020, the overall water quality remains excellent expect for station 2 located in Cancun zone. The total coliform and fecal coliform were found on lower abundance < 100 having excellent water quality expect for the station 2. The abundance of During 2020, the less abundance of fecal bacteria indicates the less influence of sewage especially from the hotel zone which were closed during pandemic. The presence of Streptococcus faecalis in station 23 in the playa del carmen signify an abnormal influence of sewage and untreated waste water into the ocean (Sirikanchana *et al*., 2020) since playa del carmen have a worst waste water management due to abrupt development of this zone for the tourism. The water quality determined through fecal bacteria indicator reveals that water quality was good among all the studied station but their source was mainly from sewage and untreated waste water which causing specific higher abundance in some stations. However, the survival of this bacteria in the seawater depends highly on pH, temperature and influx of nutrient such as nitrogen and phosphorus influence their sustainability (Li *et al*., 2019).

2019					
Zone	S.No	*Estreptococus fecalis*	*Vibrio*	*Coliformes totales*	*Coliformes fecales*
Cancun	1	30	60	30	1
	2	20	4	30	1
	3	80	12	100	30
	4	100	3	120	60
	5	0	6	1	1
	6	40	18	80	60
	7	20	0	1	1
	8	20	0	30	6
	9	40	0	1	1
Puerto Morelos	10	0	0	100	90
	11	50	0	1	1
	12	0	0	9	1
	13	30	30	3	1
	14	20	6	3	1
	15	150	6	3	1
Playa del Carmen	16	60	0	1	1
	17	40	0	60	1
	18	10	0	12	1
	19	0	0	1	1
	20	0	0	1	1
	21	20	0	20	1
	22	0	3	3	3
	23	20	0	20	1

FigureII.5. Heatmap of relative abundance of bacteria genera in the coastal water during 2019

2020					
Zone	S.No	*Estreptococus fecalis*	*Vibiro*	*Coliformes totales*	*Coliformes fecales*
Cancun	1	30	1	3	0
	2	550	300	600	600
	3	70	4	90	80
	4	2	90	80	50
	5	1	0	16	8
	6	40	10	90	50
	7	0	30	30	0
	8	50	24	60	60
	9	10	0	30	30
Puerto Morelos	10	0	0	0	0
	11	0	20	20	0
	12	15	0	3	3
	13	150	35	3	0
	14	0	0	0	0
	15	150	0	5	0
Playa del Carmen	16	150	0	1	0
	17	400	0	10	3
	18	150	0	12	6
	19	600	0	0	0
	20	150	70	6	0
	21	150	0	20	3
	22	800	0	6	0
	23	1500	80	0	0

Figure II.6. Heatmap of relative abundance of bacteria genera in the coastal water during 2020

II.5.6. NUTRIENTS

In recent decades, the coastal waters are highly influenced several changes due to rapid urbanization which leads to input of nutrients. After a certain limit, the presence of excessive nutrients causes several problems such as seawater acidification, harmful or toxic algal blooms and creation of hypoxia conditions later the species shift in plankton composition, thus causing a serious environmental threat to marine ecosystem (Glibert *et al*., 2010; Li *et al*., 2014).

Hence, the study of nutrients became an essential tool to understand the beach water qualities and its related outcome in the marine environment. Also, it is important to explore the biogeochemical cycle of nutrients by understanding their controlling factors. The following session clearly describe the spatial and temporal distribution of nutrients for 2019 and 2020 in selected beaches from Cancun, Puerto Morelos and Playa del Carmen from the Quintana Roo coast.

II.5.6.1. Hydrographic features and their distributions

The initial physicochemical characteristics such as salinity, pH, dissolved oxygen and saturation of oxygen were identified along with nutrients concentration as presented in figure II.7. The average salinity was 36.89- 36.21 ‰ for Cancun; 32- 35.07 ‰ for Puerto Morelos; 33.25- 32.16 for Playa del Carmen during 2019 and 2020 (Figure II.7a). The zonal variation of salinity manifests the nearshore water column conditions with groundwater inputs with higher evaporation rate for 2019(Rubio- Cisneros *et al*., 2018; Chen *et al*., 2019) and also the influence of untreated sewage wastes causing conservative mixing behavior (Yang *et al*., 2020).

Between the study period, 2020 shows low salinity due to seasonal variation due to terrestrial discharge due to onset of the hurricane during sample collection. Secondly, the main parameter pH was presented in figure II.7 (b) for 2019 and 2020. The average pH for the stations ranged between 8.78- 7.87 for Cancun; 8.16-7.31 for Puerto Morelos; 8.42- 7.39 for Playa del Carmen. Cancun and Playa del Carmen showed the higher pH than Puerto Morelos due to the noticed intensity of groundwater discharge prevailed in the zone. The spring ground water contribute a major variation in pH aided along with tidal mixing in the zone (Hernandez- Terrones *et al*., 2015). Thirdly, the physical parameter measured was dissolved oxygen presented in figure II.7 (c). Dissolved Oxygen values were higher for Cancun about 6.54-6.89; Puerto Morelos about 5.65-5.79 and Playa del Carmen about 5.79-5.57 (in µg/l) for 2019 and 2020. The lower ranges in Puerto

Morelos and Playa del Carmen were more like to increase organic load resulted from the arrival of sargasso leading changes in basic physicochemical properties of water (Uribe-Martínez & Liceaga-Correa, 2018). The resulting organic matter and their decomposition results in oxygen depletion causing anoxic zone which noticed in Puerto Morelos and Playa del Carmen (Van Tussenbroek *et al*., 2017; Yang *et al*., 2020).

Also, the saturation of dissolved oxygen was high for Cancun- 100- 112.45; Puerto Morelos – 85.22- 92.23 and Playa del Carmen- 88.70- 86.37 (in %) for 2019 and 2020 as shown in figure II.7 (d). The over saturation of oxygen was found in Cancun and lower saturation were found in Playa del Carmen and Puerto Morelos. The variation signifies the high biological activity and also the groundwater mixing behavior of the individual zone causing more ion exchange process affecting its equilibrium (Mohanty & Rao., 2019).

The zonal distribution of Biological Oxygen Demand (BOD), Total Suspended Solids (TSS), Particulate Organic Material (POM) and Chlorophyll- a in figure II.8 (a-b). When organic matter decomposes, it is fed upon by aerobic bacteria. In this process, organic matter is broken down and oxidized (combined with oxygen). Biochemical Oxygen Demand (BOD) is the amount of oxygen required by aerobic microorganisms to stabilize the organic material of wastewater or polluted water. Always, the biological oxygen demand proportional to the amount of organic matter, signify the rate of decomposition (Marske and Polkowski, 1972).

The average concentration of BOD (in mg / l) showed a cascading result for Cancun about 2.87 in 2019 and 4.72 in 2019. Ensuing, Puerto Morelos has a drastic increase in BOD about 8.99 for 2019 to 4.26 for 2020 and Playa del Carmen has similar BOD nearly for 8.56 in 2019 to 5.00 in 2020. It is clearly that, Cancun with less BOD when compared to other two zones evident the variation of influx of organic matter load in Puerto Morelos and Playa del Carmen resulted from the arrival of sargasso. Nevertheless, Cancun with increasing BOD when compared to 2019 which clearly manifest the influence of untreated waste water mainly from the hotel zone bordering Cancun coast, since waste water were also considered as another major for the organic matter and their corresponding BOD (Faragallah *et al*.,2009). Since, the BOD is an important parameter to identify the influence of organic matter in the water, the present results show the increasing BOD due to prevailing stress of sargasso in the region, thus creating a consequential anoxic condition and mortality of benthic organisms (Yang *et al*., 2020). The results on Total Suspended Solids (TSS) in mg/ l encountered in this study (Figure II.8 b) consists of biogenic and lithogenic material with an average value of 8.60 in 2019 which partially decreased around 4.27 in 2020 for Cancun. These results coincide with BOD, which shows a lower concentration in Cancun when compared to Puerto Morelos and Playa del Carmen. Unlike Cancun, rest of the zone showed multi fold increase of TSS from 2019 to 2020, that is from 29.35 to 28.18 in Puerto Morelos and 11.80 to 27.29 in Playa del Carmen. Since, these results clearly infer with the presence of biogenic material contributes more TSS in Puerto Morelos and Playa del Carmen, meanwhile in Cancun, the source of TDS were identified as groundwater flux in the coastal zone. However, the previous study on groundwater quality in Cancun reports the presence of total dissolved solids exceeds the Mexican drinking water about 23%, so the influx of TDS was expected along with waste water and ground water due to local fracture zone (Frausto *et al*., 2008).

Following, the results on Particulate Organic Material (in mg/ l) are presented in figure II.8 c. Cancun shows a lower concentration of POM 1.94 and 3.51 for 2019 and 2020. The highest concentration of POM was 9.38 and 7.64 for 2019 and 2020 for Puerto Morelos, and Playa del Carmen were 4.78 and 5.91 for 2019 and 2020. The POM has a decreasing trend for Puerto Morelos, while Cancun and Playa del Carmen showed an increasing trend. Overall, the presence of POM resulted from the ground water discharge and decomposition of sargasso in this zone. The increasing rate of POM infers the high rate of decomposition of sargasso and significant microbial mineralization (Guo *et al*., 2015; Chen *et al*., 2021). Though, the presence of TSS and POM in the water manifest the degrading water quality thus affecting the basic water properties, it is important to determine the later behavior of this organic material in the water become under consideration. Chlorophyll-a is considered as a good indicator to assess the phytoplankton biomass.

The Chlorophyll- a showed an increasing trend in all the three zones from 2019 to 2020 as shown in figure II.8 (d). The average concentrations in Cancun varied from 0.70 in 2019 to 1.29 mg/l in 2020; Puerto Morelos showed a variation from 4.23 in 2019 to 5.72 mg/l in 2020 and Playa del Carmen have a concentration from 1.35 in 2019 to 1.95 mg/ l in 2020. Among them, Puerto Morelos have higher concentration for Chlorophyll-a for both seasons, then Playa del Carmen and least with Cancun. The direct influx of nutrients from sub-ground discharge and the aftermath product of primary production contributes more for the chlorophyll-a which in similar trend reported in various studies (Kumar *et al*., 2018). In addition, aforementioned, the sargasso related organic matter and their contribution towards POM enhances the primary production with increase the chlorophyll-a production (Chen *et al.*, 2021). Nevertheless, the contribution of chlorophyll-a in the trophic status of the study area aids to determine the impacts of temporal changes of above-mentioned parameters.

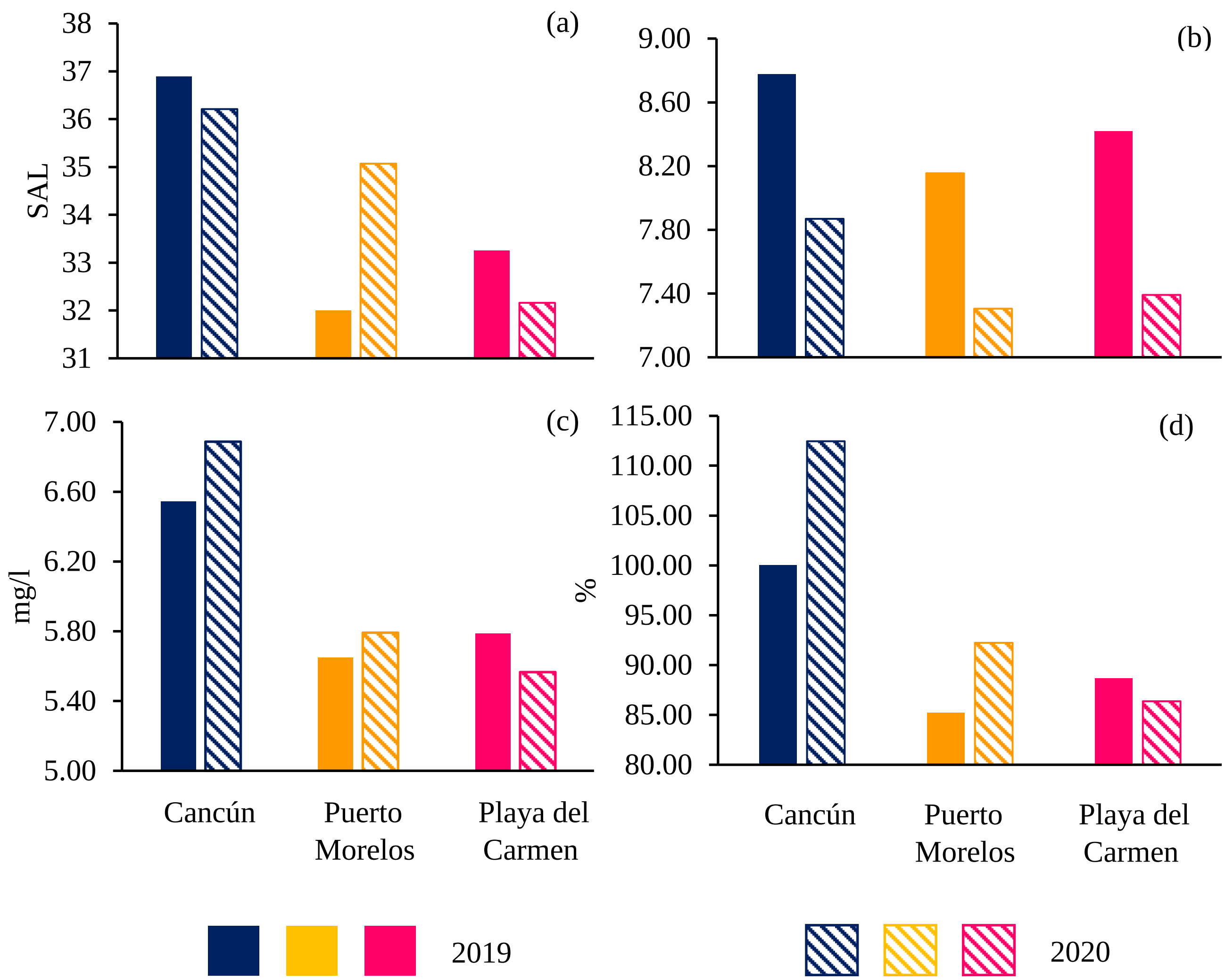

Figure II.7. Zonal distribution of a) Salinity b) pH c) Dissolved Oxygen d) Oxygen Saturation in coastal water during 2019 and 2020 in the coastal corridor of Quintana Roo

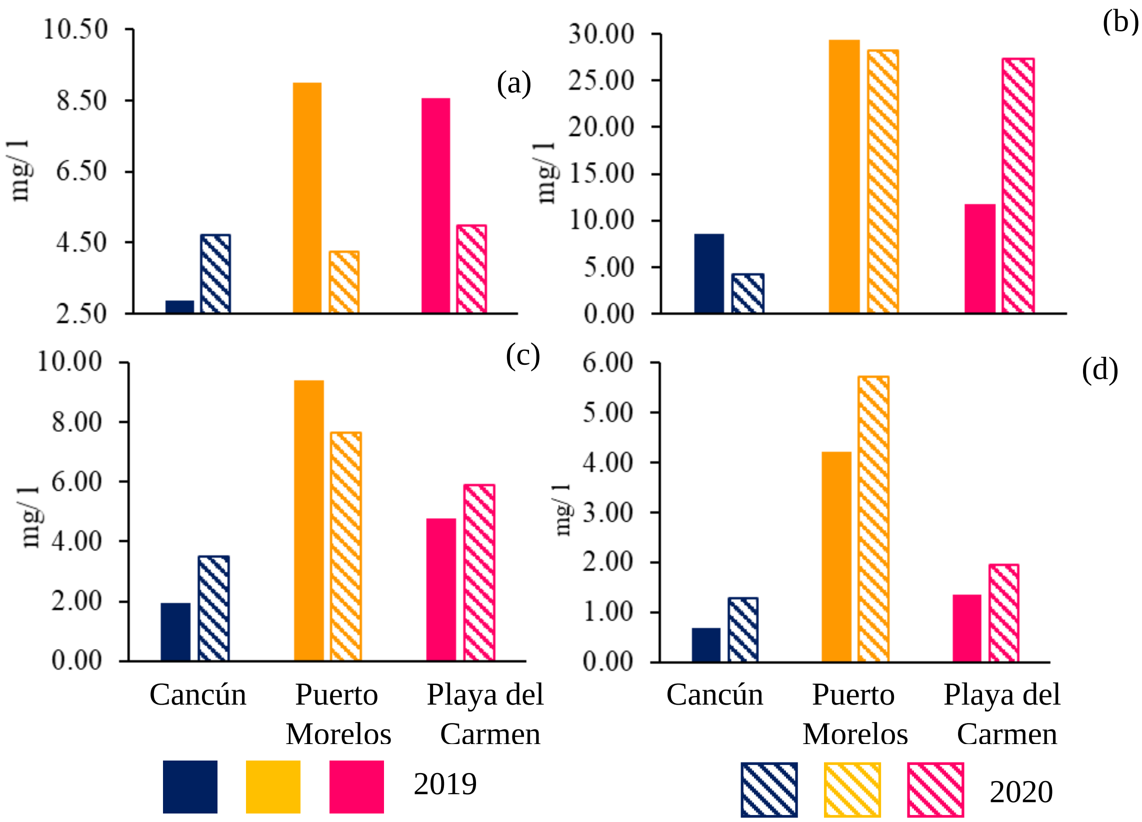

Figure II.8. Zonal distribution of a) Biological Oxygen Demand b) Total Suspended Solids c) Particulate Organic Material d) Chlorophyll in coastal water during 2019 and 2020 in the coastal corridor of Quintana Roo

II.5.6.2. DISSOLVED INORGANIC NUTRIENTS

During the study period, nutrient concentrations showed seasonal variation between 2019 and 2020 which are presented in figure II.9 (a-d) y II.10. Among the studied nutrient, DIN was high than DIP and DSi. In DIN, which is the collective concentration of NO_3, NO_2 and NH_4 were high for Puerto Morelos and Playa del Carmen than Cancun. However, there is no clear gradients was observed among the DIN, DIP, DSi for three zone between 2019 and 2020. For better understanding, the nutrient concentration (all values in µM) was discussed zone wise to perceive the characteristics of nutrient in coastal zone. The concentration of DIN (Fig II.9a-c) in Cancun were in the following order $NO_3 > NH_4 > NO_2$ in 2019 and $NO_3 > NH_4 > NO_2$ in 2020 with no significant trend of variation. In Cancun, NH_4 were relatively lower in concentration about 26.64 and 26.24 for 2019 and 2020. Their major source of origin was identified through constant input from the sub-ground discharge despite dry and rainy season which mainly controls the nutrient influx in shallow environment (Null *et al.*, 2014). Among other study sites, the coastal zone of Cancun was highly influenced by sub-ground water discharge at a rate of 3.3 m^3 d^{-1} m^{-1} which is relatively 7% of freshwater discharge into the sea (Null *et al.*, 2014). The relative abundance of NO_3 and NO_2 were 2.34 - 0.71 and 0.04 - 0.16 indicates the oxidation of NH_4 during the groundwater transport and the proceeding nitrification of NH_4 (Hernández- Terrones *et al.*, 2015). Among this period, 2019 has NO_3 which resulted from additional contribution of nutrient in the form NO_3, since the groundwater has been identified with nutrient pollution (Hernández- Terrones *et al.*, 2015). The overall DIN in Cancun manifests the principal origin through sub ground water, later in the water column by the force of oxidation contributing for NO_3 and NO_2 in this zone. For the meantime, DIN was very high for Puerto Morelos than other sites, with the abundance of nutrient was $NH_4 > NO_3 > NO_2$ for 2019 and $NH_4 > NO_2 > NO_3$ for 2020.

The abundance of NH_4 by 58.42 in Puerto Morelos contributed from groundwater especially during fresh groundwater and saline water intermixing zone. Nevertheless, the average NH_4 concentration were 336.8 µM which reported among various sites in Puerto Morelos (Null *et al.*, 2014). However, other than sub ground water discharge, the remineralization of organic mass contributes abundant NH_4 Then, the relative abundance of NO_3 and NO_2 signifies the oxidation process of the NH_4 in this zone highlighting the intense nitrification process. The nitrification of NH_4 contributed to the other form of inorganic nutrient and their abundance were mainly depends on oxygen availability of this zone. As, discussed earlier the low concentration of dissolved oxygen procures the use of oxygen for NH_4 oxidation.

Finally, Playa del Carmen showed the following concentration $NH_4 > NO_3 > NO_2$ for 2019 and 2020. The abundance of NO_3 (3.94) and NO_2 (0.03) signifies the intensified nitrification process resulted from NH_4 (34.13). The lower availability of dissolved oxygen in this zone clearly infers their usage in the nitrification process. During 2020, concentration of NH_4 (34.66) contributes for NO_3 (4.94) and NO_2 (0.20) through nitrification process. The low oxygen concentration shows the enhanced nitrification process when compared to 2020. However, as this zone was mainly affected by sargasso influx and corresponding organic mass results in mineralization contributing for NH_4 during the study period (Chavez *et al.*, 2021). In addition, the discharge of untreated waste water results in organic matter discharge, as this zone were designed for the need of increasing tourism. The overall DIN clearly infers their origin through sub ground water discharge and also by sargasso influx in Puerto Morelos and Playa del carmen. The behavior of nutrient manifests the persisting nitrification process aided by the over use of available oxygen which results to transmission to anoxic or hypoxic zone causing jeopardizing marine organisms.

The average concentration of DIP (PO_4) was high during 2019 than 2020 for all three zones was presented in figure II.9 (d). The gradient varies were for 2019 and 2020 (in µM) by 0.29 and 0.15 for Cancun; 0.39 and 0.40 for Puerto Morelos; 0.51 and 0.16 for Playa del Carmen. Since the study area is a dominant karstic terrain, the deposit of phosphates as hydroxyapatite ($Ca_5(PO_4)_3$) were highly dominant. Thus, the relative dissolution or desorption of phosphate (PO_4) in a karstic environment were highly controlled by saline – freshwater mixing rate, thus the freshwater with low HCO_3^-(Millero *et al.*, 2001). Hence, the higher concentration of PO^4 especially during 2019, infers the less adsorption behavior and higher abundance in the water column, to contrary, during 2020 and due to freshwater discharge resulted from rain during the sampling period which induce the adsorption of PO_4 by the carbonated water. Moreover, in addition to authigenic input on PO_4 into the water column, the discharge of untreated waste water which have higher concentration of detergent resulted from domestic waste contribute for the PO_4 in the study area (Saint- Loup *et al.*, 2018). Being a phosphate limited zone, the input of DIN by SGD provides a more important source of nutrient for the plankton growth (Qu *et al.*, 2017).

Dissolved silicate (DSi) is a vital nutrient required for diatoms growth in coastal water, since diatoms are the important primary producers in the ocean (Song., 2010; Kranzler *et al.*, 2019). Along with N and P, silicate also controls the growth of plankton community in the ocean. In this study, the concentration of DSi were higher for 2019 than 2020 for all three zones (in µM) as presented in Figure 3.8. In Cancun, the average concentration DSi was 21.94 and 4.84 for 2019 and 2020 respectively. But, in Puerto Morelos, the concentration was very high for 2019 by 46.03 and 2020 by 9.98. Finally, Playa del Carmen the concentration was high for 2019 by 34.93 and 2020 by 10.60. Among the study area Puerto Morelos have the highest concentration, then Playa del carmen and Cancun. The average concentration of DSi (SiO_2) was high during 2019 than 2020 for all three zones was presented in figure II.10 (a).

The seasonal variation clearly infers the DSi flux in the coastal water which mainly resulted from land-based resources later reaching coastal environment through waste water discharge (Kamatani 1984; Cloern *et al.*,2017). This goes well with this study, besides less urban use of coastal are during 2020 and their successive decrease in waste water controls their concentration. Also in coastal environment, the behavior of DSi based on physical mixing in the water and chemical adsorption or desorption process for the growth diatom community. It is obvious that, pH and salinity control the behavior of DSi for biological intake, since their uptake varies with seasons. The dynamic physical mixing in this zone causes variation in each zone and the higher abundance leads to eutrophication risk of the zone. In addition, the concentration of DSi and DIP also controls the biogeochemical cycle in this region due higher growth rates and productions (Zhang *et al.*, 2020).

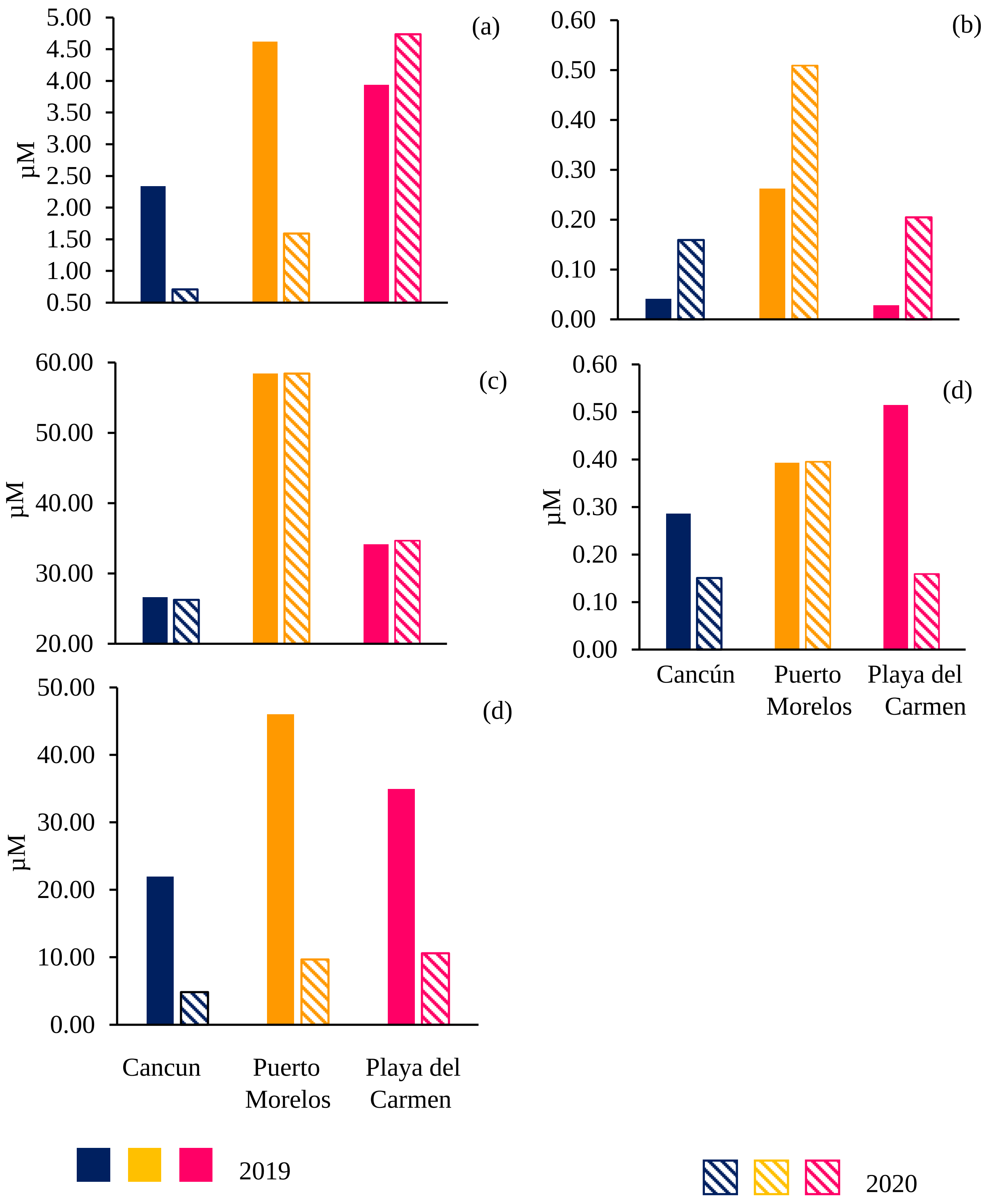

Figure II.9. Zonal distribution of Dissolved Inorganic Nutrients a) NO3, b) NO2, c) NH4 and Dissolved Inorganic Phosphorous d) PO4 coastal water during 2019 and 2020 in the coastal corridor of Quintana Roo

II.5.6.3. DIN, Total Nitrogen & Total Phosphorous

The seasonal variation of DIN, TN, TP and N/P are presented in figure II.10 (a-d). The spatial distribution of DIN was high for Puerto Morelos and Playa del Carmen and low in Cancun for 2019, while 2020 show a different trend due to seasonal influences (Fig II.10a). In general, NH_4 was the individual nutrient contributing for DIN. The overall contribution of DIN was resulted from waste water discharge with huge organic load contributing DIN in the study area. Also, the previous discussion of oxygen content clearly manifest remineralization of organic matter with the use of oxygen, later being an aerobic environment in the intertidal zone, the intense nitrification process take place which contributing for DIN (Qu *et al*., 2017). The TN concentration were high for 2020 and low for 2019, also among the zonal distribution, the Puerto Morelos and Cancun have higher concentration and Playa del Carmen with low concentration (Fig II.10b). The seasonal difference in clearly influence of waste discharge contributing for TN in this zone. As, the discharge of domestic waste has total nitrogen including organic nitrogen load into the coastal environment (Pandit and Fulekar, 2017). Hence, the TN seasonal differences clearly manifest the input of TN mainly through domestic waste influences

Later, the Total Phosphorous (TP) showed a drastic a variation between 2019 and 2020 (Fig II.10c), but among the zone Puerto Morelos have higher concentration of TP, then Playa del Carmen and finally Cancun. The higher concentration during the dry season in 2019 results from the migration and diffusion of phosphorus from sediment to surface water (Pandit and Fulekar, 2017; Qu *et al*., 2017). Thus, the process of resuspension of Phosphorous from the sediment to water were highly noticed with higher concentration, but during 2020, the changes in in-situ conditions controls and alters the resuspension of phosphorous from sediment to water. So, the availability of TP was highly dominated by seasonal factors with domestic waste influences which varies significantly within study period of 2019 and 2020. The organic load from the waste discharge contributes the TP through the decomposition process (Panseriya *et al*., 2021).

II.5.6.4. Nutrient scenario on N/P

The Redfield ratio is one of the factors to understand the need for the primary production and existing water chemistry. Thus, calculating the N:P requirements using procured results helps to find the limiting nutrition of the Caribbean region. The obtained N/P ratio during 2019 and 2020 are presented in figure II.10d. There were gradient changes in the noticed between 2019 and 2020. Between, nitrogen and phosphorous, the nitrogen was the limiting nutrition for the biological productivity in this region. The previous discussion on the trophic status of the study area shows the altering trophic status of oligotrophic region into mesotrophic and eutrophic, just creating an increasing need for the primary nutrient requirements. Among the zonal study, Puerto Morelos have high need for N, then Cancun and Playa del Carmen. The overall variation manifests, that N is the limiting nutrient which was clear through the intense nitrification process for transforming into organic N into inorganic and biological available nutrient. Also, the increasing trend from 2019 and 2020, signify their increasing biological productivity and their increasing demand for N:P, which making N as limiting nutrient. Moreover, the seasonal variation shows the groundwater discharge alters the in-situ conditions in the coastal zone resulted from the discharge of oxic water into anoxic seawater (Prakash *et al.*, 2020). Thus, the SGD with more nutrient inputs and there delayed nitrification process with the altered in-situ conditions gradually increasing the need of limiting nutrient during 2020. However, the contribution of NH_4 from the remineralization process and their corresponding nitrification process was distinct throughout the study area, nevertheless, the input of SGD and alter in-situ conditions results in more need for limiting nutrient of N in the Caribbean region.

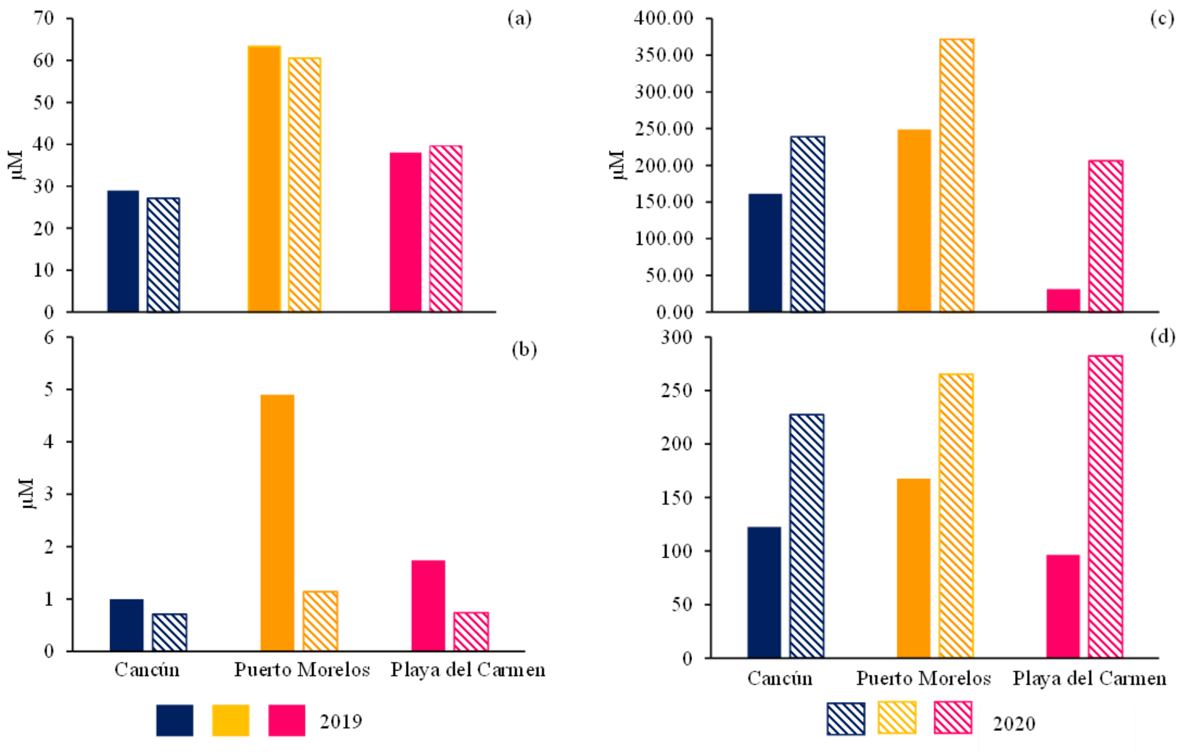

Figure II.10. Zonal distribution of DIN (a), Total Nitrogen (b), Total Phosphorous(c), N/P (d) during 2019 and 2020 in coastal water of Quintana Roo

II.5.7. TROPIC STATUS ASSESSMENT

Dissolved inorganic nutrient (DIN), phosphorus (DIP) and silicon (DSi) are the key indicators in evaluating the ecological health status of any environment which plays an essential role in the biological productivities, ecosystems functions and biogeochemical processes in marine environment (Yang *et al*., 2018). The primary outcome of nutrient enrichment was by stimulating primary productivity later leads to exceptional algal blooms, which can result in anoxic or hypoxic zone due to several changes in the water column owing to productivity (Li *et al*., 2016). Since the study area were affected by the several natural and anthropogenic, which leads to input of inorganic nutrients into the coastal zone. As discussed earlier, the nutrient concentration varied between 2019 and 2020 for three zones due to their multi-origin and their flux depends in the in-situ conditions in the water, it is essential to assess the trophic status of individual zone which helps to understand the overall trophic condition with respect to role of individual nutrient concentration for the primary production. The trophic status of the Caribbean region for 2019 and 2020 were given in figure II.11.

On the basis of analysis, the TRIX assessment using eight important parameters analyzed in this study. Among the zones, Cancun has major zones with oligotrophic status for major stations while Puerto Morelos and Playa del Carmen has combined status of mesotrophic and eutrophic. In Cancun, only station 1, 6, 8 and 9 have mesotrophic status and station 2,3,4,5 and 7 have oligotrophic status. Among the indicators used chlorophyll and DIN were the highest contributing factor for the ecological status of the Caribbean region. The stations with oligotrophic condition have moderate chlorophyll concentration for 2019 by 0.70 and 2020 by 1.79. Henceforth, Cancun zone has partial stations with oligotrophic and mesotrophic status for 2019 and 2020. The influx of DIN in this zone were controlled by the waste water discharge from the hotel zone localized in this zone. Also, due to linear relationship between DIN and chlorophyll which indicates the primary production in this zone through increasing plankton growth (Yang *et al*., 2020).

Secondly, Puerto Morelos, expect station 10 which is eutrophic by while rest of the stations were mesotrophic. Unlike Cancun, PM have mesotrophic and eutrophic status which indicates the major primary production in this zone. The influencing factors for this zone were chlorophyll and DIN, since the average Chlorophyll concentration 4.23 and 5.72 for 2019 and 2020. Also, the relative concentration of DIN which was high in this zone, consequently causing accelerated primary production. Despite being, coral reef this, the transfer of oligotrophic status to mesotrophic and eutrophic status has a high risk of affecting coral health. The major contribution of DIN were untreated waste discharge and SGD prevailed in this zone. Since, this zone was reported with high nutrient content in the seagrass and an expected eutrophication risk on a previous decadal study (Van Tussenbroek, 2011). However, there is no gradient changes were observed between 2019 and 2020. In addition, the arrival of sargassum contributes for the biomass and the corresponding chlorophyll concentration (Chavez *et al*., 2020). So, as an expected change in the ecological status of Puerto Morelos from oligotrophic to mesotrophic and eutrophic signify the jeopardizing coastal community health in the upcoming years (Perez- Gomez *et al*., 2020).

Finally, Playa del Carmen, as fore mentioned a zone developed under increasing tourism need have faced a lot of ecological disturbance. The trophic status of Playa del Carmen was between mesotrophic and eutrophic for the studied zone. The chlorophyll concentration for 1.35 and 1.95 for 2019 and 2020. Also, DIN was found higher for this zone resulted majorly from waste water discharge due to poor maintenance. The influx of sargassum and their corresponding input of POM also contributes for the nutrient influx in this zone. Among the studied zone, station 18 has attained oligotrophic condition which clearly infers low primary production due to seasonal variability in this region.

Despite being an oligotrophic region, the influx of sargassum and influence of groundwater and waste water contributes more for nutrients and other bioassay concentration. In due course of time, the incorporation of these nutrients and organic material with in-situ conditions of the water column enhances the primary production of this coastal zone (Rubio-Cisneros *et al*., 2018, Perez-Gomez *et al*., 2020). Thus, the increased primary production has several outcomes in the water column including bio algal blooms, phytoplankton growth and ultimate risk condition of water quality. Many studies on eutrophication assessment reported that the major impact of trophic status alteration was degrading water quality were change in color, turbidity and change from oxic to anoxic condition leads to community lethal, in total posing major threat to ecosystem (Li *et al*., 2014, Grosse *et al*., 2017; Yang *et al*., 2020). Hence, the transfer of oligotrophic region into mesotrophic and eutrophic zone were expected to face a serious ecosystem problem in upcoming years.

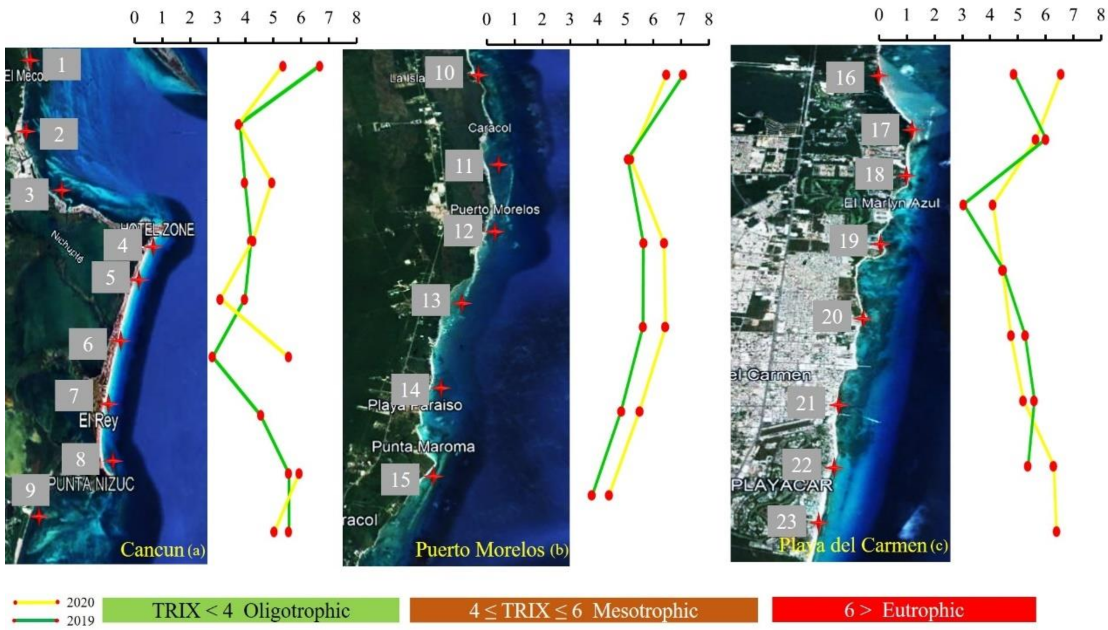

Figure II.1I. Trophic status of the Caribbean region for 2019 and 2020 for (a) Cancun (b) Puerto Morelos (c) Playa del Carmen

II.5.8. COASTAL WATER QUALITY INDEX (CQWI)

The assessment of coastal water quality serves as important environmental indicator for verifying the coastal health especially for tourism dominated area for which integrated with anthropogenic activities. The coastal water quality index was calculated using relative weightage of each water quality parameter and equation which mentioned earlier. Based on the grading scale, the coastal water quality in the Caribbean for 2019 and 2020 are presented in figure II.12. The obtained results were indicative on overall water quality of Caribbean region were *"moderate"*. Out of three zones, Puerto Morelos and Playa del Carmen have *"very good – good"* water quality and Cancun have *"moderate-very bad"* water quality expect station 1. Afore mentioned, the eutrophication has direct impact on water quality, as the eutrophication contributes more for biomass production in the form of particulate matter thus affecting the water quality, depletion of dissolved oxygen and toxic algal blooms in the coastal medium (Tekile *et al*., 2015; Chen *et al*., 2016).

In Cancun, station 1,7 and 8 has "*very good"* water quality, but rest of the stations has "*bad"* water quality. It is evident that, the overall less contamination of nutrients, POM and sargasso circulation has made clear of the water quality to maximum. However, the impact of hotel zone and their flushing of waster/urban discharge in this zone, which precured from improved water quality from "*bad to moderate"* in 2020 markedly during the pandemic. Since, the more use of beach and recreating activities mainly controls the water quality of the Cancun zone. The seasonality of the water quality was "*moderate to very good"* during 2020 and "*bad to moderate"* during 2019 which manifest the impact of anthropogenic activities and its relative impacts in water quality.

Further, Puerto Morelos zone despite with leading beaches uses and port activities, the water quality were "*very good"* during both the study period. In addition to higher concentration of POM, TSS and chlorophyll, the trophic status was limited to mesotrophic. Also, the prevailing sargasso affects the water quality majorly by the oxygen depletion for the remineralization process, Despite, these affecting stressors, most of the stations have "*very good water"* quality during both the study period. There is an understandable relationship between trophic status of the zone and the water quality, since it integrates all the in-situ conditions and prevailing biomass production. But, only station 15 has retreated into "*moderate"* water quality which results from some external contamination from the zone during 2019.

Finally, Playa del Carmen have overall water quality from *"very good"* for station 16,17, 21, 22, 23 and *"moderate"* water quality for station 18,19, 20. This zone has no variation between 2019 and 2020, nevertheless station 18, 19 and 20 which has "*bad"* water quality during 2019 that has improved into *"moderate"* water quality for 2020. This clearly infers the less anthropogenic activity in this zone helps in betterment of water quality from *"bad to moderate"*. Since, trophic status of this zone were mesotrophic to eutrophic, the water quality of this zone manifests the limited primary production which have positive results in the water quality. The majority of the station attained *"very good water"* quality during study period, but varies based on the external sources of contamination.

The CWQI indicates the *"very good"* water quality for three zones, but the seasonal variation of the showed progressive changes from 2019 to 2020 due to less anthropogenic practices of coastal resources. In 2019, few station with *"very bad"* water quality results from over anthropogenic influences along with influx of nutrients and biomass. But, in 2020, the improvement of *"bad"* water quality into *"moderate"* water quality manifesting the less anthropogenic influences due to pandemic restriction on beach uses. So, the CWQI aids to identify the coastal stressors impacts on the Caribbean region along with the anthropogenic activities.

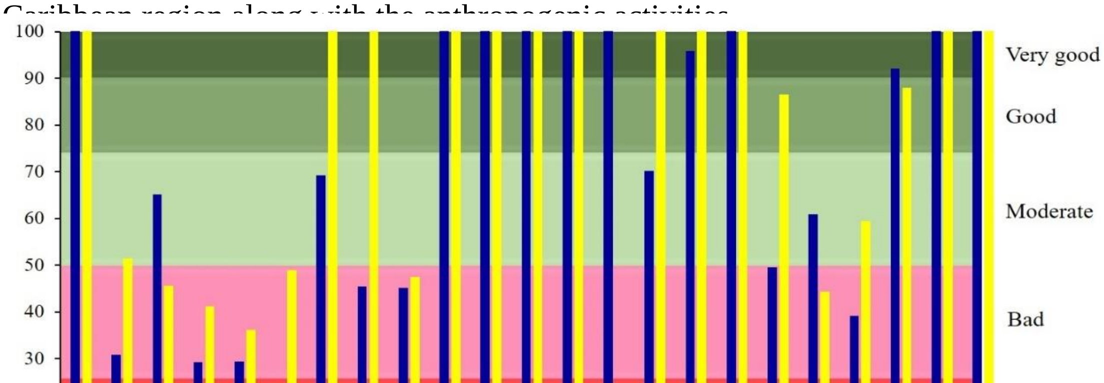

Figure II.12. Coastal Water Quality Index (CWQI) for Cancun, Puerto Morelos and Playa del Carmen during 2019 & 2020

II.5.9. STATISTICAL ANALYSIS

Hierarchical agglomerative cluster analysis (CA) was performed on the normalized dataset (Ward, 1963). The dendrogram generated in CA provides a useful graphical tool in determining the number of clusters which describe underlying process that leads to spatial variation (Simeonov *et al.*, 2003; Shrestha and Kazama, 2007; Yang *et al.*, 2010). The generated dendrogram were presented for zones during 2019 and 2020.

II.5.9.1. Spatial dendrograms in 2019

The spatial dendrogram for the study region during 2019 were presented in figure II.13 (a-c). In 2019, the spatial dendrogram for Cancun manifest the similarities which includes pH, DO, NO_3, POM, NO_2, PO_4, Chl, TP, BOD, TSS which is clustered as C1 (Fig. II.13 a). These factors are inter-related with one another which signify a dominant productivity in aquatic environment. The nutrients NO_3, NO_3, PO_4, TP indicates their use and uptake for the biological productivity with respect to their changes in BOD, DO, pH in the water (Wei *et al.*, 2016), along with the role of Chl, TSS and POM which results from the influx of sargassum. Then cluster C 2 includes salinity,

NH_4, DIN, SiO_2, SAT % which describes the contribution of NH_4 for the DIN, since highest inorganic nutrient reported in this study. The salinity controls the behavior of SiO_2 in the water column, as the study area were dominated by the sub ground influx with low salinity noticed in the study period. Later, the cluster C3 have only TN and N/P which shows limiting nutrition for the primary production in this zone were limited highly by the TN input. So, it is clear that in Cancun zone, the nutrient was highly controlled by the in-situ parameters for the corresponding biological uptake, in addition the clustering of major nutrient resembles their similar source of origin which has already reported in Caribbean coast (Perez- Gomez *et al*., 2020).

Like Cancun zone, Puerto Morelos shows similar behavior of nutrients in this zone for 2019 (Fig II.13 b). C 1 was similar like Cancun, where NO_3, NO_3, PO_4, TP were dominantly controlled by the in-situ parameters in the water column. The cluster C 2 contains salinity and SiO_4 which signify clearly shows the terrestrial origin through sub groundwater discharge with low salinity, which was identified as major SiO_4 in this zone (Null et a., 2014; Hernandez- Terrones *et al*., 2015). The C 3 have DIN and NH_4 shows the major contribution of NH_4 which results from the remineralization and their contribution for DIN (Wang *et al*., 2018). Finally, the cluster C 4 indicates the TN which limits the N/P for the primary production with oxygen saturation, which is an important condition for nitrogen and phosphorous oxygenation from the sediment-water interface (Jha *et al*., 2014). Also, TN and N/P with oxygen saturation which leads to the algal growth and the remineralization of organic matter prevailed in this zone (Yan *et al*., 2016).

Finally, Playa del Carmen also have similar nutrient behavior like other zones (Fig II.13 c). The inter-elements relationships among nutrients and in-situ conditions were similar like Puerto Morelos which is clustered as C1. The cluster C 2 have DIN, NH_4, SiO_2, salinity, which also have the same controlling conditions as noticed in the other zone. Overall, the behavior of SiO_2 were controlled salinity due to influenced sub ground water discharge. Also, it is clear for the contribution of Din mainly from NH_4, as fore mentioned the NH_4 were resulted from the remineralization process of organic material in this zone.

Finally, the TN, N/P and SAT % indicates the limiting nutrient for the primary production in this environment which mainly depends on the TN and the corresponding dependence on oxygen for the nutrient cycle under certain environmental conditions (Zhang *et al*., 2014). Thus, overall statistical analysis reveals the inter- elemental behavior of nutrients were similar among the zones where the nutrients were highly controlled by the in-situ water column conditions and also the

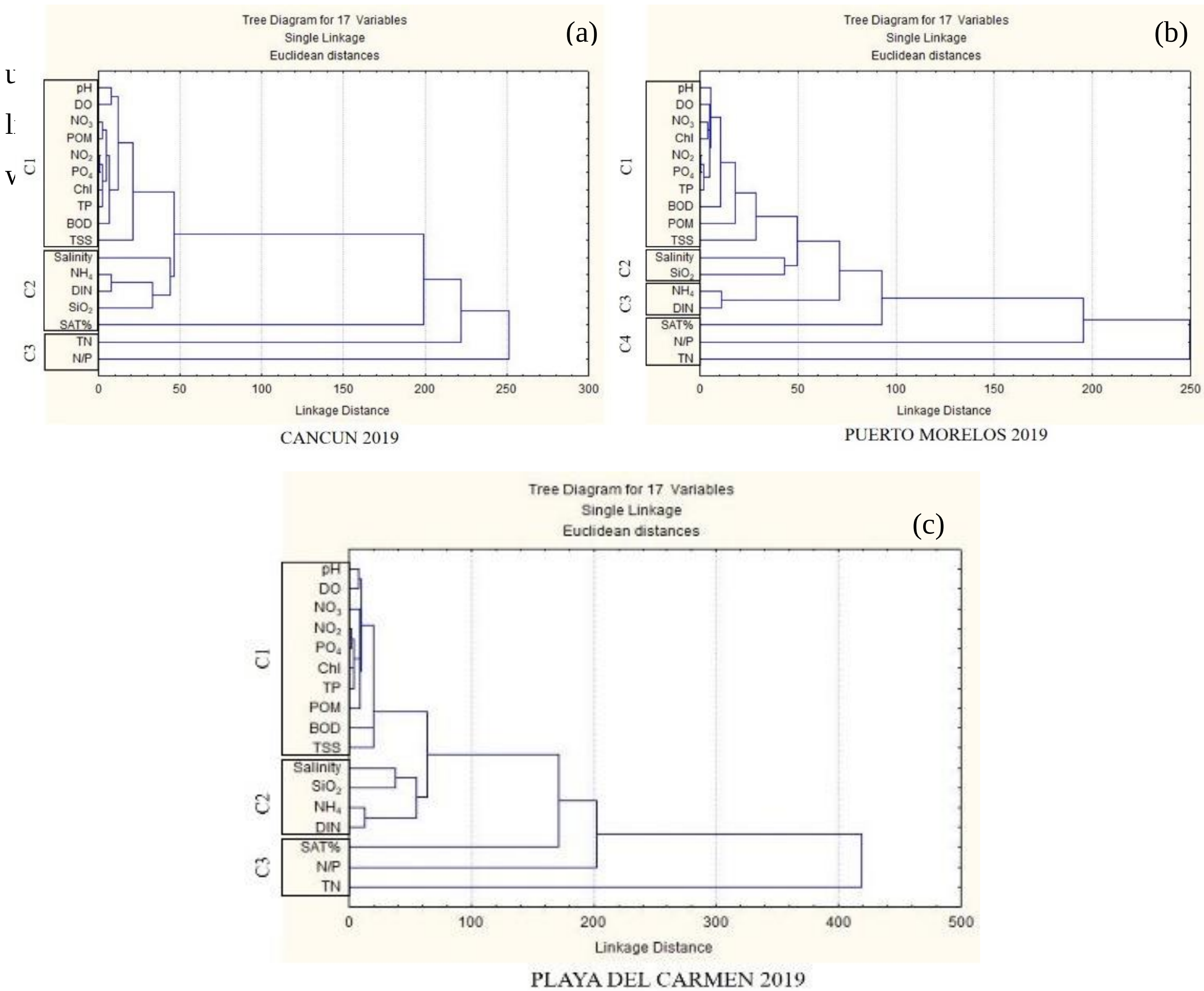

Figure II.13. Spatial dendrograms for Cancun (a), Puerto Morelos (b) and Playa del Carmen (c) for 2019 in Mexican Caribbean coast, Quintana Roo

II.5.9.2. Spatial dendrograms in 2020

The spatial dendrograms for the study region were presented in figure 2020. In 2020, the Cancun zone have four cluster such as C1, C2, C3 and C4 (Fig II.14 a- c). The cluster C 1 includes TP, NO_3, NO_2, PO_4, SiO_2, POM, Chl-a, pH, DO, BOD where there is an intact relation noticed between nutrients which indicate their similar origin, the intake of these nutrients was controlled by pH, DO and BOD, however these in-situ conditions govern the biological uptake of these nutrients. Then the cluster C2 only has TSS, where indicates their external origin through surface run off dominant during 2020. Then, cluster C3 have NH_4, DIN, DO, salinity and SiO_4 that indicates the particular behavior origin these nutrients in this period and the relation with salinity and DO manifest their influence off freshwater discharge during 2020. Since majority of the freshwater discharge controls the salinity and DO (Panseriya *et al*., 2021) which controls the behavior of DIN and intense nitrification process in this zone. Finally, the cluster C4 contains TN, N/P and SAT% also signify the same behavior as noticed in Cancun during 2019. The nitrogen was the limiting nutrition for the primary production, also their higher dependency on oxygen dependence for their biological uptake.

Secondly, Puerto Morelos have five cluster of C1, C2, C3, C4 and C5 as showed in figure II.14 b. So, the cluster C1 contains NO_3, NO_2, PO_4, SiO_2 and TP cluster together which is undergoing oxidation in the presence of in-situ conditions such as pH, DO and BOD indicates the dependence of oxygen for the nutrient cycle and relative biological uptake in this zone. Also, the Chl-a and POM shows their degradation of OM resulted from the sargasso influx and surface runoff and the corresponding use of Chl-a for photosynthesis. The cluster C 2 contains TSS and salinity and the cluster C 3 signify the intense nitrification process of NH_4 accounting for DIN in this zone. The cluster C 4 contain only SAT% that indicate their external supply due to seasonal influences (Panseriya *et al*., 2021). Finally, the cluster C5 have TN and N/P which impose the nitrogen as the limiting nutrient in this zone for the biological productivity (Kong *et al*., 2017).

Finally, Playa del carmen have five clusters such as C1, C2, C3, C4, C5 as presented in figure II.14 c during 2020. In C1 the elements were very well clustered between nutrients NO_3, NO_2, PO_4, SiO_2 and TP and their origin resembles the similar origin. Among them, PO_4 and SiO_2 resembles their similar origin from sediments and their resuspension during low pH (Pandit and Fulekar, 2017) by later their behavior was highly controlled by pH, DO and BOD, signify their oxygen uptake from the water column and corresponding changes in the pH (Kong *et al*., 2017). Also, the POM and Chl-a were having the same behavior like Puerto Morelos. The cluster C2 have only TSS and salinity which indicate the phytoplankton growth, as their growth was limited by slight salinity variation and TSS variation for their uptake (Sir Buana *et al*.,2021). Then cluster C3 have DIN and their relative ammonification contributes for NH_4 in this zone, later this ammonia undergoes nitrification process depend on the oxygen concentration. The cluster C 4 have only SAT% which varies due to seasonal influences. Finally, the cluster C 5 have TN and N/P which indicates total nitrogen contributes more for the productivity with nitrogen a limiting nutrition in this zone.

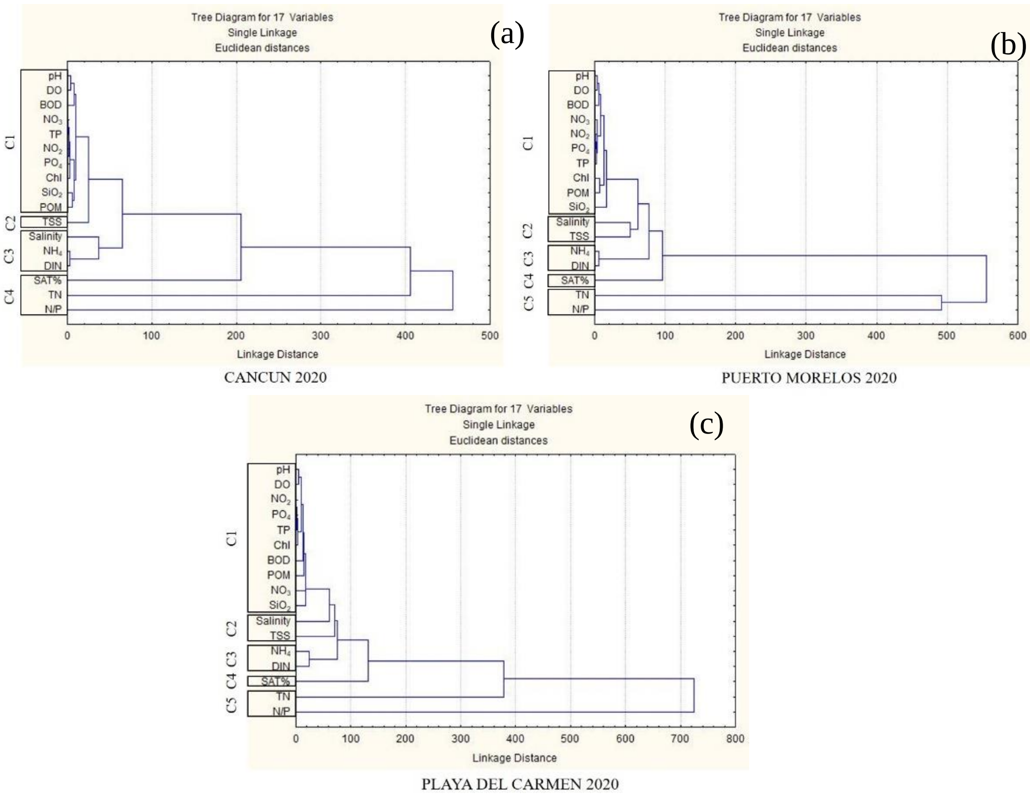

Figure II.14. Spatial dendrograms for Cancun (a), Puerto Morelos (b) and Playa del Carmen (c) for 2020 in Mexican Caribbean coast, Quintana Roo

II.5.10. COMPARATIVE STUDIES

II.5.10.1. Metals

Comparison values of dissolved trace metals with other tourist beaches and coastal regions around the world indicates a twofold increase of Ni, tenfold increase of Pb and As as presented in table II.6 (Srichandran *et al*., 2016; Santos-Echeandía *et al*., 2009; Nour & El-Sorogy, 2020; Reis *et al*., 2017; Pavoni *et al*., 2020; Achary *et al*., 2016; Armid wt al., 2020; Tian *et al*., 2020; Zhao *et al*., 2018; Wang *et al*., 2019; Li *et al*., 2017; Wanh *et al*., 2018; Broecker & Peng, 2016). Likewise, comparing the permissible limits with reference to EPA, and CONAGUA (EPA, 2020; CONAGUA, 2016) there is a two-to-ten-fold increase in the coastal region for most of the metals (except Sr, V) indicating that the strong developmental activities all along the coast in the coastal

(c)

cities and tourism related pleasure trips have exerted the pressure on the coastal waters. Compared to other coastal beaches Cr, Ni, Pb, Cd and As indicates enrichment of two to five-fold which is mainly due to tourist, various developmental activities in coastal cities as well as the higher presence of organic material in the beach waters where many low oxygen regions are observed indicating reducing environment mobilizing the dissolved trace metals.

Table II.6. Comparison of dissolved trace metal concentration (in mg $L^{-1} \times 10^{-3}$) in sea water from different coastal regions of the world

Location		Method	Fe	Mn	Cr	Cu	Ni	Co	Pb	Zn	Cd	Sr	V	As	References
Gulf of Suez, Egypt		AAS	1.94	-	-	0.043	0.01	-	0.51	0.23	0.09	-	-	-	Nour & El -Sorogy, 2020
Rosetta coast, Egypt		ICPMS	0.22	-	-	-	0.006	-	0.006	0.013	-	-	-	-	El Sorogy & Attiah, 2015
Portuguese Coast		*	-	-	-	0.057	-	-	0.002	0.091	0.001	-	-	-	Santos-Echeandía *et al*., 2019
Northwest coast, Portugal		AAS	0.149	0.832	0.0041	0.434	-	-	-	9.4	0.0013	-	-	-	Reis *et al*., 2017
Gulf of Trieste, Italy		ICPMS	3.51	16.9	0.031	0.434	-	-	0.08	31.2	-	-	-	2.31	Pavoni *et al*., 2020
Southwest coast of Bengal		ICPMS	-	-	4.03	5.76	-	-	5.48	53.96	1.95	-	-	-	Achara *et al*., 2019
Bay of Bengal & East coast of India		ICPMS	-	7.34	-	-	-	-	1.39	0.01	0.01	-	-	-	Srichandran *et al*., 2016
Kendari Bay, Indonesia		ICPMS	-	-	0.085	-	-	-	0.009	-	00.015	-	-	-	Armid *et al*., 2020
Yellow Sea, South Korea		ICPMS	-	-	0.21	2.47	1.73	-	0.11	1.4	0.04	-	-	1.23	Tian *et al*., 2020
Laoshan Bay, China		FAAS	-	-	1.23	1.5	-	-	0.81	1.81	0.12	-	-	1.16	Wang *et al*., 2019
Xiangshan Bay, China		**	-	-	0.22	0.34	-	-	19.3	16.8	0.22	-	-	2.6	Zhoa *et al*., 2018
Yalujiang estuary, China		AAS, ICPMS	-	-	0.13	2.86	-	-	0.68	14.93	1.18	-	-	1.8	Li *et al*., 2017
Yellow River East, China		AFS, FAAS	-	-	-	1.16	-	-	5.61	14.9	1.18	-	-	2.59	Wang *et al*., 2018
Ocean average concentration		-	0.04	-	-	0.12	-	-	0.001	0.4	0.07	-	-	-	Broecker & Peng, 1982
Cancun	(2019)	ICPMS	1974	678	502	1300	3319	3163	6615	1461	868	8900	1081	10	This study
Playa del Carmen			2040	705	444	1313	3262	3173	6610	1347	898	7025	806	12	
Tulum			1796	713	407	1251	3075	3002	6330	1399	856	3805	380	10	
Cozumel			1747	628	412	1264	3089	2965	6319	1234	849	2352	250	11	
Cancun	(2020)		2928	1369	704	2939	2388	1359	4122	1866	1452	10211	1398	3492	
Playa del Carmen			2041	830	560	2052	1713	1158	3022	1272	1004	7008	907	2328	
Tulum			533	422	189	828	462	384	1518	584	349	3172	313	591	
Cozumel			368	263	163	675	1086	342	1181	495	301	2757	330	483	
Water quality criteria		-	-	-	5	0.31	0.82	-	0.81	8.1	0.88	-	-	3.6	EPA, 2020
Mexican Permissible limits		-	-	-	1000	4000	2000	-	500	10000	200	-	-	200	CONAUGA, 2016

AAS- Atomic Absorption Spectrometry; FAAS- Flame Atomic Absorption Spectrometry; ICPMS- Inductively coupled plasma mass spectrometry; *- Stripping voltammetry; **- Spectrophotometry

II.5.10.2. Comparison studies of nutrients

The comparison of nutrient from various coastal water environment across the world has been presented in table II.7. and along with SGD influx rates reported respectively. The mean concentration for DIN, DIP and DSi was presented in units as reported in individual study and this present study was reported in µM. Among the country which compared with the present study, DIN was observed one-fold decrease in Jiaozhou Bay (Xing *et al*., 2017); Daya Bay (Wang *et al*., 2017); Bohai Sea (MEE, 2020); Maowei Sea (Chen *et al*., 2018) and South China Sea (Gao *et al*., 2020) when compared to the Caribbean region. Also, Japan and Korea have low concentration of DIN when compared to the present study area (Sugimoto *et al*., 2016; Hwang *et al*., 2016); Hong Kong (Luo *et al*., 2014) and Mediterranean Sea (Rodellas *et al*., 2015). However, in Mexico, the DIN reported in La Paz Bay was also found similar to the present region (Urquidi- Gaume *et al*., 2016). In addition, DIN concentration reported in Cancun, Puerto Morelos, Sian Ka'an and Xcalak were found to have the high concentration (Null *et al*., 2014) when compared to present study, also the SGD influx rates were taken into account since this data were beach ground water, where its concentration was differs from the present study.

Among, the nutrients compared DIP and DSi were found high in the present study when compared to other parts of the world. DIP showed a higher concentration for Japan, Korea, China and lower for Hong Kong (Sugimoto *et al*., 2016; Hwang *et al*., 2016, Wang *et al*., 2017 and Luo *et al*., 2014). But DIP was higher for La Paz Bay (Urquidi- Gaume *et al*., 2016) and for previous studies reported in Cancun, Puerto Morelos, Sian Ka'an and Xcalak (Null *et al*., 2014). Finally, for DSi, the present study area showed a two-fold decrease when compared to La Paz Bay in Mexico and Maowei Sea in China. But, as observed by Null *et al* (2014) DSi was low for Cancun, and almost same for Puerto Morelos as noticed in this study. Among the concentration, 2019 showed a distinct variation when compared to 2020, also showed a multi-fold lower concentration for DIP and DSi, but higher for DIN.

In the context of SGD, the present study area was also affected by SGD influx for nutrient inputs. Among the compared area, Maowei Sea from China has highest SGD influx rated (Chen *et al*., 2018). In Mexico, La Paz Bay and Xcalak have found with highest SGD influx rates. When compared among the study sities in Caribbean region, Cancun have more SGD influx rates than

Table II.7. Comparison of DIN, DIP, DSi reported in various coastal water environment across the world

Country		Location	DIN	DIP	DSi	Unit	SGD influx	References
Japan		Obama Bay	0.54	2.1	0.56	10^{-3} mol m^{-2} d^{-1}	0.61 cm d^{-1}	Sugimoto *et al.*, 2016
Korea		Geojo Bay	2.0	3.0	5.9	10^{-3} mol m^{-2} d^{-1}	5.0 cm d^{-1}	Hwang *et al.*, 2016
China		Maowei Sea	33	39	69.5	10^{-3} mol m^{-2} d^{-1}	36 cm d^{-1}	Chen *et al.*, 2018
China		Daya Bay	14	24	37	10^{-3} mol m^{-2} d^{-1}	28-31 cm d^{-1}	Wang *et al.*, 2017
China		Bohai Sea	73.3	-	-	mmol m^{-2} yr^{-1}	-	MEE, 2020
China		Jiaozhou Bay	147.6	-	-	mmol m^{-2} yr^{-1}	-	Xing *et al.*, 2017
China		South China Sea	16.8	-	-	mmol m^{-2} yr^{-1}	-	Gao *et al.*, 2020
Hong Kong		Tolo Harbor	0.6 - 0.14	0.005	-	mmol m^{-2} d^{-1}	1.2-3.0 cm d^{-1}	Luo *et al.*, 2014
Europe		Mediterranean Sea	0.66	0.002	-	mmol m^{-2} d^{-1}	0.1–1.7 cm d^{-1}	Rodellas *et al.*, 2015
Mexico		La Paz Bay	2.0-52	4.0-94	7.0-160	10^{-3} mol m^{-2} d^{-1}	10-18 cm d^{-1}	Urquidi- Gaume *et al.*, 2016
		Cancun	49.6	0.8	36.2	µM	8.6 10^6 m^3 km^{-1} yr^{-1}	Null *et al.*, 2014
		Puerto Morelos	337.5	0.7	46.5		0.7-3.9 10^6 m^3 km^{-1} yr^{-1}	
		Sian Ka’an	49.5	0.9	39.1		0.5 10^6 m^3 km^{-1} yr^{-1}	
		Xcalak	250.9	0.3	21.4		112 10^6 m^3 km^{-1} yr^{-1}	
		Puerto Juarez (cold front)	10.78	2.92	-	µg L^{-1}	-	Perez- Gomez *et al.*, 2020
		Puerto Juarez (dry)	4.88	0.84	-			
		Puerto Morelos (cold front)	8.87	2.9	-			
		Puerto Morelos (dry)	3.89	0.74	-			
	2019	Cancun	29.02	0.29	21.94	µM	-	This study
		Puerto Morelos	63.30	0.39	46.03			
		Playa del Carmen	38.09	0.51	34.93			
	2020	Cancun	27.11	0.15	4.84			
		Puerto Morelos	60.52	0.40	9.68			
		Playa del Carmen	39.60	0.16	10.60			

Puerto Morelos and Sian Ka’an. However, this influx in the Caribbean region varies depend on seasonal influences. The recent studies on DIN and DIP in Puerto Morelos and Puerto Juarez during cold front and dry season were observed one-fold decrease from the present study values (Perez- Gomez *et al*., 2020). The seasonal variation was considered as important factor for this variation, however, the increasing nutrient concentration for the present study area shows the increasing nutrient and their respective impacts on Caribbean coast

Thus, the overall comparison of nutrients aids to understand the importance of understanding SGD influx rates and their relative discharge of nutrient enriched ground water into coastal environment. Among the nutrients, DIP and DSi was contributed to the coastal region when compared to DIN. But, the study area also goes well with trend as DIN were record high and DIN and DSi was low when compared with others parts of the region. In China, most of the studies reported the causes for this nutrient contribution were resulted from anthropogenic activities such as industrial effluents, waste water discharge, agricultural irrigation and fertilizer application which were contributing more for nutrient in the coastal environments. But, most of the studies described the greater influence of SGD along with anthropogenic activities which contributing more nutrients even to oligotrophic region such as Mediterranean Sea, just changing the trophic status of coastal environment as observed in this present study area.

CHAPTER - III

QUALITY AND EFFICIENCY OF CERTIFICATION OF THE BEACHES ON THE CARIBBEAN COAST: PERCEIVED PERSPECTIVES OF THE BEACH USERS ON THE CURRENT QUALITY OF THE BEACHES

III.1. INTRODUCTION

Coastal areas are complex interface system between marine and terrestrial environments and their interactions are very dynamic and fragile subsystems. The two interacting and independent subsystems are natural and socioeconomic. Since, the outcome of these two subsystems are highly sensitive, the main intention to withstand this impact was to establish a sustainable relationship between these two subsystems. The socioeconomic activities involve the practice of various physical drivers available in the coastal environment, generating employment, revenues and cultural importance. Tourism, one of intense economic drivers practiced in the coastal environment, attained global attention with abrupt growth and increasing demand from users' (Rangel- Buitrago *et al*., 2013). Thus, to meet this growing demand, the implementation of several infrastructures was carried out to meet the requirements and demand of the users. The modern requirements involve, the easy access with various socio- environmental services like security, cleaning, hospitality, accommodation which lead to intervention and alteration of the existing natural areas.

In few decades, the coastal tourism promoted many economic activities through environmental interactions through various processes makes them as high environmental sensitivity (Onofri and Nunes, 2013). To support the demand of tourism, the infrastructure and some transport arrangements are required, thus contributing more towards physical development of resorts, transport connivences and respective pollution from vehicle emissions, sewage related pollution and environmental degradation. The global environmental impact of tourism is limited by documenting, however Holder (1988) proposed "*self- destruct theory of tourism*" which states the development of any natural areas became a great destination for mass tourism with necessity for low- density settlement expanding over natural areas. Wiese (1996) documented this theory through an irreversible environmental and socio- environmental degradation in Cancun, which held a variety of marine life with several openings to the lagoon. Quarries were constructed to link the mainland to the island thus restricting the flow of fresh water into the lagoon. Due to eventual growth of tourism caused groundwater pollution which was well noticed in this region.

III.2. LITERATURE REVIEW

II.2.1. ECOLABELING PROGRAM

Traditionally, assessing environmental impacts begins with a detailed identification of pressures and system components, following by the identification and the classification of impacts according to their magnitude (Canteiro *et al*., 2018). Nowadays, ecolabelling schemes for tourist attractions are common among developed countries because they allow the development of sustainable tourism promotion strategies at local, national, and international levels. The objective of ecolabels is not only to maintain quality tourism but also to enhance the physical elements, encouraging the emergence of products and services compatible with sustainable environmental development in both the short- and the long-term (Morgan, 1999). On the other hand, ecolabels are good for the tourism industry, tourist companies, and tourists. Provision of beach quality awards attempts to achieve an optimal balance between recreation, tourism and conservation (Williams and Morgan, 1995). This corresponds to the aim of beach managers to provide a beach with recreational services without damaging a natural state of beaches (Williams and Micallef, 2009). One of the important aspects of an effective use of beach quality awards is a differentiation of beach types. All beaches cannot be managed in the same way, and quality criteria must correspond with natural characteristics of a particular area and level of development (Williams and Micallef, 2009). Otherwise, an attempt to standardize all beaches with respect to the level of services and facilities will lead to the higher development of rural areas and the degradation of natural and pristine sites. The trend to perceive beach spaces as a tourists and economic resource is the main reason behind the creation of standard mechanisms to certify their “environmental quality”. Some authors advocate a beach management based in the provision of services, facilities and infrastructure to meet out beach users’ demand on coastal environment by understanding the beach user’s satisfaction as a quality service (Yepes *et al*., 1999; Mir- Gual *et al*., 2015).

However, to overcome the impacts from tourism which was mainly the beach quality deterioration, the application of some management practices and strategies towards achieving "*coastal environmental quality*" was followed with certain environmental attributes. The concept of eco labeling began over 25 years ago. Font (2002) developed the first tourism eco- label termed as "beach certification" as blue flag campaign approached in 1985 and implemented in 1987. The blue flag is one of the most importance ecolabel programs in the world successfully hosted its flag across 45 countries in six continents. Europe, where 93% of the blue flag recognitions were found which includes Spain, France, Greece, Italy, Portugal, Denmark and the United Kingdom among which 62% of the total blue flag beaches located in European side of the Mediterranean Sea. Conversely, the Eastern and Southern Mediterranean beaches have 15% of blue flag beaches and Morocco have 0.5% of blue flag beaches. In African continent, South Africa with 66 blue flags covering 1.5% of the total blue flag beaches in the world. The other countries like Mexico, Canada and the Dominican Republic stands out with 1.25, 0.8% and 0.6% of the total, respectively (Merino *et al*., 2020). The blue flag certification is set of criteria to meet our series of rigorous environmental education and management, safety and security and water quality parameters. Once a beach receives a Blue Flag, it needs to continue to meet the imperative criteria for the entire beach season.

Most of the criteria are mainly focused towards the management of the natural resources, meanwhile, other criteria that compel municipalities to provide information of the actual situation of the beach act as a tool to improve the quality of management, as the actual situation becomes public and the adequacy of the local authority's management is exposed. Finally, some criteria refer to services available to beachgoers that are not linked directly to either the sustainability of the management of the area or the cleanliness of the water and the sand. According to Font (2002) Blue Flag has had an impact on the choice of destination, to the point of being considered as a sign of prestige, while on the other hand, the fact of not having it can also mean that the beach does not meet the standards. The information on blue flag criteria is shown in table 2.1.

III.2.2. BEACH QUALITY INDEX

The coastal tourism management is a set of actions in order to achieve certain tourism purposes in the coastal area by combining natural material and social resources. As the blue flag program temporality reward the beaches with the requirements aimed for clean beaches, however this blue flag certification lacks its own long way on beach management by avoiding whole some consideration on physical aspects on beaches. Though blue flag criteria focus on environmental management which mainly focused on clean environment through strict waste disposal and recycling system, sensitive area management under the control of local municipality or authorizing committee, sustainable means of transportation in the beach area and easy access, which obviously fail to address other impacts on environmental factors. Henceforth, it is essential to focus on all physical, biological and social environmental factors for obtaining "high quality beaches" (Leatherman, 1997; Mir- Gual *et al*., 2015). Therefore, the consideration on every unique environmental factor has become one of the important factors towards beach quality. On this aspects, Beach Quality Index (BQI) was used that evaluate the environmental and ecological status of a beach, also to evaluate the services and facilities that are provided to beach users' (Ariza er al., 2012). This BQI used a beach management tool along with evaluating the status of the beach with respect to several indicators proposed by Morgan (1999) and William and Micallef (2009). The indicators are aimed to achieve optimal physical usage and development of beach resources with respect to physical elements of a beach environment along with the social needs and satisfaction of the beach users' (William and Micallef, 2009). Therefore, BQI is an integrated tool which includes quality improvement of the beach recreational uses and protection of coastal environment and ecosystem.

III.2.3. ROLE OF BEACH USERS ON BEACH QUALITY ASSESSMENT

The beach quality studies are studied by considering some of the physical, social, environmental and social- related aspects. In the view of the social- related aspects, it is essential to consider the view of beach quality perceived by the users. An initial step to understand and acquire the understanding of public attributes and perceptions are considered as important factor for further studies (Vaz *et al*., 2009). Roig- Munar (2001) believes that more attention has been given to visitors than to the state and needs of coastal ecosystem, often due to lack of knowledge of the managed environment. Koutrakisa *et al*. (2001) define that the analysis of beach visitors is an important component in the definition of beach management policies, and the settings of administration priorities (Santos *et al*., 2005). The analysis of visitor perception is common to meet the need to better understand their behaviors and preferences on different aspects of the beach, as environmental quality, water quality, marine debris, and other issues such as the granting of the

Flag blue (Pereira *et al*., 2003; Shivlani *et al*., 2003). Also, the study of beach user perception endorses that social and ecological formation of the beaches which can be optimized through exploring the preference of their users' and their attributes towards the beach they visit, also the user's feedback regarding the policies which have been implemented (Breton *et al*., 1996; Magas *et al*., 2018).

The usage of social science research methods has contributed to bottom-up decision-making processes and to promote users as stakeholders during the planning process. With physical and biological parameters which was considered as main factors during assessment, the users'' perception can contribute towards a holistic understanding of the current situation for a data-based public management practice where integrated planning decisions have led to higher users'' satisfaction levels, higher quality coastal area and a more competitive and sustainable tourism destination. Thus, this approach can contribute to the sustainable development of beaches, increase the beach management effectiveness and promote higher satisfaction levels of beach users.

III.2.4. CERTIFICATION SCHEMES IN LATIN AMERICA

Globally, a large number of award schemes for providing quality standards for beaches. In Latin America, research on beach management has only received more attention in the last two decade (Barragan, 2001), with efforts concentrated on the generation of indices to assess the state of the beaches (Botero *et al*., 2015). In Latin America and the Caribbean (LAC), the Beach Certification Schemes (BCS) was a recent phenomenon. The general information on Beach Certification Schemes (BCS) in Latin America and Caribbean are presented in Table III.1.

In Mexico, the Beach Certification Schemes began with Clean Beach Programme, which focuses mainly on beach water quality. In 2003, the department of environment, health and tourism and Clean Beaches Committees were agreed to create a Mexican beach certification, later then by three years, the Secretariat of Environment and Natural Resources (SEMARNAT in Spanish) published the Mexican Standard Norms for clean beaches on the name of official gazette as "NMX- AA-120-SCFI-2006". Unlike, other countries, Mexico involves the national tourism authority for the beach certification. Once, the beach meets out the quality standards, upon receiving the request, SEMARNAT directs it to the Mexican Institute of Standardization and Certification (IMNC). After approving, a beach is hoisted with a flag valid for 2 years.

Table III.1. Beach certification schemes in Latin America and Caribbean

Country	Beach certification scheme	Creation/ latest version
Costa Rica, Panama	Bandera Azul Ecologica	1996/2011
Brasil, Puerto Rico, México, Dominican Republic	Blue Flag	2004/2014
Ecuador	INEN 2631:2012	2012
Argentina	IRAM 42100	2005
Peru	Premio Ecoplayas	2006/2008
Colombia	NTS-TS-001-2	2007/2011
Cuba	Playa Ambiental	2008
Uruguay	Playa Natural	2003/2008
México	NMX-AA-120-SCFI-2006	2006

The NMX-AA-120 Standard considers two types of beaches for certification: (a) Recreational, defined as those where leisure activities are performed; and (b) Beaches under Priority Conservation, being those located within the territorial limits of various types of protected areas. NMX-AA-120 standard has a first category of General Requirements, which include mapping and bathing water quality aspects. Once these are fulfilled, each type of beach has specific criteria, but categories are almost similar such as water resources, litter, coastal infrastructure, biodiversity, safety and security, and environmental education. In beaches with priority for conservation, further requirement is included relating to noise pollution. For the second half of 2012, 14 beaches were certified between the Pacific coast and the Caribbean, being the former where the majority (11) are located (Botero *et al*., 2015).

Brazil, Mexico and Colombia are leading the efforts to improve management of tourist beaches and are among the 11 countries participating in the Red Iberoamericana PROPLAYAS, which is composed of specialists focused on the design and implementation of methodological tools and practical applications for the integrated management of beaches (Botero *et al*., 2013, 2015). Since 2003, Mexico also hoisted the Blue Flag from FEE campaign by quality criteria from water quality, environmental education and management, safety and services. So far, Mexico has 66 blue flags by holding first for having high number of blue flag beaches in the American continent.

The beach certification schemes are works on indicators based on environment, amenities, security and safety, education and information, and management. The effectiveness of this beach certification schemes has highest level of compliance when analyzed by their indicators for the blue flag at 37% and NMX at 29%. In order to identify the strengths and weaknesses of each BCS, relative effectiveness should be measured with regard to different categories of indicators. The majority of BCSs were found to be the most effective in terms of biophysical and sociocultural indicators, with the exception of Blue Flag, which was most effective in terms of institutional indicators, rather than biophysical ones (Zielinski and Botero, 2015).

The eastern corridor of Quintana Roo has 19 blue flag beaches by meeting out quality standards proposed by FEE. However, due to prevailing natural and anthropogenic stressors prevailed on this coast, several environmental matrices have been altered thus affecting the quality standards. So, an integrated beach quality assessment for understanding the beach quality will be futile. Hence this study, helps to identify the status of the existing beach quality practices in coastal corridor of Quintana Roo by analyzing environmental indicators.

III.3. GENERAL OBJECTIVE

The main aim of this work to evaluate the quality of beaches from several beaches in the eastern corridor of Quintana Roo.

III.3.1. SPECIFIC OBJECTIVES

- Evaluate the beach quality among public, private, rural and blue flag certified beaches.
- Document the characteristics of physical, biological, social and contaminant indicators present in the beach.
- Identify the major disturbing environmental stressors affecting the beach quality.
- Advocate the perception of beach users for the preferences on the beach awards and beach quality.
- Elucidate the prospective ideology on improvising quality standards for beach qualities.

III.4. METHODOLOGY

III.4.1. FIELD SURVEY

The eastern coastal corridor of Quintana Roo has many wonderful beaches which was considered for beach quality studies. Nearly 56 beaches were considered for the survey which were grouped under the type of beaches such as private beach, public beach, rural beach and blue flag certified beach. A criterion of environmental beach quality assessment for these types of beaches was designed based on four environmental indicators (n=50), weighting score system, rating score system and assessment and classification system (Morgan,1999; Nelson *et al*., 2000; Micallef at al., 2004).

The beach survey was physically carried out for the analysis of this indicators and evaluated according to the rating score provided for each indicator. The indicators which are taken for consideration are described as follow as,

III.4.1.1 Physical factor

The physical factor describes the beach characters such as beach length, width, sand size (physical observation), landscape etc. according to Elmanana *et al* (2005). The physical indicator mainly evaluates the geomorphic features of the beach which includes color of the sand, predominant beach material with sand bed characters noticed in the beach. Overall, the physical indicators have ranging scores between 9-44 and the respective physical indicator score were marked in the evaluation sheet.

III.4.1.2. Social factor

The social factor mainly based on tourist's satisfaction which mainly concerns towards safety, accessibility and several tourist facilities availabilities (*n=22*). The tourist's facilities such as hotel, restaurant, information centers, car parking, water and safety equipment, warning alarm system and information signs were considered as social factor. The degree of quality was observed and evaluated with corresponding scores in the evaluation sheet ranging from 22-110 in total.

III.4.1.3. Pollution factor

The pollution was used to assess the beach quality by the observation of pollutants and their presence or absence of pollutants in the beach. The indicators are water color, clarity, presence of any floatable solids or litter in the water, presence of litter on the beach, noise from motor vehicle, water sports activities such as boat, jet-skiing, odors from engines, boat exhausts or any road vehicles. These above mentioned were evaluated with the score ranges of 13-42.

III.4.1.4. Biological factor

The biological factor focuses on tourists' health by the analysis of indicators through visual observation techniques and information from tourists. The presence of flora and fauna along the beach, any presence of endangered species and dangerous species like jelly fish or weever fish, presence of flies and cockroaches, presence of any breeding or nestling area, by then the overall scores ranges from 6- 20 with 6 indicators. These indicators are carefully evaluated and marked in the sheet for further analysis.

The beach users' perception on beach quality and beach awarding schemes were obtained by survey on selected beaches. The questionnaire was adopted from previous survey question for the determination of beach quality (Williams and Micallef, 2009). The questionnaire consists of demographic details, user's preferences on beach selection, since there is relationship exists between age and their environmental behavior as a tourist (Leonidou *et al.*, 2015). Also, the respondents were asked for the information on beach certification programs, later their preferences towards certified and non-certified beaches. The opinions on improvising quality standards were collected for further decision-making aspects. The design was based on the collection of data from self-administered hard copy questionnaires, including structured and unstructured questions. The model of beach quality evaluation (William and Micallef, 2009) presented as annexo 2.

III.4.2. DATA VALUATION

The above explained factors were analyzed by the beach quality index (Morgan, 1999) and the beach quality evaluation (Williams and Micallef, 2009) by observing the indicators and opinions from beach users. The obtained data were manipulated further for the complete understanding of beach qualities using following methods.

III.4.2.1. Beach Quality Index

In this study the criterion of environmental beach quality assessment was based on “physical” (9 indicators), “social” (22 indicators), “pollution” (13 indicators) and “biological” (6 indicators). The weighting score were calculated by weighing all factors according to the priorities where the highest priority was given to physical, and social, pollution and biological was lower, and mark was 4, 3, 2 and 1 mark, respectively. The scoring system of 50 indicators (rating score system) were given as annexo 1. The Beach Quality Index was calculated by marking the rating the above-mentioned indicators, totaled and assessed by Simple Weighting Score Equation by Morgan (1999) and classified into four class of A, B, C and D.

Based on the estimated beach scores obtained from physical (n=9), social (n= 22), pollution (n=13) and biological (n= 6) indicators, beach quality was calculated by some weighting score equation proposed by Morgan (1999). The formula of BQ is follows as,

$$\text{Beach Quality (BQ)} = W_p \Sigma R_{i\text{-}n} + W_s \Sigma R_{i\text{-}n} + W_{poi} \Sigma R_{i\text{-}n} + W_b \Sigma R_{i\text{-}n}$$

Where, W_p, W_s, W_{poi}, W_b are the weighting score of physical, social, pollution and biological factors which is 4,3,2 and 1 respectively. While, $R_{i\text{-}n}$ is the rating scale of indicator 1,2,3….n.

Using this formula, the obtain beach quality scores were classified for quality categories as given in table 4.2. Thus, Morgan (1999) proposes classification systems for beaches based on different aspects that are important users’, attending on sociological studies derived in each one of the beaches, Williams and Micallef, 2004, proposed a wider-scoped approach, which includes the user’s perception.

Table III.2. Classification of beach quality

Class	Score	Beach quality standard
A	491.0 – 610.0	Excellent beach quality
B	372.0 – 490.9	Very good beach quality
C	253.0 – 371.9	Fair beach quality
D	134.0 – 252.9	Poor beach quality

. The obtained data were manipulated using “Microsoft excel”. This survey results were classified as per factors contributing for beach qualities and related with users’ preferences for more beach certification in the study area. In order to obtain the conceptual scenes for upgrading quality standards, some of the parameters which was affecting the present quality of the study area were considered and surveyed with open ending questions.

III.5. RESULTS AND DISCUSSION

III.5.1. PROFILE OF BEACH USERS’

The results of the demographics obtained through the survey indicated the age of the respondent’s ranged minimum from 15 to maximum of 75. Among the respondents, the highest response was received from the age group of 26-35, followed by 36- 45, 15-25, and least responses were received from the age group of 46-55, 56-65 and 66-75 as presented in III.1. The demography of the users’, also involved the origin of the respondents, 88% respondents from various parts of Mexico, while 6% respondents from USA and Canada and 6% from other parts of the world. Since the survey were conducted during partial lockdown period of the pandemic time, the international tourists were limited, thus the relevance of survey local tourists has increased. Then, the frequency of their visit was taken into account by providing the following options as “Weekly”, “monthly”, “biannual” and “annual” as shown in figure III.2.

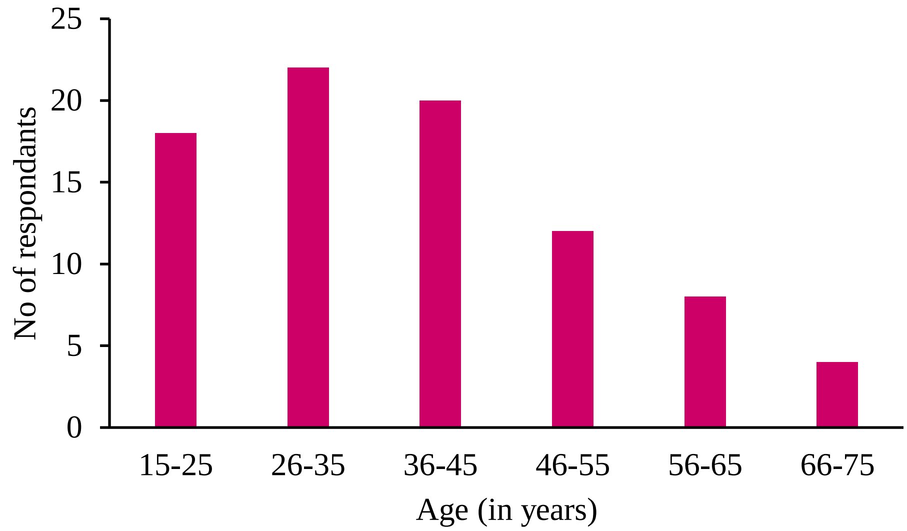

Figure III.1. Age group of the respondents

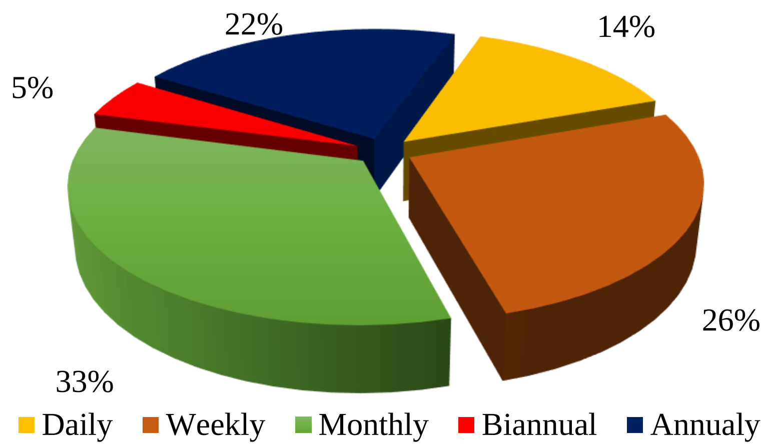

Figure III.2. Frequency of the beach visit by the users'

Since the survey was dominated by local tourist response, it shows a significant relationship towards the dominative response for the "monthly", "weekly" and "daily" visit frequency to the beach. About 33% of the respondents were visiting the beach monthly, 26% of the respondents were visiting the beach "weekly" and 14% of the respondents were visiting "daily". The daily visit clearly signifies the respondents visit to the beach for pursuing their eco-dependent activity in the beach, where the "monthly" and "weekly" shows the visit frequency from the local tourists. The “annual” visit of the respondents accounted for 22% and “biannual” visit of the respondents were 5%. The annual and biannual visit frequency were highly noticed among the international respondents. The overall responses were distributed among weekly, monthly and annual frequency of the visit to the beach.

The purpose of the beachgoers was recorded during the survey, which was provided by major four activities practiced in the beach. In case of any external options, that was recorded and added under “others” category. Most of the respondents were preferred for the visual observation of the scenery or landscape, which is nearly 57%. This clearly manifest, the importance of landscape in the coastal tourism (Jędrzejczak, 2004). Following, the respondents preferred to visit the beach for walking which holds up 21% and swimming for 18%. Only 4% of the respondents preferred the beach to practice sports activates. The visit purpose of the beach users was presented in figure III.3. The scenic beauty of the beach is the main factor which governs beachgoers visit and the walking is second general activity practiced in the beach (Pascoe, 2019), especially in the berm of the beach where the people spend most of the time during the stay. The moderate response for swimming and least practice of sports activity resembles the least or less use of water zone (Usher, 2021) when compared to sandy zone of the beach. However, the distribution of this response signifies the dual use of sand and water zone of the beach in the tourist aspects.

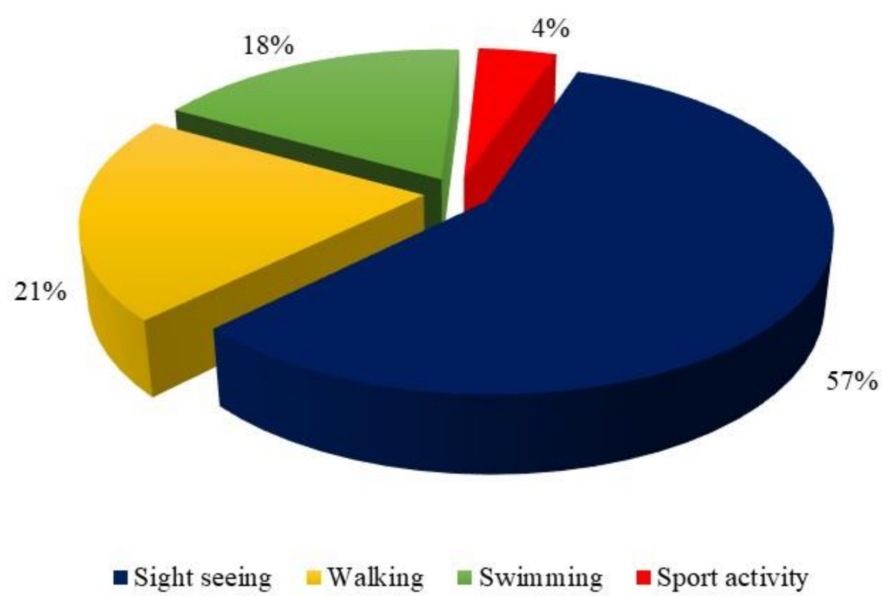

Figure III.3. Purpose of visit to the beach

III.5.2. BEACH USERS' OPINION ON BEACH SELECTIONS

The choice of selecting a beach varies on many factors. According to users' response, the landscape was outstanding aspect by occupying 23%, cleanliness and famous spot were the next leading aspects by same considerable level for 15%, the security and local connection were another aspect which have preferences for 11% among the users. The accommodation was the next factors which accounts for 8%, also this factor was noticed highly among the private beaches, where the users prefer to have quality accommodation than other preferences. Only 7% of the users selected litter free beach as first choice, which was quite unexpected, since 15% of the users preferred for a clean environment that seems slightly justified for the clean-up programs conducted by governmental and non-governmental organizations. The complementary choices like attraction and reputation have only 4% and 5% of the preferences. Finally, the blue flag unanticipated with 1% of the users' preferences. The beach users' preferences on choosing a beach are presented in figure III.4. The higher preferences on landscape (scenery) and cleanliness, moderate preferences towards the security and local connections give the impression on common reported factors by the different beach users from other part of the world (Vaz *et al*., 2009).

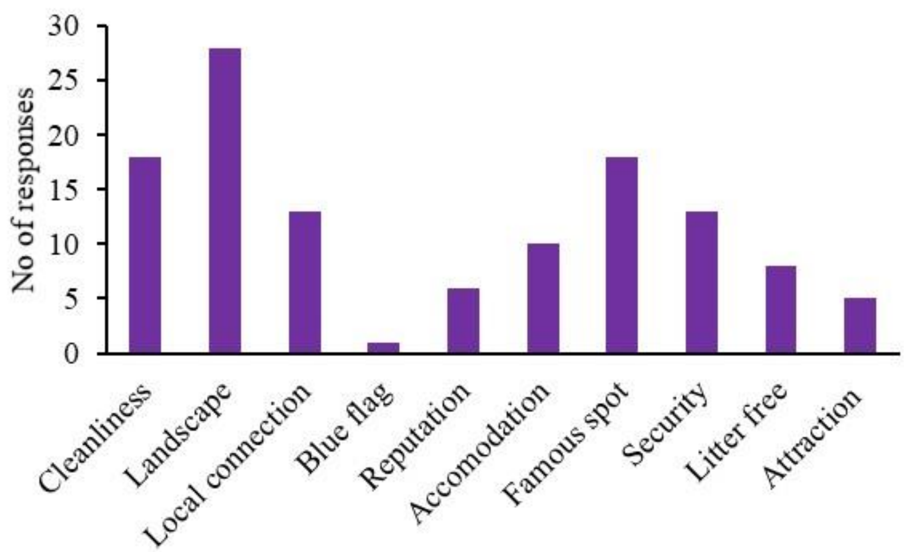

Figure III.4. Beach users' preferences on choosing a beach

As a part of the survey, the unpleasant factors affecting beach environment from the users' aspects were collected. Among the provided factors, the presence of algae or any floatable was the most unpleasant factor in the beach accounting for 28%. However, the coastal corridor of Quintana Roo was highly affected by the influx of sargassum, the beachgoers consider the sargassum as a major unpleasant factor since, the arrival affects the coastal landscape and other environmental impacts including smell. Thus, the algae being considered as most unpleasant factor which was influenced from the problem prevailed in the study area. The presence of litter was considered as second unpleasant factor by having 20% response. The smell, poor water quality and influence of visible waste water discharge noticed near the beach were considered as unpleasant factor accounts for 14%, 13% and 12% respectively. But these responses show a clear perspective of the beach users by expecting clean beach with no litter. The presence of excrements was considered as least unpleasant factors by 8% of the response and the option "others" involves the various factors such as bad or absence of installations, difficult access etc. which accounts for 5%. However, the presence or living of animals were considered as pleasant factor received from beach users, but their excrements make them uncomfortable (Jędrzejczak, 2004). The graphical presentation of the responses for the unpleasant factors in a beach according to beach users are presented in figure III.5.

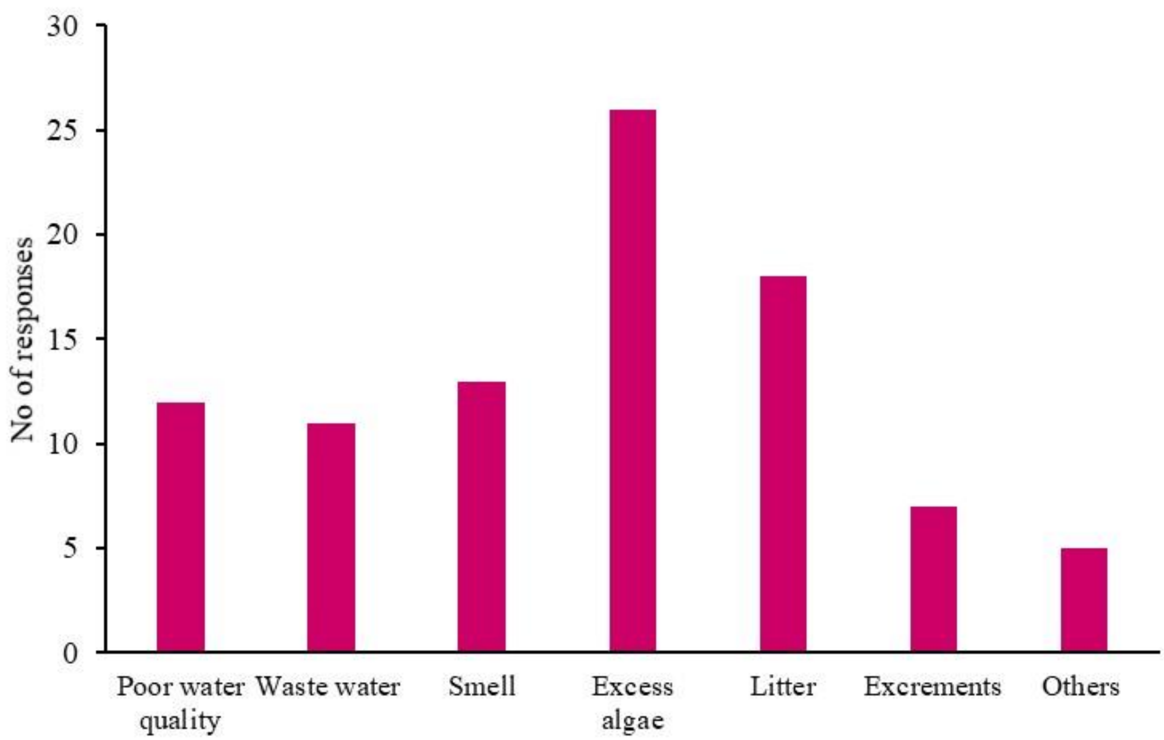

Figure III.5. Beach users' opinion about unpleasant factors in a beach

Though, the presence of algae considered as most unpleasant factors, the respondents considered this as a serious factor, since the coastal corridor of Quintana Roo is highly affected by sargassum which makes the beachgoers more uncomfortable. Then, the presence of litter was the second unpleasant factor which was observed as common factor affecting beach quality by destroying the scenic beauty of beach making it less unattractive. The beach litter was considered harmful to beach users by causing physical injury and other health issues. The perception of international tourists on beach litter revealed a direct negative relationship between beach litter with water and sand quality (Adam, 2021). Also, the presence of beach litter makes the beach users difficult to pursue any kind of recreational activities which was undertaken at the beach (Rayon-Viña *et al*., 2019). The presence of litter and excessive algae were evidenced in the study area which was recognized as most unpleasant factor in the beach as shown in figure III.6.

Figure III.6. Photographs showing (a) & (b)the presence of litter entrapped in the dried sargassum (c) the presence of fresh sargassum

III.5.3. EVALUATION OF BEACH QUALITY FROM BEACH USERS

To understand the quality of the beach, the surveyed beaches were evaluated depend on the factors selected by the respondents. The evaluation of the beach quality based on the beach management principles proposed by Williams and Micallef (2009). This study values the beach user's perception on beach qualities by estimating the presence of contaminant factors in the beach. Though, the presence of pollutants or contaminants varies according to the beach, the contaminants which surveyed here was based on the physical observation of the beach during the survey. Hence, the presence of contaminants was recorded from the respondents, which indicates the litter and excessive algae was considered as the main contaminants which is affecting the present beach quality.

The presence of litter and excessive algae was the highest contamination factor with responses accounts for 26% and 23% respectively. This clearly infers that the respondents clearly valued the beach by the physical presence of litter as anthropogenic factor and excessive sargassum from natural event. The sargassum has generated several post-impacts on the beach environment such as decomposition of sargassum with generation of mass organic material which affects the sand and seawater color, the continuous drying of sargassum in the beach generated unpleasant smell with an invasion of dangerous insects during drying process. The local municipalities and private organization also facing several problems during the disposal of dried sargassum.

The next contaminant was smell, where 20% of the respondents consider smell as major contaminant of the beach. The smell is another contaminant generated from the sargassum decomposition, which causes several health problems for the local community for their longer exposure. The next contaminant is the "waste water", though the study area lacks surface runoff through river channels, the waste water was considered as contaminant with the responses of 18%. This opinion clearly infers the awareness of the groundwater pollution persists in the study area. Since, the study area lacks surface runoff through river channels, the groundwater discharge is the main factor for the influx of several contaminants which affects the coastal ecosystem (Hernández-Terrones *et al.*, 2015). Also, the survey was conducted during the onset of hurricane "Marco", all the rainwater runoff were entered the beach by natural openings, this causing temporary discomfort for the beach user making the response "waste water" as major contaminant in the beach.

The least option on discolored water and spumes were accounts for 8% and 5% of the responses respectively. The "discolored water" indicates the presence of foreign material which affects the clarity of the seawater. The decomposition of the sargassum generates tiny organic particles, which changes the seawater color in the bathing zone. Thus, the discolored water is a prevailing problem in the study area imposing as major contaminant in the present beach quality. The least option was "spumes" which is natural and anthropogenic phenomenon. Though, the presence of spumes noticed only in particular beaches, where the inlet of lagoon was present. The overall survey reveals the presence of algae and litter was considered as major contaminant affecting the beach quality of the study area. The graphical presentation of the major contaminant affecting beach quality was shown in figure III.7. The photographs shown in figure 4.8 evidences the altered water color in the bathing zone.

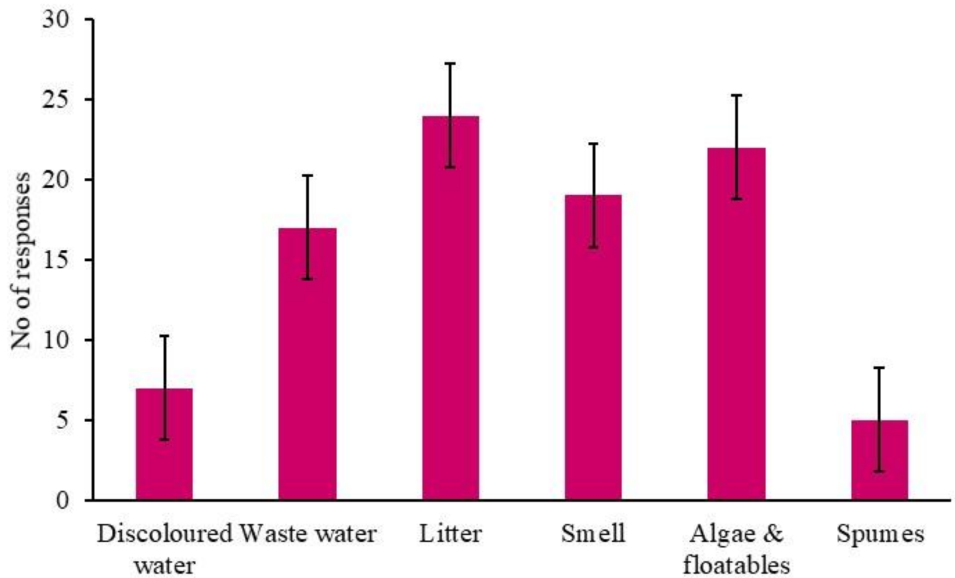

Figure III.7. Opinions from beach users for major contaminants affecting beach quality

Figure III.8. Photograph evidences the discolored & affected water after arrival of Sargassum

The overall evaluation of beach quality was conducted to perceive the beach user's consideration on beach quality elements. The factors such as water quality, landscape, presence of litter, safety and facilities were considered as beach quality elements with the scaling from excellent, good, fair and poor. Each beach area, depending on its characteristics, attracts different kinds of users with different interests, which condition their actions. There is certainly a need for some basic services on beaches, but the main demand is to consume space for sunbathing and relaxation. According to the National Healthy Beaches Campaign, beach users' focus is clean, safe, healthy beaches to play and relax on, but sometimes, unfortunately, visitors arrive at a beach to find it dirty, overcrowded, or severely eroded or to find the water polluted. Henceforth, consideration of these factors helped in estimating the users' choice about beach qualities and their preferred activities in the beach (Mkwara *et al*., 2015). This study shows an excellent beach quality by the following order,

Excellent: Landscape > Safety > Facilities > Litter > Water quality

Good: Facilities > Litter > Landscape = Safety > Water Quality

Fair: Water Quality > Litter > Safety = Facilities > Landscape

Poor: Safety > Facilities > Litter = Water quality > Landscape

The evaluation of the beach quality in these factors showed a varied results based on beach characteristics and users' preferences. The landscape was the only factor which was qualified as highest factor with excellent quality. This result infers the landscape is the most governing factor on the beach quality. Since, the study area is well known for its unique landscape for tortoise blue sea and white sand, the landscape was considered as major factor for visiting the beaches. Among, the surveyed beaches, the private beaches in Cancun and beaches in Puerto Morelos were grouped for excellent landscape and safety when compared to beaches in Playa del Carmen. The category "good" was received from most of the respondents for all the surveyed factors. The public and private beaches in Cancun, Playa del Carmen and Puerto Morelos were ranked for good quality for landscape, safety and litter factors. The fair category was noticed for water quality especially in Cancun, Playa del Carmen and Puerto Morelos beaches. The poor quality was identified for water quality, litter and landscape factors which was noticed for beaches in Cancun and Playa del Carmen. The graphical representation of beach quality from beach users' aspect are shown in figure III.9.

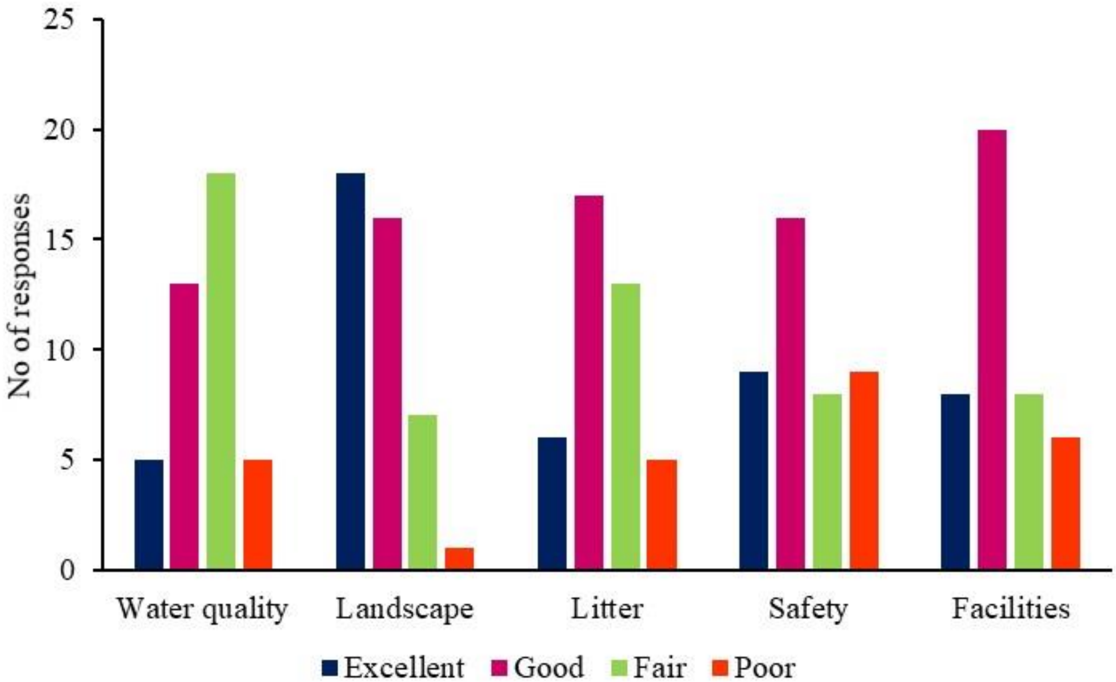

Figure III.9. Evaluation of beach quality from beach users' aspect

Hence, the beaches in Cancun, Playa del Carmen and Puerto Morelos shows a varied qualities based on factors considered for estimation. The poor water quality and presence of litter with degrading landscape was related with the influx of sargassum which affects the beach quality in general. The safety and facilities were at good and excellent quality in the private beaches which provides for the private beach users. The public beaches which lack the basic facilities and regular cleaning of sargasso has resulted the beach users to opinion towards poor beach quality. This study clearly infers the variations in beach quality among private and public beaches based on the services provided to the beach users and impact created from beach cleaning practices which was high among the private beaches.

III.5.4. BEACH QUALITY INDEX

This section of beach quality assessment by an index was considered based on physical, social, pollution and biological indicators proposed by Morgan (1999). The total number of beaches (*n=56*) were separated as public, private, rural and blue flag certified beaches and each of the indicators were evaluated on each kind of beaches. The evaluated individual beach indicator is presented in the figure 4.10. The analysis of physical indicator reveals the presence of beach berm with good sand grain size with the absence of any rocky shore. The blue flag certified beaches yield overall score for 70% followed by public and private beaches, but the rural beach have poor physical condition with the lack of maintenance. The landscape and scenic beauty contribute for more among the various types of beaches. The figure III.10 (a) presents the scores of physical indicator evaluation. Though, the blue flag beaches show importance towards beach features, a small group of beachgoers gave the least importance to the non- blue flag beaches which gives a non-influential view on beach features (Lucrezi & Saayman, 2014).

The social indicator which focuses on tourist's satisfaction on safety, accessibility and facilities in the beach. Among the surveyed beaches, the blue flag certified showed a higher score towards social indicator (figure III.10 b), since blue flag beaches provided more environmental services as the part of their regulations. The private beaches provide the same tourists facilities with a pay of cost thus gaining next leading score after blue flag beaches. The public and rural beaches score the least, since the absence or less availability of the facilities. Another finding obtained from beach user survey reveals that the blue flag beaches have more attraction than the non-blue flag beaches because of the facilities provided for the beach users satisfaction (Dodds & Holmes,2020). The rural beaches lack complete facilities for beach users, provoking a straight need for development of the rural beaches with basic beach facilities with environmental management strategies (Klein & Dodds, 2017).

The biological indicator has focus on tourists' health and the obtained scores for the biological indicator are presented in figure III.10 (c). The result indicates the rural beaches have more significant scores for biological indicators, since the tourists' activities in blue flag, private and public beaches has worsened the presence of fauna in the beach area. Though the private and blue flag beaches hoist the breeding area of an animal under environmental management policies, the accommodation of some of the animals were high in rural than other beaches due to human occupation and usage of beach area.

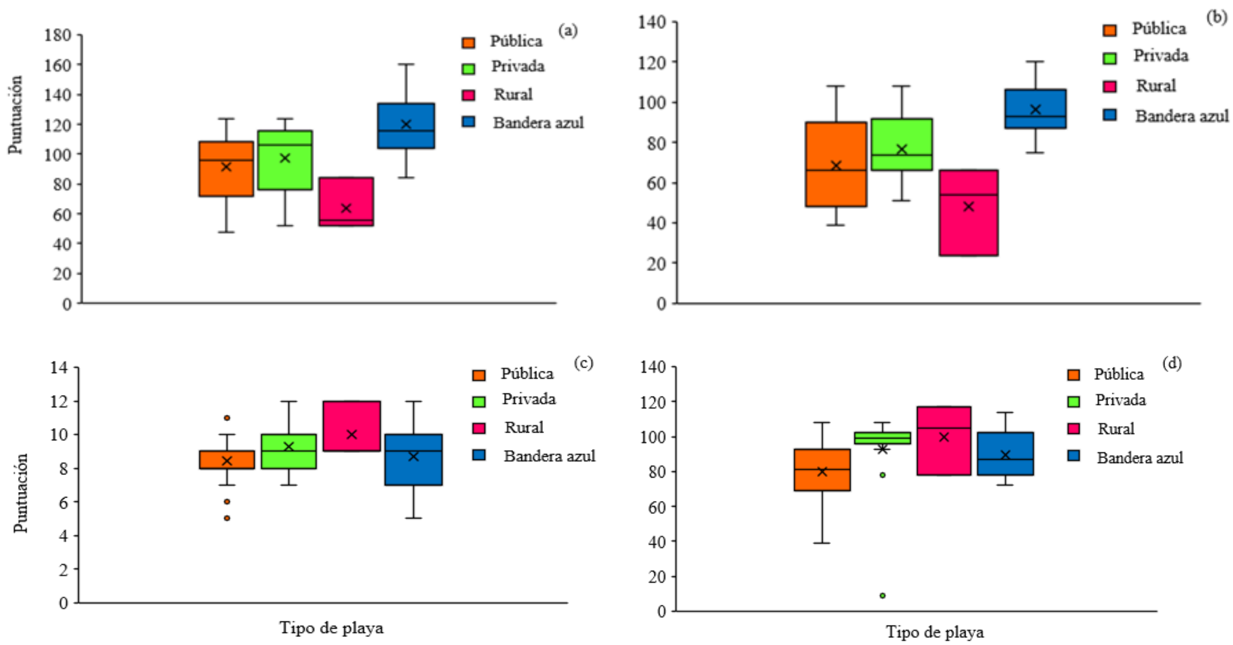

Figure III.10. Evaluation of physical (a), social (b), biological (c) and pollution (d) indicators for different beach type

The pollution indicator mainly impresses towards the beach qualities through the presence or absence of certain pollutants. The scores of pollution indicators are presented in figure III.10 (d). There was a significant similarity was noticed between blue flag beaches, private and rural beach with high scores and public beaches with least scores. This was a surprising result which ensures the bathing water quality in blue flag beaches which is left uninvestigated in the public and rural beaches. The litter clean-up activities in blue flag and private beaches show a significant weightage for the beach quality, as the beach users prefers clean and litter free beach (Dodds & Holmes, 2018). This key finding indicates the individual analysis of the indicators have more quality for blue flag and private beaches, followed by public and rural beaches. The present practices of blue flag programs show a significant result with the standard beach quality.

Table III.3. Information of beach qualities for different types of beaches

Beach type	Name of the beach	Beach quality
Public	Cancún – Playa Azul, Playa Blanca Playa del Carmen – C 22, C 25 Tulum - C 33 Cozumel Island - C 43, C 44, C 52, C 53, C 54, C 55, C 56 *(nameless)*	Poor
	Cancún - C 1, C 5, C 8, Ultramar terminal Playa del Carmen – C 18, C 19, C 21, C 23*(nameless)* Tulum – C 32 *(nameless)* Cozumel Island – C 57 *(nameless)*	Fair
Private	Playa del Carmen – Moon Palace Tulum –, Akumal Cozumel Island- Fiesta Inn	Poor
	Cancún – Isla Blanca Playa del Carmen - Bahía Solimán, Tankah Tres Bay, Playa Cobe, C 28, Punta Esperalda, Punta Xcalco Tulum – Riviera Dreams, Playa Xpu Ha Cozumel Island – Playa Paradise, Restaurant Alberto, Playa Palancar, Playa Chen Rio	Fair
Rural	Arrefice Pamul, Punto Venado, Punta Sur	Poor
Blue flag	Cancún - Playa las Perlas, Marina Chao, Playa Tortuga, Playa Langostas, Playa Caracol, Playa del Carmen - Playa Chac-mol, Playa Marlín, Playa Ballenas, Playa Delfines, Playa Mirador, Playa 88, Playa Esmeralda, Puerto Morelos	Fair

The assessment of beach quality index endorses the results that overall quality of the beaches was low. Based on the type of beaches. the blue flag certified beaches, private and some of the public beaches have fair quality, while rural and few of private and public beaches are poor quality. This study astonishingly found that none of the surveyed beaches has excellent and good beach quality. The information of beaches is provided in table III.3. The total score obtained from each indicator were used to calculate the beach quality which presented in figure III.11

Among the beach surveyed, the blue flag certified have fair beach quality for all beach present in Cancun and Playa del Carmen. This clearly endorses the components of blue flag beaches which contains bathing water quality, environmental education and management, safety and facilities,

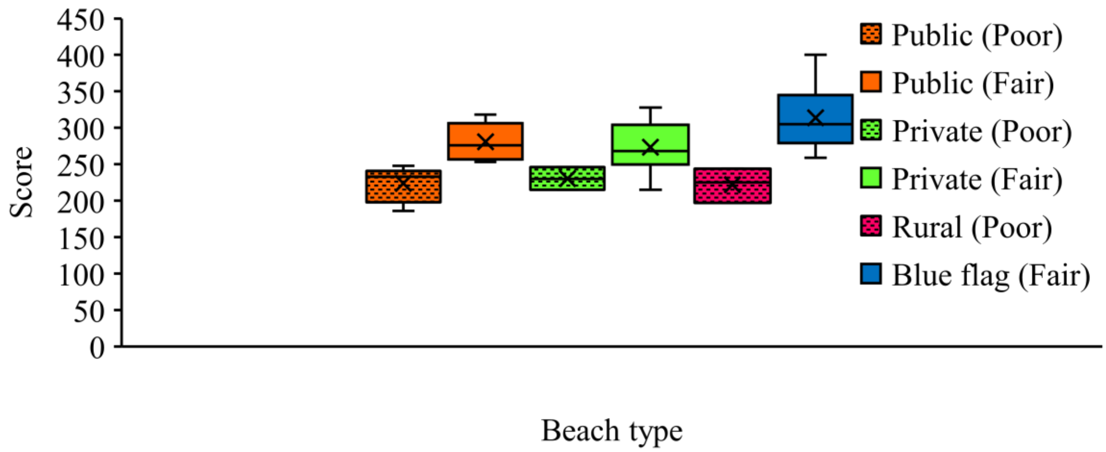

Figure III.11. Beach Quality Index (BQI) for different types of beaches

which in turns leads to positive perceptions on quality standards within the program. A study about perceived benefit of Blue Flag identified that there is an improvement in environmental quality when the minimum standard at a beach needs to be met and results in improvement (Pencarelli *et al.*, 2016). If the blue flag beaches already met the imperative requirements has impact on environment towards protection and management (Klein & Dodds, 2017). Some of the blue flag practices for water quality and environmental management and services are given in figure III.12. Other than blue flag beaches, some of the private and public beaches showed fair beach quality from Cancun, Playa del Carmen, Tulum and Cozumel Island.

Unlike, blue flag beaches, these beaches lack standard protocols for quality, but the private beaches have regular beach cleaning practices, several services and facilities provided for beach users. On the other hand, the public beaches with fair beach quality resulted from the influences of local municipalities and government. The zonal municipalities and non-governmental authorities practice sustainable management by removing sargassum and other litter clean up in the beach. The lack of social facilities and services were considered as major debasing factors for achieving fair or good beach quality. The rural beaches despite their remote access and subtle beach users, there is lack of several quality elements which remains unidentified for the quality improvement.

Thus, the key finding of beach quality analysis remarks the private and blue flag certified beaches in Cancun, Playa del Carmen and Cozumel have many practices and standards for environmental importance thus imposing a positive result on beach quality. However, the public and rural in Playa del Carmen, some remote beaches in Tulum and Cozumel Island have low maintenance and lack of several socio- environmental facilities have poor beach quality, which needs more application of environmental standard for improving beach quality. It is evidential that the implications of beach awards contribute a significant result on beach environmental quality (Semeoshenkova & Newton., 2015). Nevertheless, this study determined that the majority of private sector consider the Blue Flag program as a communication, funding or educational tool for attracting more tourists rather than a tool for effective environmental protection. Thus, this vision on blue flag programs concerns a serious approach towards environmental protection and management promoting beach qualities. The facilities and information provided from a blue flag beach are presented in figure III.12.

Figure III.12. General information and facility provided by a blue flag beach

III.5.5. EFFECTIVENESS OF BEACH CERTIFICATION SCHEMES IN CARIBBEAN REGION

The beach quality assessment in the coastal corridor of Quintana Roo reveals that most of the beach were clarified for fair beach quality, among which blue flag and private beaches were noticed high than other types of beaches. Thus, to understand the effectiveness of the blue flag program in the Quintana Roo, the beach users were surveyed for blue flag aspects. The question about the existence of blue flag gives an explicit response for “Yes” by 36% and “No” by 64%. It is astonishing that majority of the beach users are not aware of the blue flag program, only a least people among the beach users were well aware of the blue flag program. The graphical presentation about the existence of blue flag concepts among the beach users in figure III.13. A similar study about the beach visitors’ responses to ecolabels and their perceptions of the environmental value of these values showed a very low knowledge among the beach users (Fairweather *et al.*, 2005; Merina & Prats., 2020). However, a study conducted in Canada which informed that 85% of the visitors preferred blue flag beaches than non-blue flag beaches only for the quality services and facilities (Dodds & Holmes, 2020) imposing the importance of quality criteria for the blue flag program.

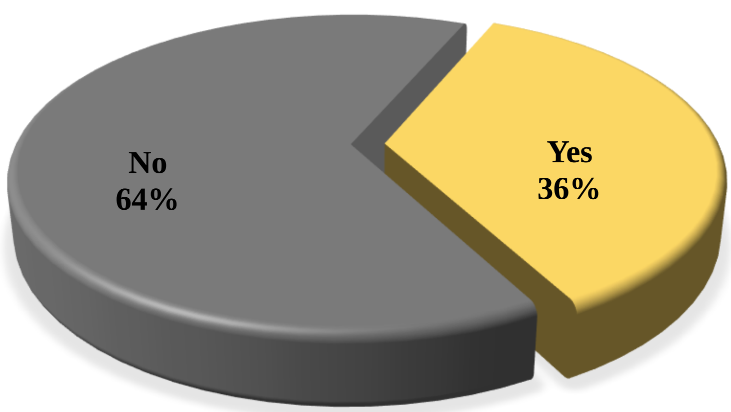

Figure III.13. Beach users’ consideration on existence of blue flag concepts

As, the majority of the beach users were not aware of the blue flag program, a brief explanation on blue flag program was done among the respondents who were not aware of blue flag program.

After the explanation, further questions on beach users' satisfaction towards blue flag criteria were conducted. The results were biased, despite the lack of knowledge on the blue flag, majority of the respondents were satisfied with the present quality criteria which accounts for 67%, while only 33% of the respondents were not satisfied with the present quality criteria, intriguing for more development on the program. This clearly infers the increasing beach tourism and simultaneous pressures and human impacts thus, imposing a need for more beach management programs in Quintana Roo. The graphical representation of beach users' satisfaction on blue flag quality criteria are presented in figure III.14.

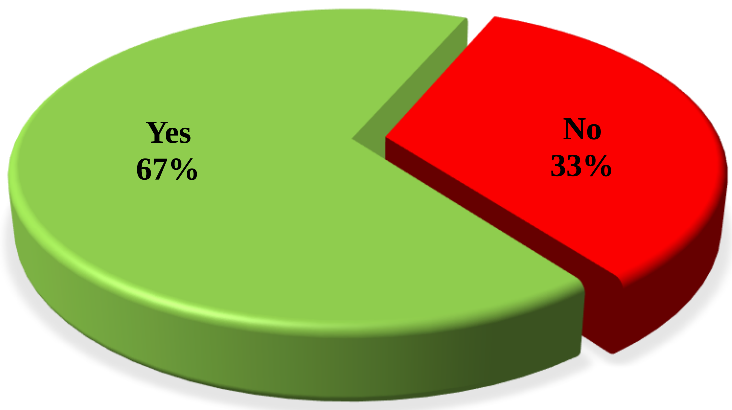

Figure III.14. Beach users' satisfaction on present blue flag criteria

Secondly, the reason for choosing a blue flag beach among non- blue flag beaches were observed. The majority of the respondents preferred water quality for choosing blue flag beaches. This clearly infers the need for water quality also future consideration for improving water quality apart from bathing water quality. A recent study about beach users' experiences in blue flag beaches showed a signification relationship between water quality and facilities were found. This study also found the beach users were satisfied with water cleanliness, water clarity and non-satisfaction towards algae presence than the non-blue flag beaches (Dodds & Holmes., 2020). Overall, the satisfaction of beach users showed that blue flag beach goers showed over importance for water quality, this study also supports this finding by having high responses for water quality for choosing blue flag beaches. The general presentation on reasons for choosing blue flag beaches are presented in figure III. 15.

The next leading reasons for choosing blue flag beaches were cleanliness. Since, blue flag beaches have cleanliness as their imperative criteria for certification, most of the blue flag beaches achieves 100% cleanliness of the beach by conducting regular beach cleaning programs. The beach was identified for macro and micro litter such as plastics, cigarette butts by grid methods, later the quality about of the beach was announced in the information board by using “macro litter index”. By this methods and practices, the cleanliness was achieved to maximum in the certified beaches, however, the new emerging marine pollution of microplastics, left unconsidered for intense beach quality especially on sandy area of the beach. Finally, the facilities were considered least option for choosing blue flag beaches. Among the facilities provided, the presence of washrooms or change rooms, designated swimming area and presence of garbage containers in the beach area were considered as most needed facilities among the beach users (Dodds & Klein., 2020). The access for persons with disability and dog-friendly user area and environmental – educational signages were considered as least required facilities among the beach users. Henceforth, the availability of facilities gained more attention among the blue flag beaches than non-blue flag beaches. In total, the water quality, cleanliness and facilities were the reasons for choosing beach quality, but improving these criteria were strongly suggested for more beach quality, despite increasing beach pressures from tourism.

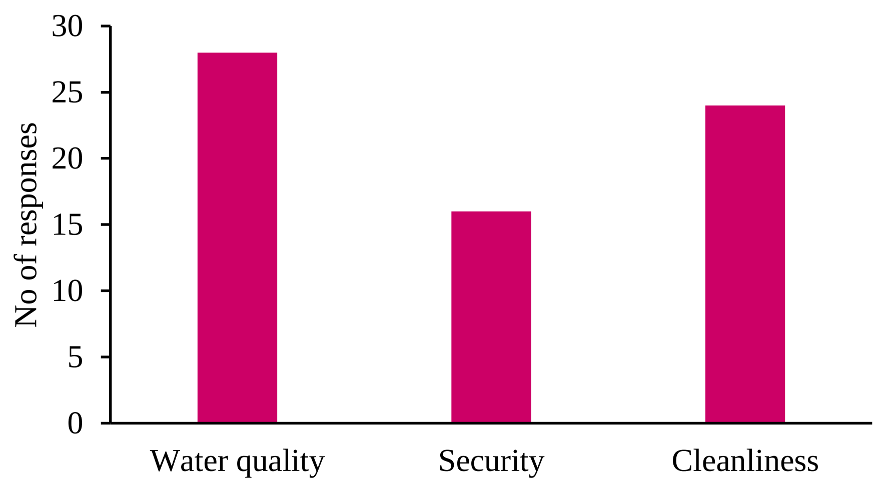

Figure III.15. Reasons for choosing blue flag beaches

III.5.6. FUTURISTICS PERCEPTION ON BEACH QUALITY BY BEACH USERS'

This study investigated the beach qualities and also the effectiveness of beach awards and their contribution towards beach quality. Overall, studies provided a underlining information that the awarded beaches have fair beach qualities, also the private beaches achieved fair beach quality. The worrisome pictures of rural and some of the public beaches need an immediate managing system for accomplishing standardized beach quality. The rating system used in this study using indicators have a disadvantage, since it would be possible for a beach to be totally deficient in a single important element (e.g., have badly polluted bathing water or be substantially contaminated with oil) and still record a high to moderate overall rating score. An important aspect of future beach rating studies of this type should be a requirement that beaches should meet minimum standards for a range of the most important beach aspects (as required by some existing beach awards), in order to achieve a particular overall rating level (Morgan, 1999). Since, there are still lack of clarity which lead to different opinions about blue flag which is acknowledged only for attracting more tourists by provided several user-friendly facilities for the beach users, but conservation and beach management remains contradictory (Klein & Dodds, 2017). The findings in this study advocate that the beach users are favorable for certification programs. Also, it is clear that beach users prefer blue flag beaches for the quality standards such as water quality and cleanliness, thus compelling more quality criteria towards high excellence of quality. However, the private beaches with blue flag charge the beach user in order to use the facilities, only the public beaches with blue flag provide it for free to cost. The study on beach users' opinion for paying on beach facilities found that beach users feel they should not have to pay for beach access and facilities (Oh *et al*., 2010).

By understanding the present view on beach quality and certification, a survey conducted among the beach users to perceive the opinion about more quality standards showed strong results which is presented in figure III.16. Among the parameters survived, the beach users opinioned to have information about nutrients and trace metals about 29% of the responses. Since, nutrients are the principal factor governing the coastal ecosystem (Zhang *et al*., 2020) through coastal eutrophication. In addition to the groundwater input of nutrients due to carbonate terrain of Quintana Roo, the massive influx of sargassum have also contributing the nutrient content (Van Tussenbroek *et al*., 2017).

The presence of the toxic metals also affects the coastal water quality by posing toxicity for the organisms and affects human health (Martinez – Soto *et al*., 2016). Thus, by having a basic information on nutrients and toxic metals, it will be preferred by the beach users to have a clear idea about the coastal ecosystem. Though, the bathing water quality doesn’t characterize by nutrient and metal concentration, the study of these factors helps to understand the quality of the coastal ecosystem. The next factor which was preferred by beach users was sediment quality by 22%. However, the blue flag standards have macro litter index for the sediment quality, the study of other pollutants in sediments left uninvestigated. There are several sediment quality guidelines proposed for assessment of trace metals in sediments (Li *et al*., 2014). Using this sediment quality guidelines, the future study of metals in sediments helps to a framework information on beach environmental matrices. Also, the microplastics, a Holocene marine pollutant has grabbed beach users’ attention on a large scale. Nearly, 16% of the respondents preferred to have information on microplastics quantity apart from macro-litter index.

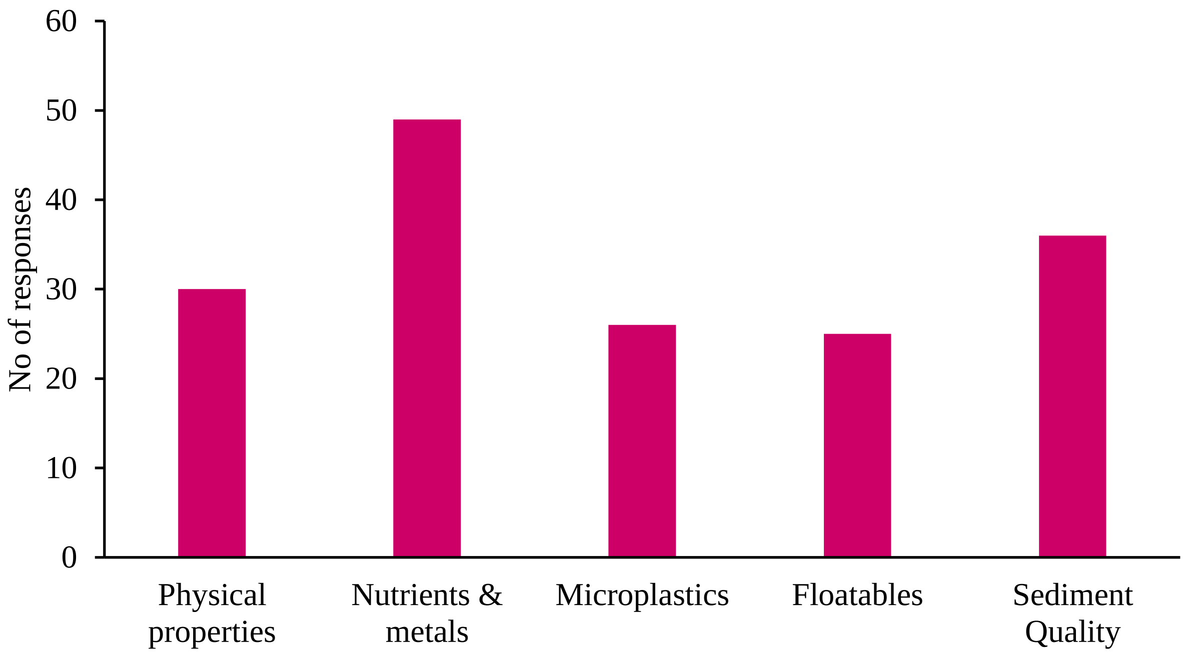

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Figure III.16. Beach users’ opinions for additional quality criteria for blue flag certification

The greater responses were received for physical parameters of the water accounting for 18% of the responses. Since most of the beach users prefers to have good water quality, the information about bacteriological parameters were displayed at information signage. Since the determination of basic physical parameters such as pH, temperature, Total Dissolved Solids (TDS) are feasible to measure, thus these parameters were considered as most important criteria for more quality standards. Finally, the parameter “floatable” has responses around 15% from the respondents. Since, the floatable results majorly from boats, other sports activities like jet skiing, sailing, yatching and a basic information about floatable which is oils or other phenolic compounds, helps to have information on water quality to the maximum. In line with this perspective, the obtained opinions from the beach users need a holistic approach which have received in order to address several coastal environmental issues and improvising the quality standards for the beach certification programs. Though, the feasibility for analyzing several factors remain difficult and limitations in background research. So, the involvement of government authorities is highly encouraged for promoting future lines investigations by the seasonal analysis of these parameters to yield an upgrading beach quality with the supply of additional quality standards to respond the degrading beach ecosystems.

CONCLUSION

The present work on assessment of beach quality and its environmental status on the Caribbean coast of Quintana Roo was an initial contribution which has obtained the novel outcomes. The framework of this research involves the analysis of several coastal environmental indicators and the assessment of their quality which was considered as a holistic approach for the landscape management. The following were the outcomes obtained during this study.

The coastal zone and vulnerability are main factors which affects the coastal landscape under longer duration, but the Caribbean coast were no exceptional to these morphological changes. The analysis of land use / land cover in the Caribbean coast revealed a drastic change from 1990 until 2020. The detailed study of the land cover and land use manifests the complete changes in Cancun, Playa del Carmen, Tulum and Cozumel Island. The overall changes inflict the pre-exists land cove which has changed into built up land for the development of tourism and urban development dated from recent 50 years in the Caribbean coast. Among, the study zone Cancun and Playa del Carmen has changed into complete built- up land than Tulum and Cozumel Island. This clearly intensify the complete change in coastal landscape which has undergone several anthropogenic pressures. In addition to this, the Tourists Urbanization Index (I_{TU}) and Beach Alteration Index (I_{BA}) showed a spectacular change for every 10 decadal period. The urbanization index were in increasing trend since 1990, which resulted due to increasing urban demands. In the morphological aspects, the Beach Alteration Index showed that the coast has faced severe changes during 1990-2000 due to natural and anthropogenic causes. However, it is clear that the landscape has been modified and undergone changes since recent decades, which was expected to have phenomenal alterations in the upcoming years.

The water quality being an important quality indicator was assessed by using water quality parameters. The spatial and temporal variation of pH and temperature infers the up changing the physical conditions of the Caribbean coast. The Dissolved Inorganic Nutrients (DIN), Dissolved Inorganic Silicate (DSi) and Dissolved Inorganic Phosphate (DIP) were high for Puerto Morelos and Playa del Carmen, low for Cancun. The general analysis of inorganic nutrients and Chlorophyll, BOD, TSS and POM infers the intense remineralization of organic matter which was majorly resulted from the influx of sargasso and their relative decomposition and submarine groundwater discharge in some sites of the study area. Later, with adaptable condition near the coastal zone, the nitrification process controls the nutrient cycles and biogeochemistry of the water. The trophic status assessment shows that trophic status of Mesotrophic in Cancun and Puerto Morelos and Eutrophic in Playa del Carmen, despite being an oligotrophic zone. The trophic status has a direct relationship with the presence of biomass load and the dynamic nutrient cycle. The quality of water calculated using the procured results shows the majority of the water quality were very good – good, but some sites with very bad – bad water quality shows an external influence of organic and nutrient loss which affects the quality of the water. The bacteriological parameters as an additional quality indicator reveals that all over the coastal zone have good water quality as per bathing directive.

The dissolved trave metal (Fe, Mn, Cr, Cu, Ni, Co, Pb, Zn, Cd, Sr, V, As) analysis and their geochemical behavior are ascribed through the local geological formation and later transition in the saline-mixing zone. Fe and Mn were resulted from oxidation of organic matter and their reductions in low oxygen level. The Co and Ni are released in dissolved phase in the sediment-water interface. Cu, Ni and Pb are resulted from the high use of ferry services and urban development of coastal zones. The statistical analysis indicates their inter-elemental relationship which act in the presence transiting physical conditions. The higher disponible of Pb and correlation with other elements indicates the biological uptake in the dissolved phase. The non-conservative behavior of Co, Cu, Ni and Pb were also well noticed. The spatial and temporal variation infers the anthropogenic pressures during pre-lock down and post lock down period. The variation in use of coastal zone during pandemic and their respective impacts on the coasts were clearly seen. However, despite the higher concentration of Ni and Pb, the Caribbean coast is not contaminated with reference to the beach water standards. Henceforth, using severe quality indicator, the costal water of Caribbean region has good water quality, but due to persisting natural and anthropogenic stress, the change in trophic status and influx of nutrients imposing a predictable impact in the coastal ecosystem.

Finally, the assessment of Caribbean beach quality using environmental indicators includes physical, pollution, biological and social indicators using rating scales for beach quality. Since, the Caribbean coast have private, public, blue flag awarded and rural beaches, the individual quality indicator analysis exhibit an astonishing result that only private, blue flag awarded and some of the public beaches have fair quality and rest of the beaches with poor beach quality. The environmental standards policies followed by most of the private and blue flag beaches aids to fair beach quality when compared to public and rural beaches. In addition, the efficiency of blue flag awarded beaches also establish positive results in beach quality owing to quality standards. The social perspective on beach quality and blue flag awareness were low. However, the tourist's perspective towards quality criteria satisfaction revealed a need for development of quality parameters which includes basic properties of water, information displays about nutrients and toxic metals. The presence of sargassum was one of the major factors which degrade the quality of the beaches at present from the user's perspective. It was clear that most of the beach users prefer the Caribbean beaches for landscapes, cleanliness and reputation. But it was clear that the current beach quality was highly degraded by the sargassum influx which was evident through aforementioned results. Nevertheless, the beach quality evaluation from the beach user's aspect reveals that the beach qualities were good and excellent for landscape (private beaches) and facilities, while poor quality for beach waters which was mainly affected several external factors prevailed in the study area.

The Caribbean coast in Mexico hosts beautiful beaches recognized as world famous destination, was studied for quality assessment using multi-elemental approach. This novel study on beach quality assessment aims to accomplish the beach landscape management using geo-environmental indicators. It is evident that the present beach quality was highly affected by several natural and anthropogenic stress which makes a worrisome scenario in future, besides, the increasing demand and use of beaches. Henceforth, it became essential deed to frame an improvised quality standards and management practices to achieve the beach quality in the Caribbean coast.

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ANEXOS