UNIVERSITI PUTRA MALAYSIA

DEVELOPMENT OF MAPPING METHODS FOR SEAGRASS MEADOWS IN MALAYSIA BY USING LANDSAT IMAGES

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FSPM 2015 12

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MOHAMMAD SHAWKAT HOSSAIN

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

October 2015

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DEDICATION

To my wife, whose image needs no enhancement

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the degree of Doctor of Philosophy

DEVELOPMENT OF MAPPING METHODS FOR SEAGRASS MEADOWS IN MALAYSIA BY USING LANDSAT IMAGES

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October 2015

Chair : Japar Sidik Bujang, PhD
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In Malaysia, seagrasses commonly inhabit shallow intertidal waters, lagoons, mangrove, coral reef and shoal in subtidal zones. The seagrass meadows that previously inhabited the coasts of Peninsular Malaysia (West Malaysia) and Sabah (East Malaysia) were extensive and now have become sparse or scattered due to natural and anthropogenic disturbances. Scientists and managers require a fast and low-cost approach to map and assess the habitat loss or potential damage to the seagrass resources. A critical review of 195 studies revealed that, in the past four decades, advances in the application of remote sensing (RS) methods, notably using Landsat imagery, were identified for seagrass habitat mapping. Mapping capabilities of Landsat were not tested in different tidal regimes, characterizing seagrass habitats in relation to water turbidity and depth regimes, and understand spatiotemporal dynamics from multi-date images due to lack of appropriate methods and data, including unresolved Scan Line Corrector (SLC)-off data gaps in Landsat 7 Enhanced Thematic Mapper (ETM)+ images.

The specific objectives of this study were to: (1) characterize the research on seagrass RS methods through a review of the peer-reviewed literature, (2) assess the performance of Landsat 7 ETM+ SLC-off gap-filling methods and image enhancement techniques (ETs) with different water depths for methodological improvement in seagrass resource mapping and monitoring, and (3) apply mapping approach on seagrass habitat, water turbidity and relative water depth mapping and monitoring.

A statistical assessment and an evaluation of the twelve SLC-off and four SLC-on images covering seagrass meadows of Sungai Pulai estuary, Johor, Malaysia were conducted for data loss estimates. This analysis revealed a 2% systematic error attributable to a gradual increase of SLC-off stripes from the central nadir path towards the edge of the scene. The random shifting of SLC-off stripes caused a 11.07 ha Tanjung AdangLaut shoal (TALS) completely invisible. The next study was focused on assessment of the geometric and radiometric fidelity of images reconstructed by three potential gap-filling methods: (1) Geostatistical Neighbourhood Similar Pixel Interpolator (GNSPI),

(2) Weighted linear regression algorithm integrated with Laplacian prior regularization, and (3) Local Linear Histogram Matching methods. The statistical measures of reconstructed images were in favor of the use of GNSPI as opposed to other gap-filling techniques for Sungai Pulai estuary seagrass distribution mapping.

To assess the variation in performance of Landsat image enhancement for Sungai Pulai estuary seagrass maps, with different Mean sea-level tide heights (MSLTHs), a comparison was conducted between histogram equalization (HE) and manual enhancement (ME) based mapping approaches. The enhancement techniques were applied on true-color composites (red, green, and blue layer stacks) of thirty-three Landsat images (1989-2014) with MSLTHs between -0.281 and 0.234 m. The assessment found that ME substantially improved image quality compared to the HE with MSLTH thresholds between -0.218 m and -0.085 m. ME improved visual interpretation of Landsat images for seagrass detection and distribution mapping of Merambong shoal (MS), Tanjung Adang Darat shoal (TADS), TALS, and Seluyong mudflat (SMF).

An integrated mapping approach, combining Landsat ME and seed pixel regional growing tool was examined to delineate seagrass boundary accurately. This approach was found suitable (with >75% overall accuracy) to map five classes-of-interest, i.e., seagrass, land, sand/mud, human settlement, coral and coral rubble for twelve islands of Coral Triangle Initiative (CTI), Sabah. The resulted map estimated seagrass areal coverage to be 274 ha, of which most seagrass meadows occurred in relatively shallow water areas covering about 158 ha. Issues of spatiotemporal changes in seagrass habitat were addressed through assessing the ability of the integrated mapping approach on multi-date Landsat images for mapping and monitoring seagrass resources of Punang-Sari estuary, Lawas, Sarawak, Pengkalan Nangka lagoon, Kelantan, and Paka lagoon, Terengganu of Malaysia. Applying this integrated approach on forty-nine Landsat 5, 7 and 8 images, produced an accurate multi-date seagrass habitat maps. Additionally, the results indicated that a noticeable loss of seagrass habitats at varying magnitude occurred between 2000 and 2014 for Punang-Sari, between 1998 and 2014 for Pengkalan Nangka, and between 1988 and 2014 for Paka. The natural event mainly sand shifting was the main cause of seagrass loss for Punang-Sari Lawas. Coastline change was identified as the most significant factor that caused seagrass spatial cover loss of the Pengkalan Nangka lagoon.

The mapping approach and the map products produced in this study will provide a useful tool for detection, distribution mapping and monitoring changes of seagrass and associated resources for coastal management and conservation programs.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia
sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

PEMBANGUNAN KAEDAH PEMETAAN UNTUK PADANG RUMPUT LAUT DI MALAYSIA DENGAN MENGGUNAKAN IMEJ LANDSAT

Oleh

MOHAMMAD SHAWKAT HOSSAIN

Oktober 2015

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Di Malaysia, rumput laut biasanya terdapat di perairan pasang surut cetek, lagun, bakau, terumbu karang dan beting di zon subtidal. Hamparan rumput laut yang dahulunya terdapat di sepanjan pesisir pantai Semenanjung Malaysia (Malaysia Barat) dan Sabah (Malaysia Timur) adalah luas dan kini menjadi kurang atau tertabur kerana gangguan semulajadi dan antropogenik. Saintis dan pengurus memerlukan pendekatan pantas dengan kos yang rendah untuk pemetaan dan menilai kehilangan habitat atau potensi kerosakan terhadap sumber rumput laut. Ulasan kritikal terhadap 195 kajian menunjukkan bahawa empat dekad yang lalu, kemajuan dalam kaedah aplikasi penderiaan jauh (RS), terutamanya menggunakan imej Landsat telah dikenal pasti digunakan untuk pemetaan habitat rumput laut. Keupayaan pemetaan Landsat dalam rejim pasang surut yang berbeza, hubungkait habitat rumput laut dengan kekeruhan air dan regim kedalaman, dan dinamik spatio-temporal dari imej pelbagai tarikh tidak digunakan sepenuhnya disebabkan kekurangan kaedah yang sesuai, termasuk tiada penyelesaian bagi jurang data “Scan Line Corrector (SLC)-off” dalam imej Landsat 7 Enhanced Thematic Mapper (ETM)+.

Objektif spesifik kajian ini adalah untuk: (1) mencirikan kajian kaedah RS rumput laut melalui ulasan sorotan literatur, (2) menilai prestasi kaedah pengisian jurang “Landsat 7 ETM+ Scan Line Corrector (SLC)-off” dan teknik peningkatan imej (ETs) dengan kedalaman air berbeza untuk penambahbaikan kaedah pemetaan sumber rumput laut dan pemantauan, dan (3) mengaplikasi pendekatan pemetaan pada habitat rumput laut, kekeruhan air dan pemetaan kedalaman air relatif dan pemonitoran.

Penaksiran statistik dan penilaian terhadap dua belas imej “SLC-off” dan empat imej “SLC-on” terhadap hamparan rumput laut di muara Sungai Pulai, Johor, Malaysia telah dijalankan untuk anggaran kehilangan data. Analisis ini menunjukkan 2% ralat sistematik disebabkan peningkatan berperingkat jalur “SLC-off” dari laluan pusat nadir ke arah pinggir imej. Peralihan rawak jalur “SLC-off” menyebabkan 11.07 ha beting Tanjung Adang Laut (TALS) tidak kelihatan. Kajian seterusnya memberi tumpuan kepada penaksiran geometrik dan imej radiometrik bina semula menggunakan tiga kaedah potensi jurang-pengisian:(1) “Geostatistical Neighborhood Similar Pixel Interpolator” (GNSPI), (2) Regresi linear berwajaran bersepadu dengan penyusunan semula sebelum Laplacian dan (3) Kaedah “Local Linear Histogram”. Analisis statistik menunjukkan imej yang dibentuk cenderung kepada penggunaan GNSPI berbanding dengan teknik jurang pengisian lain untuk pemetaan taburan rumput laut di muara Sungai Pulai.

Untuk menilai perubahan dalam prestasi peningkatan imej Landsat pada peta rumput laut di muara Sungai Pulai dengan perbezaan min ketinggian aras air laut pasang surut (MSLTHs), perbandingan diantara penyamaan histogram (HE) dan peningkatan manual (ME) telah dijalankan. Teknik peningkatan telah digunakan pada komposit warna sebenar (susunan lapisan merah, hijau, dan biru) ke atas tiga puluh tiga imej Landsat (1989-2014) dengan MSLTHs diantara -0.281 m dan 0.234 m. Penilaian menunjukan bahawa ME meningkatkan kualiti imej berbanding dengan HE dengan nilai ambang MSLTH diantara -0.218 m dan 0.085 m. ME meningkat tafsiran visual imej Landsat untuk pengesanan dan pemetaan taburan rumput laut beting Merambong (MS), beting Tanjung Adang Darat (TADS), TALS dan dataran berlumpur Seluyong (SMF).

Pendekatan pemetaan bersepadu menggabungkan Landsat ME dan alatan berasaskan perkembangan piksel serantau telah diuji untuk memisah sempadan rumput laut dengan tepat. Pendekatan ini didapati sesuai (dengan ketepatan keseluruhan >75%) untuk pemetaan lima kelas yang penting iaitu rumput laut, tanah, pasir/lumpur, penempatan manusia, karang dan serpihannya untuk dua belas pulau di “Coral Triangle Initiative” (CTI), Sabah. Keputusan mendapati anggaran keluasan rumput laut adalah 274 ha, dimana sebahagian besar 158 ha hamparan rumput laut terdapat di kawasan air cetek. Isu perubahan spatiotemporal di habitat rumput laut ditangani melalui penilaian keupayaan bersepadu ke atas pelbagai tarikh imej Landsat untuk pemetaan dan pemantauan sumber rumput laut di muara Punang-Sari, Lawas, Sarawak, lagun Pengkalan Nangka, Kelantan dan lagun Paka, Terengganu, Malaysia. Menggunapakai pendekatan bersepadu ini ke atas empat puluh sembilan imej Landsat 5, 7 dan 8, telah menghasilkan peta habitat rumput laut pelbagai tarikh yang tepat. Sebagai tambahan, keputusan menunjukkan bahawa kehilangan ketara habitat rumput laut pada pelbagai magnitud berlaku antara tahun 2000 dan 2014 untuk Punang-Sari, di antara tahun 1998 dan 2014 untuk Pengkalan Nangka, dan di antara tahun 1988 dan 2014 untuk Paka. Peristiwa semula jadi terutamanya peralihan pasir adalah punca utama kehilangan habitat rumput laut di Punang-Sari Lawas. Perubahan pesisiran pantai telah dikenal pasti sebagai faktor paling penting yang menyebabkan kehilangan litupan rumput laut di lagun Pengkalan Nangka.

Pendekatan pemetaan dan produk peta dihasilkan dalam kajian ini akan menjadi alat yang berguna untuk pengesanan, pemetaan taburan dan pemantauan perubahan rumput laut dan sumber berkaitan untuk program pengurusan dan pemuliharaan pesisir pantai.

ACKNOWLEDGEMENTS

During my candidature, I received assistance from many people and organizations. In particular, I am indebted to my supervisors Prof. Dr. Japar Sidik Bujang, Assoc. Prof. Dr. Muta Harah Zakaria and Prof. Dr. Mazlan Hashim. Thanks to Prof. Dr. Japar Sidik Bujang for initiating the project and for providing me with the opportunity to conduct interesting research. In addition, thank for your guidance and support over the course, encouragement, and for providing me with a unique opportunity to learn about aquatic remote sensing and coastal resource management. Thanks to Assoc. Prof. Dr. Muta Harah Zakaria for providing technical advice and field research support. Thanks to Prof. Dr. Hashim for providing the software support.

I would like to express my gratitude to the following people and organizations who assisted me during my candidature: Feng Gao (USDA-ARS Hydrology and Remote Sensing Laboratory), Xiaolin Zhu (Colorado State University), Huanfeng Shen (Wuhan University), Zeng Chao, and Pringle Matthew (DSITIA Australia).

I am grateful to the organizations that funded this project, including: the Ministry of Science, Technology and Innovation, Malaysia; the Japan Society for the Promotion of Science; Establishment of Research and Education Network on Coastal Marine Science in Southeast Asia; and the Universiti Putra Malaysia.

This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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LIST OF ABBREVIATIONS

ADCP	Acoustic Doppler current profiler
ALOS	Advanced Land Observing Satellite
AOI	Area of interest
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
AUV	Autonomous underwater vehicle
CASI	Compact Airborne Spectrographic Imager
CBERS	China Brazil Earth Resources Satellite
CL	Coastline
CTI	Coral Triangle Initiative
EnMAP	Environmental Mapping and Analysis Program
ET	Enhancement technique
ETM	Enhanced Thematic Mapper
GNSPI	Geostatistical neighborhood similar pixel interpolator
HE	Histogram equalization
HSR	High spatial resolution
IAS	Image assessment system
IK	IKONOS
IM	Inter-monsoon
IOFF	Interpolation off
ION	Interpolation on
IQ	Image quality
ISODATA	Iterative self-organizing data analysis technique
KML	Keyhole Markup Language
LIDAR	Light detection and ranging
LLHM	Local linear histogram matching method
LPGS	Level 1 product generation system
LPRM	Laplacian prior regularization method
LSR	Low spatial resolution
LUC	Land use and cover
MBES	Multi-beam echo sounder
ME	Manual enhancement
MERIS	Medium Resolution Imaging Spectrometer
MODIS	Moderate Resolution Imaging Spectroradiometer
MPA	Marine Protected Area
MS	Merambong shoal
MSLTH	Mean sea-level tide height
MSR	Medium spatial resolution
MSS	Multi-spectral sensor
NDTI	Normalized Difference Turbidity Index
NDVI	Normalized difference vegetation index
NDWI	Normalized Difference Water Index
NEM	Northeast monsoon
NIR	Near infrared
OBIA	Object-based image analysis
OLI	Operational Land Imager
PCA	Principal component analysis
PMSC	Piecewise multiplicative scatter correction technique

PNBE	Palawan/North Borneo Ecoregion
QB	QuickBird
RS	Remote sensing
RT	Radiative transfer
RWD	Relative water depth
SBES	Single-beam echo sounder
SIS	Sediment Imager Sonar
SLC	Scan Line Corrector
SMF	Seluyong mudflat
SPOT	Satellite Pour l’Observation de la Terre
SRM	Spectroradiometer
SSS	Side scan sonar
SWM	Southwest monsoon
TADS	TanjungAdangDarat shoal
TALS	TanjungAdangLaut shoal
TIRS	Thermal infrared sensor
TM	Thematic Mapper
TOA	Top-of-atmosphere
UAV	Unmanned airborne vehicle
UC	User controlled
USGS	United States Geological Survey
WLR	Weighted linear regression algorithm
WV	WorldView

CHAPTER 1

GENERAL INTRODUCTION

1.1 Background

The seagrass ecosystem is composed of seagrass meadows, co-occurring with benthic micro- and macro-algal beds, coral reefs, and its surrounding environment. Seagrass is widely distributed in tropical, subtropical, and temperate coastal waters around the world. In Malaysia, seagrasses commonly inhabit shallow intertidal waters (Bujang and Zakaria 2003; Norhadi 1993), lagoon (Zakaria et al. 2000), mangrove, coral reef flat (Bujang et al. 2001) and shoal in subtidal zones (Bujang et al. 2006). There are currently 16 seagrass species (Bujang and Zakaria 2011), distributed along the coastline of 4809 km and coastal lagoons of Malaysia. Seagrasses can optimally grow in temperate waters between 11.5°C and 26°C, and for tropical/subtropical species the range is between 23°C and 32°C (Lee et al. 2007). In addition to temperature, its growth is chiefly controlled by light irradiance, water column, and sediment nutrients. Seagrass meadows play an important functional role in ecosystems by stabilizing sediment and improving water clarity, which enhances seagrass growing conditions (van der Heide et al. 2011). They provide a suitable substratum for epiphytes, influence ocean-wide primary productivity, produce organic carbon by sequestration (Macreadie et al. 2014), and interact with mangrove and coral reef (Green and Short 2003) ecosystems. Other seagrass functions include maintaining biodiversity, which has a potential biochemical utility and the resilience of the coastal environment (Unsworth et al. 2014a). As seagrass is being a part of the food-web structure, it acts as a food source for a wide range of marine species and provides habitat for fish and vulnerable species (Blandon and zu Ermgassen 2014), including dugongs or sea cows (*Dugong dugon*), seahorses (*Hippocampus* spp.), endangered green turtles (*Chelonia mydas*) and functions as a feeding ground for seasonal migratory birds such as *Egretta garzetta* (Bujang et al. 2006). Thus, seagrasses play a critical role in the equilibrium of coastal ecosystems and form extensive meadows, supporting high biodiversity and providing numerous ecosystem services, including fisheries that support the livelihoods of millions of people in the coastal areas (Björk et al. 2008; Ondiviela et al. 2014). Costanza et al. (1997) estimated ecosystem service value of seagrass as US $34,000 per hectare per year.

Despite their importance, seagrass ecosystems are continually being threatened by multiple anthropogenic activities that eventually cause their degradation and rapid habitat loss (Waycott et al. 2009). In Malaysia, seagrass meadows that previously inhabited along the coasts of Peninsular Malaysia and Sabah (East Malaysia) were extensive and they have become isolated patches, chiefly due to increased sedimentation and sand mining for coastal development (Bujang et al. 2006). According to the Categories and Criteria of the International Union for the Conservation of Nature (IUCN) Red List of

Threatened Species, 14% of all seagrass species are at an elevated risk of extinction, and three species (*Phyllospadix japonicas*, *Zostera chilensis*, and *Z. geojeensis*) are certified as endangered (Short et al. 2011). The seagrass environment is under increasing pressures from natural disturbances, such as windblown waves, sediment movement, freshwater intrusion, invasion by algae and competition among seagrass species. It is predicted that commercial fish and seafood stocks will significantly reduce and may reach the point of no recovery by the 21st century, if no immediate action is taken for mitigation (Short et al. 2011). Malaysia had already lost seagrass meadows at unknown temporal rate and spatial extent/coverage due to known human activities such as land reclamation, sand mining, dredging for coastal development and fishing by pull net (Zakaria and Bujang 2011).

The risk of seagrass and associated species extinction highlights the need for: (1) assessing their present state, biodiversity, spatial pattern, and dynamics at appropriate spatial and temporal scales (Kenworthy et al. 2006; Sagawa et al. 2010), (2) understanding processes of degradation (Lee et al. 2007), (3) identify causes of degradation (Collado-Vides et al. 2007), and (4) monitoring programs to manage, restore or creation of seagrass meadows (Duarte 2002; Short et al. 2007). To understand the dynamic nature of seagrass ecosystems and predict response of seagrass meadows to their future environmental changes (Unsworth et al. 2014a), it is useful to conduct a synoptic monitoring of change in community structure, such as species composition, cover, and biomass, across the whole system. Since these interactive processes interplay from small (<1 km^2) to large (>100 km^2) spatial scales, conventional field survey methods are difficult to conduct, requiring many manpower, time and cost (expensive) to conduct over a large spatial scale. The development of remote sensing (RS) methods becomes an imperative supplementary to conventional method due to its rapidity, large area coverage, and repeatability of observations.

Maps produced through image classification are also limited by their thematic resolution, defined as the number of categories or classes that they depict. In contrast to terrestrial applications, the absorption of light in sea water limits the amount of spectral information that can be used in the classification of benthic habitats (Dekker et al. 2006). The benthic habitat maps often elucidate seagrass presence or absence (binary) utilizing optical remote sensing methods under the complex marine environment. Such a binary map is created from pixels counted for seagrass presence or absence, equivalent to a spatial resolution of each pixel. These sharp boundaries imply certainty or accuracy though this is rarely evaluated or stated explicitly in mapping studies (Arnot et al. 2004; Philibert et al. 2008). The degree of uncertainty introduced through classification is a function of the spatial and thematic characteristics of the sensor data and the classification scheme, and could be expected to differ when considering seagrass meadows with different spatial patterns (Barrell and Grant 2013) and tidal regimes (Knudby et al. 2010).

There are various methods employed for seagrass mapping and assessment of areal coverage, distribution, abundance, and biomass (Borfecchia et al. 2013; Knudby and Nordlund 2011; Mumby and Edwards 2002; Phinn et al. 2008; Roelfsema et al. 2014; Soo Chin Liew and Chew Wai Chang 2012; Urbański et al. 2009). There is no single technology or approach that is suitable and capable of measuring all seagrass parameters (e.g., presence/absence, cover, species, and biomass). Techniques developed for mapping and assessing changes in the seagrass environment are limited by existing approaches, because traditional image-based interpretations (pixel-based classifications) of multispectral RS data are typically sensor specific, site specific and often time specific (Kutser et al. 2006). Object-based image analysis through image segmentation, a pre-processing technique for generating a seagrass classification map, is still a developing field (Radoux et al. 2011). The validation/accuracy assessment of classified maps is fundamentally different from point/pixel-based validation (Congalton and Green 2009) due to the sampling unit (i.e., objects vs. pixels).

The Landsat is the only satellite that provides continuous global inventory data (Wulder et al. 2008) on 16-day repeat cycle with 30 m pixel resolution, can be used to map seagrass meadows from local (Yahya et al. 2010) to regional-scale (Torres-Pulliza et al. 2013) and monitoring spatial and temporal changes (Lyons et al. 2012). Recent studies (Barillé et al. 2010; Kim et al. 2015; Knudby et al. 2010; Lyons et al. 2012; Lyons et al. 2013b; Massicotte et al. 2013; Meyer and Pu 2012; Pu et al. 2014; Roelfsema et al. 2013a; Roelfsema et al. 2014; Ryu et al. 2014; Torres-Pulliza et al. 2013; Wicaksono and Hafizt 2013; Zhao et al. 2012) have demonstrated that the free availability and accessibility of Landsat archives, including Multispectral Scanner, Thematic Mapper, and Enhanced Thematic Mapper (ETM)+ from Glovis (http://glovis.usgs.gov) and Earthexplorer (http://earthexplorer.usgs.gov), which host extensive coastal zone cover data and include long time-series (1972 to present), have increased the use of these data in seagrass resource management. Researchers have used Landsat images as a retrospective monitoring and mapping tool for seagrass resources (Knudby and Nordlund 2011; Lyons et al. 2013b; Torres-Pulliza et al. 2013; Wabnitz et al. 2008). Simultaneously, the limited ability to estimate changes of small areal coverage seagrass meadows from Landsat imagery is also reported (Lyons et al. 2013a; Lyons et al. 2012).

Landsat 7 ETM+ images acquired before 2003 are designated as Scan Line Corrector (SLC)-on scenes. ETM+ images acquired after 2003 are designated as SLC-off scenes. There are large data gap areas in the SLC-off scenes, and the pixels outside the data gaps maintained their spectral quality (Storey et al. 2005). The discontinuity of data acquisition within a large Landsat archive occurred because a) the acquisition of Landsat MSS data was terminated in late 1992 and b) although Landsat 5 (TM) remains operational, routine acquisition was halted in November 2011 (USGS 2015) when the system reached its design life, as planned (Bédard et al. 2008).

The use of Landsat 7 ETM+ is limited because of the Scan Line Corrector (SLC) failure, which makes it impossible to produce images for the entire swath by constraining the system's applicability (USGS 2010). The SLC-off stripes can contribute to classification errors, particularly in mapping seagrass meadows. The seagrass meadows with continuous or fragmented spatial pattern could be erroneously classed as patchy distribution patterns for both the types when SLC-off stripe(s) cross over the meadows. There is a need to investigate an appropriate ETM+ SLC-off gap-filling algorithm through testing the efficacy of an already developed algorithm that was particularly implemented for terrestrial mapping (Chen et al. 2011; Zhu et al. 2012). It can increase the usability, where cloud cover also limits adequate Landsat data availability for seagrass resource mapping and monitoring.

Studies on seagrass cover maps using an object-based image analysis approach on high-resolution imagery (QuckBird, WorldView2, and IKONOS) are well tested (Lyons et al. 2012; Roelfsema et al. 2014). However, interpretation of data is subjective, and utility of seed pixel growing algorithm (Adams and Bischof 1994; Pratt 2007) offer an objective method of segmentation of optical RS data into spectrally similar regions, and are not yet well tested or accepted.

Seagrass habitat maps representing the spatial distribution of seagrasses and associated organisms are a prerequisite for effective ecosystem monitoring (Neckles et al. 2012), change detection (Roelfsema et al. 2013a), understanding species-environment relationships (Boström et al. 2006), and predictive modeling with respect to the process that structure the landscape (Bell et al. 2006). However, many questions remain unanswered regarding the application of mapping tools and indices for seagrasses, water quality, and marine landscape in general; how do one produce maps depicting landscape pattern, water quality and seagrass habitat attributes? to what extent the maps can explain the causes and processes of seagrass habitat degradation and provide information on the possible natural recovery or restoration success? how much detail can be interpreted from the produced maps and benefit the seagrass managers or conservationists? can the maps inform about the seagrass ecosystem components and lead to better design a coastal development plan for sustainable seagrass resource management? (Bell et al. 2006; Malthus and Mumby 2003; Phinn et al. 2005; Roelfsema et al. 2013a; Sleeman et al. 2005).

1.2 Thesis objectives

The overall objective of this study was to improve seagrass resource mapping capabilities by integrating SLC-off image optimization methods and operational mapping approaches for different seagrass environments in Peninsular Malaysia, Sarawak, and Sabah.

The three specific objectives of this research were to:

1. characterize the body of work on seagrass remote sensing methods through a review of the peer-reviewed literature;
2. assess the performance of ETM+ Scan Line Corrector-off gap-filling methods and image enhancement techniques with different water depths for methodological improvement in seagrass resource mapping and monitoring; and
3. apply mapping approach on studies of seagrass distribution, water turbidity, and relative water depth mapping and monitoring.

1.3 Thesis outline

This thesis is structured as a series of nine chapters that is illustrated in Figure 1.1. Chapter 1 provides an introduction to the seagrass ecosystem and management related issues and limitations associated with RS-based seagrass habitat mapping and monitoring at broad spatiotemporal scale. Chapter 2 synthesizes the body of work on recent advancements, major challenges in RS-based methods used for mapping and monitoring seagrass resource and highlights areas where potential future research could be focused in the seagrass RS applications through a review of peer-reviewed studies (objective 1). It compares the performance of optical, acoustic, and within those RS methods used for seagrass habitat classifications, and discuss the information needed for the scientific management of seagrass resources. Chapter 3 describes the study sites, satellite image acquisition, and pre-processing techniques, and general methods often used to analyze data in this research. Chapter 4 assesses the implications of thematic accuracy and uncertainty on studies of small to large seagrass patches using SLC-off data; demonstrates random shift nature of SLC-off stripes between multi-date images; estimate data gap statistics for interpolation off and on images; and describe SLC-off data gap-filling considerations prior to choosing image pairs for mapping Sungai Pulai estuary seagrass resources (objective 2). Chapter 5 compares performance of ETM+ SLC-off gap-filling methods for mapping seagrass resources through statistical validation tests; and discusses potential use of gap-filling algorithm for producing thematically accurate maps for smaller to larger seagrass patches from reconstructed SLC-off images (objective 2). Chapter 6 compares the seagrass habitat classifications extracted from visual quality of enhanced images with different Mean sea-level tide heights (MSLTHs); determines MSLTH thresholds with an ability to recognize intertidal and subtidal seagrass meadows of Sungai Pulai estuary; estimates spatiotemporal seagrass cover changes from multi-date enhanced image analysis; and discusses benefits and constraints of enhancement technique for seagrass applications (objective 2). Chapter 7 illustrates classed image consisting distribution and extent of seagrass, coral, coral rubble, sand/mud, land and human settlement within CTI, Sabah region using image enhancement method, integrated with seed pixel growing technique, and *in-situ*, and *ex-situ* data sources; outlines seagrass habitat map production technique characterized by different relative water depths; distribution map of seaweed culture areas; and discusses implications of enhancement technique for Marine Protected Area (MPA) network design and mapping at large spatial scale (objective 3). Chapter 8 demonstrates seagrass habitat map production methodology for the intertidal and subtidal seagrass meadows of Lawas (West Malaysia) and lagoons of Terengganu and Kelantan (East Malaysia) using image enhancement, integrated with seed pixel growing technique, and *in-situ*, and *ex-situ* field data, under different water turbidity and depth gradients; estimates seagrass and coastal land cover changes from multi-date images including SLC-off gap-filled data; and explains the causes of seagrass habitat degradation from enhanced images and witnessed by field-based expert knowledge (objective 3). Chapter 9 provides a summary of previous chapters and discusses the constraints and opportunities for implementing image enhancement integrated with seed pixel growing techniques for implementing seagrass distribution and change analyzes maps as a priority for planning and management of seagrass resources. Chapters 4, 5, and 6 are focused on the methodological improvement, and Chapters 7 and 8 are focused on operational applications of the image optimization method, and validated through this research (Figure 1.1).

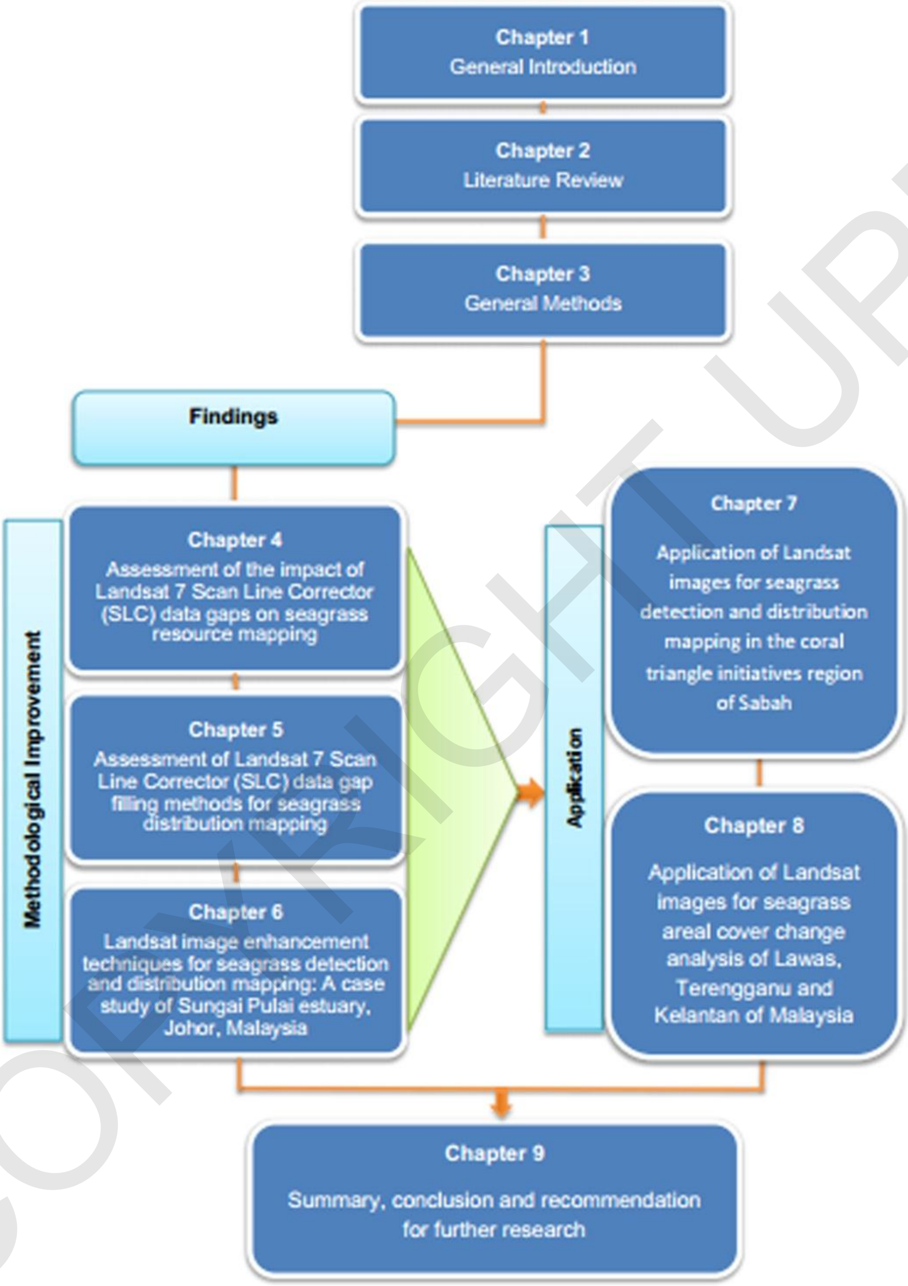

Figure 1.1. Schematic diagram of chapter structure of this research.

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