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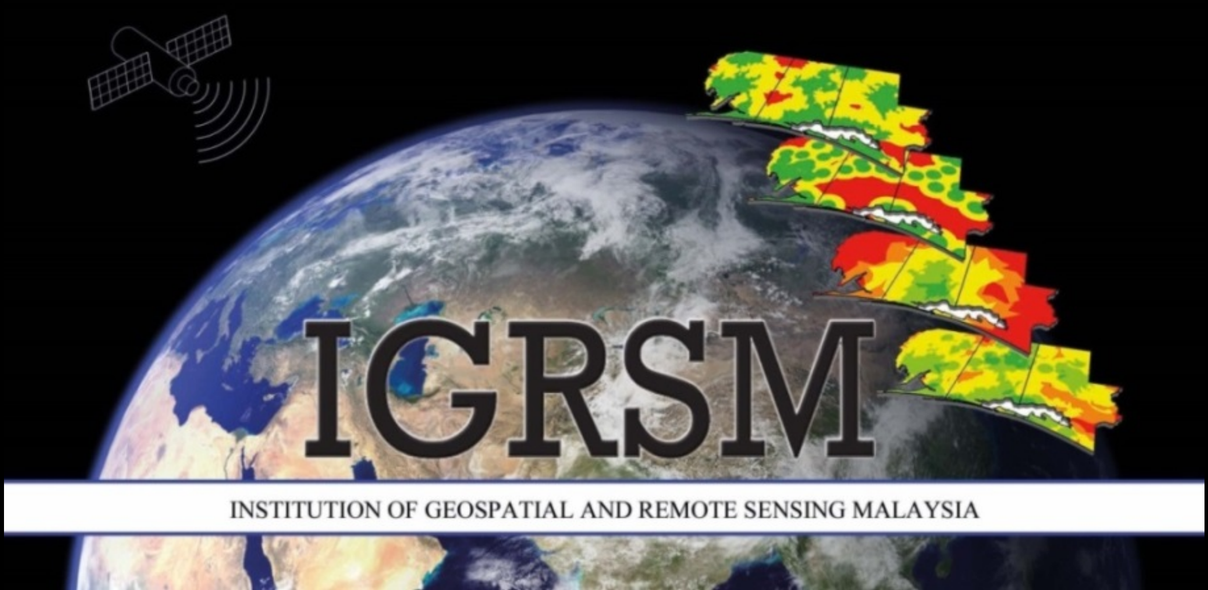

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Keywords: *Keyword 1; keyword 2; keyword 3; keyword 4; keyword 5.*

1. TOPIC 1

Paragraph 1.

Paragraph 2.

1.1 Sub Topic 1

Paragraph 1.

Paragraph 2.

2. TOPIC 2

Paragraph 1.

Paragraph 2.

Figure 1: Title of figure.

Table 1: Title of table.

Content	**Content**	**Content**
Content	Content	Content
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Equation 1 (1)
Equation 2 (2)

REFERENCES

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<u>Books</u>

Serra, J. (1982). *Image Analysis and Mathematical Morphology*. Academic Press, London.

<u>Book Chapters</u>

Goodchild, M.F. & Quattrochi, D.A. (1997). Scale, multiscaling, remote sensing and GIS. *In* Quattrochi, D.A. & Goodchild, M.F. (Eds.), *Scale in Remote Sensing and GIS*. Lewis Publishers, Boca Raton, Florida, pp. 1-11.

<u>Journals / Serials</u>

Jang, B.K. & Chin, R.T. (1990). Analysis of thinning algorithms using mathematical morphology. *IEEE T. Pattern Anal.*, **12**: 541-550.

<u>Online Sources</u>

GTOPO30 (1996). *GTOPO30: Global 30 Arc Second Elevation Data Set*. Available online at: http://edcwww.cr.usgs.gov/landdaac/gtopo30/gtopo30.html (Last access date: 1 June 2009).

<u>Unpublished Materials (e.g. theses, reports and documents)</u>

Wood, J. (1996). *The Geomorphological Characterization of Digital Elevation Models*. PhD Thesis, Department of Geography, University of Leicester, Leicester.

CREATING A VIBRANT SPACE INDUSTRY FOR MALAYSIA: THE NEED FOR A SPACE ACT

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ABSTRACT

Malaysia is deep in space, but the local space industry is somehow quite blurred. Space is currently placed under the aerospace sector, and with over than 120 aerospace companies in the country, the aerospace industry is considered a healthy industry, contributing to about 2 % of the Malaysian gross domestic product (GDP), albeit real 'space' players being almost invisible. Under the National Aerospace Blueprint released by the government in 1997, the scope of the space sector is only small satellite making, launch and operations and some earth observation applications. This paper describes the current status of the space industry in Malaysia, for both the upstream and the downstream activities. This industry is currently driven purely by commercial and business forces as well as supply and demand requests of the market, with minimum government input. It is felt that active interventions by the government would make the local space industry more significant, and the plan to have a space policy implemented would be a pre-requisite in charting the growth of the industry. For this, the National Space Policy has been drafted with the intent of catalysing the development of the industry. As a follow up to that, the Malaysian Outer Space Act (MOSA) is also proposed, mainly to establish the appropriate entities to drive the industry development as well as regulating its activities, and more importantly establishing Malaysia as a responsible space player, namely in fulfilling its obligation in the international forum.

Keywords: *Local space industry development; upstream and downstream segments; regulating the industry; space act.*

1. INTRODUCTION: MALAYSIA IN SPACE

Satellite technology and its downstream applications have matured especially in various applications in telecommunications, remote sensing and navigation. It is increasingly being exploited by private enterprises for commercial purposes. The global space industry has already become a multi-billion dollar economic sector generating revenues of over USD 304 bil. in 2012 (Space Foundation, 2013).

Malaysia's active participation in the space industry started in the mid-1990s with the launching of two communications satellites, MEASAT-1 and MEASAT-2, and a micro satellite, TiungSAT-1. The use of satellites to broadcast international events, which marked the beginning of satellite communications applications, was well received in Malaysia way back in the 1970s. Following that, images from satellites have been routinely used for weather monitoring as well as remote sensing (RS) applications, while the earliest use of satellite navigation was in international boundary determination works, utilising the predecessor of the Global Positioning System (GPS), the TRANSIT. Various local companies, mostly through joint-ventures with international partners, offer related services in those areas. Up until present, these players are multiplying in its numbers and offerings, blooming on its own, driven mainly by the commercial supply and demand needs of the market. Some have expanded their markets, covering significant regional and global customers. One local player that has successfully gone global, MEASAT Satellite System Sdn. Bhd., is an example of an exceptional space player (Subari *et al*., 2014). All of these developments in the space sector are happening in the absence of any space policy or legal framework.

Countries like the US, UK, Russia, Sweden, France, South Africa and South Korea have already adopted specific laws and regulations that govern all or most space activities carried out from their territories or by their citizens. China, Germany, Canada and Japan have passed a few specific laws and have also made some necessary modifications to relevant existing general laws in order to extend their application to space activities. In comparison, Malaysia does not have laws that regulate the local space players.

This paper looks at the space industry in Malaysia in terms of its current status, and the extent of activities and local players, looking at the downstream industry segment as the new focus of the industry, which is more prevalent than the upstream activities. These activities are mainly driven by the commercial supply and demand, blooming on its own, with minimum interventions from the government. It is felt that active interventions by the government, by virtue of a relevant policy and act, would make the industry more significant with rapid and vibrant growth. In this respect, the plan to have the Malaysian Outer Space Act (MOSA) drafted is discussed.

2. THE MALAYSIAN SPACE INDUSTRY

2.1 Industry Overview

Broadly, the space industry includes players or companies involved in the space economy in providing goods and services related to and deriving from space (both science and technology). Space economy has been defined as to include "*all public and private actors involved in developing and providing space-enabled products and services. It comprises a long value-added chaining, starting with research and development actors and manufacturers of space hardware, and ending with the providers of space-enabled products and services to final users*" (OECD, 2007).

Under the National Aerospace Blueprint released by the Malaysian Industry Government High Technology (MIGHT) in 1997 (MIGHT, 1997), the space sector is considered as under the aerospace sector, so the industry is assumed to be very much related. The aerospace industry on one hand is considered as a healthy industry, currently having more than 120 companies, contributing slightly less than 2% of the Malaysian gross domestic product (GDP). On the other hand, the real space industry is small, with the scope of the space sector under this blueprint only covering small satellite making, launch and operations, and some earth observation (EO) satellite applications. The applications of satellite technology are not included. While there are various space-related industries locally flourishing, these are currently not identified as space industry. These include industries related to the applications of satellite systems, such as satellite communications, EO and satellite navigation. More recently, space tourism could be another possible inclusion into the industry.

The Malaysian space industry, covering the commercial and civilian sectors, can be segmented into upstream and the downstream segments. The upstream segment includes satellite manufacturing and operations, and the associated ground components supply and maintenance. The downstream segment includes the applications and services of satellite systems, namely communications, EO and navigation, and other support activities, such as finance and insurances.

2.1.1 The Upstream Segment

The space industry was generally known to only covering this segment, the real 'space' thing. It includes spacecraft manufacturing (satellites), its sub-systems and components, launching technologies and services, and its operations. Within this segment, local players' involvement is small, being limited to the following:

i. Satellite manufacturing

Currently, two local companies are involved in satellite manufacturing, MEASAT and Astronautic Technology Sdn. Bhd. (ATSB). While MEASAT, a private company, procures their satellites from foreign satellite manufacturers, ATSB on the other hand, a government-owned-company set-up as part of the government's strategic initiative for building the country's satellite technology capacity, develops their satellites in collaboration with foreign technology partners. Satellite making is a high capital and high risk business, so it is foreseen that the number of local companies involved will not grow in the next several years. As a note, MEASAT spent roughly over RM 4.5 bil. for procurement of their four communications satellites (the MEASAT series), while ATSB spent about RM 200 mil. on TiungSAT-1 and RazakSAT, which are an experimental and research & development (R&D) satellites respectively.

ii. Satellite operations

MEASAT operates their own satellites, MEASAT-1, MEASAT-2, MEASAT-3 and MEASAT-3a, from their ground control stations in Cyberjaya and Langkawi. Although the operations are local, their services are regional. The Ku-band capacity of MEASAT-1 and MEASAT-2 gives Direct-to-Home (DTH) broadcasting services to users in Malaysia, Eastern Australia, India, Indonesia (Sumatra and Java), the Philippines, Taiwan and Vietnam. MEASAT-3 provides 24 high powered C-band transponders to users in Eastern Europe and Africa in the west, and Japan and Australia in the east. Revenue for MEASAT for transponder leasing alone in 2005 and 2006 was RM 132.2 mil. and RM 137.5 mil. respectively (Brown, 2007).

On the other hand, TiungSAT and RazakSAT are both operated by the government body, the National Space Agency of Malaysia (ANGKASA), via their ground control station at the Malaysian Space Centre, Banting, Selangor. Both have ceased operation, in 2004 and 2010 respectively, and did not generate any revenue back to the government, as they were capacity building initiatives in satellite technology for the country.

iii. Ground stations

There are more than five companies in Malaysia that are involved in the business of setting-up of ground stations for satellites. These include activities on the supply, installation, maintenance and services of its components and systems, such as antennas, satellite receivers and robotic telescopes. Most of these companies are involved in the supply and maintenance of the ground station facilities in operation. It is understood that most of the equipment are imported from international suppliers.

iv. Launch Services

Launch services are still not available in Malaysia, although there have been talks on developing an area in Sabah for a launch site since the late 1980s, but until now nothing is concrete. There are also proposals for aircraft assisted launch services, making sea-launch services available in Malaysia, the development of a space-port, and others.

2.1.2 The Downstream Segment

It is the downstream segment that is more vibrant as well as having a multitude of activities involving many local players. The largest component would be on the streams of applications from the three satellite technologies; communications, EO and navigation satellites. Other component would be activities based on products of these satellites.

i. Communications satellites

The largest segment of the satellite downstream market is communications satellites. Operating their own satellites gives MEASAT the full range of activities, starting from transponder leasing down to providing telecommunications services. Other players would be telecommunications companies, such as Maxis (a sister company of MEASAT), Telekom, Celcom, and Digi, which are offering telecommunications-related services, either through leased transponders from MEASAT or from other foreign satellites. The telecommunications market was valued at RM 14.9 bil. in 2005 and RM 18.6 bil. in 2006, while the broadcasting services (ASTRO) was at RM 1.72 bil. in 2005 and RM 2.0 bil. in (2006) respectively (SIRIM, 2008). There is also internet services, for example by Telekom, but this value is still small.

ii. EO satellites

The EO activities are the next important segment, with the Malaysian Remote Sensing Agency (ARSM) servicing the government's needs in satellite imageries, and several private companies, such as Espatial Resources and Sky-Shine Corp (M) Sdn. Bhd., giving the remote sensing communities value-added data services. The overall market value of the local EO industry is still small, within several million ringgit, with ARSM's revenue being only RM 560,000 in 2005 and RM 820,000 in 2006 respectively (SIRIM, 2008).

iii. Navigation satellites

The navigation satellite segment is the latest, but growing quite rapidly over the EO segment. Starting in late 1970s for the highly accurate international boundary position determination, the users expanded more to low accuracy position-based-services such as navigation and tracking. While the government operates GNSS-related infrastructures for high accuracy positioning-based-services (PBS), such as the MyRTK Network by the Department of Survey and Mapping Malaysia (JUPEM) and SISPELSAT by the Marine Department, most general navigation communities are served with the basic signal via the use of commercial terminals.

Comparison of revenues of the downstream and upstream segments, it is clear that the downstream segment outweighs the upstream segment significantly. From the SIRIM report, as indicated in Figure 1, the downstream industry is valued at more than 99% (worth about RM 28.63 bil.).Within that segment, the telecommunications sector is valued at 90%, while the rest are from the navigation and RS sectors.

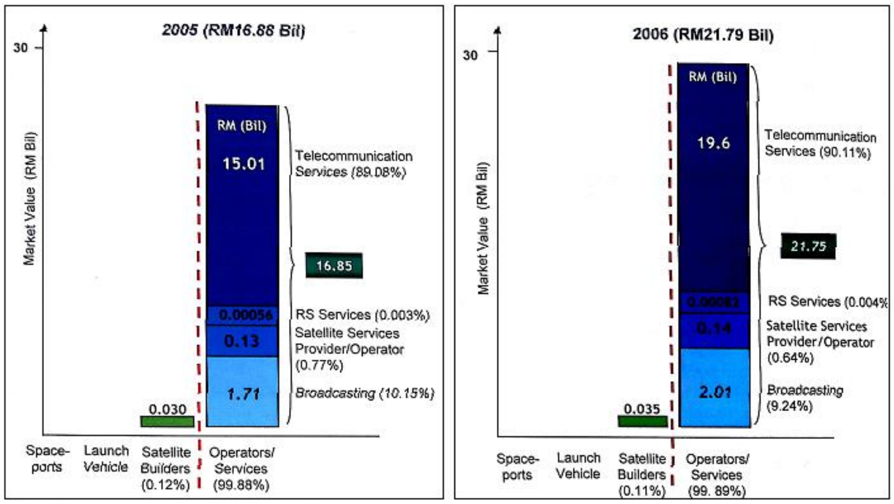

Figure 1: The Malaysian space industry market volume for 2005 and 2006.
(Source: SIRIM, 2008)

2.1.3 The New Sector: Space Tourism

Space tourism is the new addition to the list - although it would not be in the market until 2016 or beyond, active pursuance is being made by some (Collins, 1990). From an estimate of about one thousand passengers per year at USD 100,000 per flight, it has been suggested that the demand for low Earth orbit tourist flights could reach one million passengers per year at a price of around USD 10,000, representing revenues of some USD 10,000 mil. per year.

Space tourism in Malaysia is pursued by the Space Tourism Society - Malaysian Chapter (STS-MC), a not-for-profit organisation registered in 2011. STS-MC has reportedly launched a commercial project for the development of a spaceport in Malaysia. STS-MC also runs a R&D programme for suborbital spaceplanes, known as the Malaysian Research for Rocketplane Design & Development (M-R2D2), in partnership with the Swiss Propulsion Laboratory, Switzerland and Talis Enterprise, Germany (STS-MC, 2014).

2.3. The Need to Regulate The Industry

In the absence of any regulating mechanism, activities within the industry are running on its own, most of the time taking commercial and business interests as the guideline or framework. Several cases are mentioned here to illustrate the need of a certain regulatory guideline to be in place, to ensure the positive growth of the industry vis-à-vis the national interest:

i. Satellites as a strategic asset

Most space infrastructures, one example is satellites, is considered a strategic asset to the country, although it may be owned by a private entity. From the view point of the international space treaties, objects in space are state-owned, whilst from the national view point, it is a dual-use technology of national interest. When MEASAT-2 was renamed to AFRICASAT-2, it was meant to reposition it to a new slot to cover the African region, which was done purely on a commercial basis by the owner, without any consideration of the related authorities in Malaysia. Due to the non-existence of space laws in the country, the Malaysian government had no say in this strategic decision by MEASAT.

ii. Ensuring the national benefit on the geo-synch orbital slot

The Malaysian allocation of the geo-synch orbital slot is currently leased to MEASAT on a long-term basis for an undisclosed fee. Two issues are of pertinence here. Firstly, the geo-synch orbital slot is a national asset, in which the country should receive a quantum of fee commensurating its value. For example, each country is allocated orbital slots by the International Telecommunications Union (ITU). Countries are not supposed to lease their bit of outer space to others, but there is no law forbidding this practice. Over the years, countries such as Tonga and Tuvalu have sought to generate income from their orbital slots by leasing it to interested parties, with much controversy (Bender 1998). Secondly, MEASAT is given sole usage of the orbit. This should come with a caveat for unforeseen future needs of the country for the slot.

iii. Ensuring safe-of-use for the public

One of the requirements to ensure public safe-of-use of global navigation satellite systems (GNSS) signals is to regulate the signals and operators of other terrestrial uses of the signals close to it. In order to avoid interference of GNSS signals, efficient technical regulations (and technology oriented licensing) and appropriate derogations are required. An example of this is the *LightSquared* interference on the Global Positioning System (GPS) L1 signal. The act should strive for greater flexibility in the use of spectrum between satellite and terrestrial uses, leaving it for the market to decide on the most efficient use of spectrum.

iv. Space tourism

Space tourism is still new, but it has caught interest in Malaysia as well. There is a Malaysian chapter of Space Tourism International, and several Malaysians are on the final list of the Space X programme that promises a trip to space in 2016. When Malaysian launched its first astronaut (*Angkasawan*), it was done with the Russian government, a seasoned space player, in collaboration with the International Space Station consortium members, such as NASA. While astronaut safety is of no issue, participants of space tourism will not be subjected to thorough regime of safety measures such as rigorous training and tests, and thus, will be on own their own risk-taking mercy.

v. Encouraging industry growth

A framework of guidelines is needed to encourage the growth of the industry. These could be in the form of assistances, such as levies, incentives and tax exemptions, as well as to have a policy that encourages growth. One mention here is the RS industry. The Malaysia government has given its commitment that it will not ask Google Earth to blur images of the country's military facilities to avoid terrorist attacks. The Defence Minister at the time, Dato' Seri Najib Razak, who is Malaysia's current Prime Minister, has said doing so would indirectly give their location anyway; "*The difference in, or lack of, pixelation of images of the military facilities compared to the surrounding areas will make it easy for visual identification.*" At the same time, there is a policy restricting the open distribution of satellite images with resolution of 5 m or better, and the appointment of ARSM as the sole distributor of satellite images and sole R&D entity for satellite images.

3. CREATING A VIBRANT SPACE INDUSTRY

3.1 The Space Policy: Framework for Local Space Industry Development

The National Space Policy (NSP) is the strategic document that charts the way forward and provides the framework of development in the space sector for the country (Mustafa and Hassan, 2014). The document envisions on building the nation's capability to embrace space as a strategic sector for the national wellbeing towards achieving Vision 2020 and beyond.

This can be achieved by developing the country's potential in the space sector to support the development of the new economy, and strengthening national security. The listed objectives of the NSP are:

1. To build up space infrastructure and industry for economic benefit and safeguarding the nation's sovereignty.
2. To empower the civil society in enriching their quality of life through information from innovative application of space technology.
3. To capitalise/harness on space as the frontier for new knowledge generation towards contributing to scientific and technological advancement.
4. To ensure critical mass of talent in space related sector to support the realisation of the space policy.

The NSP identifies seven major thrusts with its own strategies that are in line with the defined vision, mission and objectives of space development in Malaysia. The identified space activities are strategic for their contribution to the success of Vision 2020. One of the policy thrust directly related is Thrust 4: Local Space Industry Development.

If we are to realise our vision, the industry will need to feel confident enough to aggressively and significantly increase the amount it invests in R&D, and its capabilities and people. It will need to take the required risks involved in grasping new opportunities in order to be first to market with innovative services. The plans of action proposed are in conjunction with Policy Thrust 1: To Develop the Space Industry.

Malaysia does possess a healthy and vibrant downstream space industry, and the proposed programmes are in fact a catalyst to stimulate this sector to greater heights. These programmes are very much in line with the US' policy of using GPS to invigorate its downstream GNSS industry. The continued application of these strategies, which will stimulate innovation and market development, combined with our downstream industry strengths, such as communications, RS and GNSS, will ensure that our space industry continues to thrive.

If ever there was a time to be bold with industrial strategy, it is now and the proposed plans of action say it all. We should seize the opportunity to take the existing Malaysian space sector and transform it into a foundation stone of our future economy. There are six proposed plans of actions, which are: the establishment of a Space Corporation; setting-up of incubation programme; creation of special status space-related companies; leveraging space in the national information & communications technology (ICT) infrastructure; having national space industry standardisation; and harmonising local space-related policies (ANGKASA, 2012).

3.2 The Space Act: A Catalyst for A Vibrant Industry

There is no doubt that a space act can catalyse a more vibrant space industry for any nations. The need for national space legislation is seminal, especially because our nation is increasingly looking to privatise and commercialise space assets, expand capabilities in space exploration and scientific discovery, commercialise its capabilities to build satellites, and offer launch services from its facilities.

South Korea participated in space development in the 1990s, slightly earlier than Malaysia. Despite its short history, Korea has been increasing its technological capabilities with the successful experience of several national projects. The Korean government established a long-term space development plan in 1996, and in 1998, established the Commercial Space Act, which suggests a clear way forward for space development up to 2015. Space activities in Korea are expected to grow in the future and this is partly due the space act that is supporting the growth of the industry.

In view of this emerging development, the authors are guided by the belief that a national space act should to be legislated. Some of the salient roles of the act in creating a vibrant space industry for the nation are as follows.

i. Creating a clear and transparent guideline

As most space-related ventures require long lead time to commercialisation, a clear and transparent regulatory guideline is needed for the industry in order to accelerate investment, and to ensure the growth and development in this capital intensive - high return strategic sector. Legal and regulatory certainty and predictability is also required by commercial operators and potential investors to encourage innovation and attract investments into the industry. In satellite communications, for example, the commercial business model is based on a long lead time to market, long operational satellite service lives of approximately 15 years (commercial communications satellites) and high upfront costs. Regulatory and pricing certainty is required for the length of such period of time to give certainty and security to potential investors.

The non-existence of a space regulatory framework has resulted in existing satellite infrastructure (that was built in good faith based on legitimate expectations and in compliance with a terrestrial regulatory regime, such as the Malaysian Communications and Multimedia Commission (MCMC)) being potentially limited in what should be the profit-returning years of later life, with changes to the regulatory framework having adversely impacted the ongoing business case. Under the current commercial environment, Malaysian satellite operators and service providers are smaller in terms of market capitalisation, turnover, etc. as compared to terrestrial fixed and mobile operators. This affects their ability to pay for spectrum access on a purely mass market commercial model, leading to possible opportunity barriers for smaller companies and new entrants.

ii. Setting up an entity to nurture and grow the industry

The present government entity overseeing the development of the space sector in Malaysia is the National Space Agency (ANGKASA), a department under the Ministry of Science, Technology and Innovation (MOSTI). ANGKASA does not have the power to regulate and enforce the regulations, as well as not being the right setup to drive the growth of a new industry. ATSB on the other hand is a government linked company (GLC) taking up satellite project development for the government. The act could provide ANGKASA, for example, regulatory powers to license various operators and service providers. In the case of growth of new sectors, such as ICT and biotechnology, entities such as MDec and BioTech Corporation were formed by the government to drive the respective sectors. Clearly, for the space industry to have similar growth, a Space Corporation or the like is also needed.

iii. Regulating the industry and its players

Again, when consideration in regulating the space industry is put forward, the issue is not always to generate income for the government, but rather it is on ensuring the positive growth of the industry, safe-of-use for the public and keeping the interests of the country intact.

iv. Streamlining import and export controls

Satellite systems and components are governed under certain export regimes, such as the US International Traffic in Arms Regulations (ITAR) and Missile Technology Control Regime (MTCR). Currently, there is no arrangement between Malaysia and the various countries implementing such regime restrictions, so dealings are done purely by the entities involved. A government-to-government (G-to-G) arrangement would facilitate such transactions.

To cite an example, when Malaysia's second EO satellite, RazakSAT, was launched by SpaceX, a private launcher from US in 2009, using the Falcon 1 launcher, there was two cubesat satellites which were supposed to be launched along with it. Although the launch was from Kwajelein Island in the Pacific, the integration was done in the US. For some technical reasons, the integration and launch of the two cubesats was not done, so they were left in the US, awaiting for SpaceX's future launches. Since then, the Falcon 1 launcher was discontinued, and ATSB was unable to get back their cubesats from the US, a case pending which is still unresolved until today.

v. Making Malaysia a responsible space player

The space act is not only needed as the legal basis for regulating domestic space-related activities. It is also to ensure that individuals or organisations carry out space related activities, either inside or outside the country, in conformation with the international space treaties and other obligations. In fact, the space act is a pre-requisite for the country to ratify those treaties.

Article VI of the Outer Space Treaty provides that states are internationally responsible for "*national activities in outer space*", including cases where these activities are "*carried on by non-governmental entities*". This responsibility pertains to "*assuring that national activities are carried out in conformity with the provisions set forth in the present Treaty*". Article VII of the treaty provides that states are "*internationally liable for damage to another state or its natural and juridical persons*" if such damage is caused by relevant space objects. The particular state or states are to be held liable in respect of a specific space object causing damage is determined by a fourfold criteria. In a cumulative fashion, this concerns the state which "*launches*" the space object; the state which "*procures the launching*" of that space object; the state "*from whose territory*" the launching of that space object occurs; and the state from whose "*facility*" that space object is launched. It is clear that until and unless the act is enacted, Malaysia will not be able to ratify the international space treaties.

4. CONCLUSION

The local space industry is doing ok. What is further needed is to reorganise the sector, and putting in government support for the industry to grow and contribute back to the economy as well as the strategic growth of the country. For that, Malaysia needs a good plan for its space ventures, a good policy as well as a relevant act to implement its plan and regulate its activities.

Malaysia needs to act fast to ensure that the strategic space industry can contribute to its vision to become a fully developed nation by 2020. A new scope of the local space industry needs to be defined and further developed, incorporating the currently in place downstream space applications. An appropriate space policy and its associated space law are much needed to enable this sector to be developed fully. The space policy is currently underway; next, the Malaysian Outer Space Act (MOSA) is thus proposed. It is believed that apart from providing the legislation needed, the other salient role of the act is in creating a vibrant space industry for the nation.

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MONITORING OF THE VARIABILITY OF PRECIPITABLE WATER VAPOUR OVER KLANG VALLEY, MALAYSIA DURING FLASH FLOODS

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ABSTRACT

Klang Valley is a focal area of Malaysian economic and business activities where the local weather condition is very important to maintain its reputation. Heavy rainfall for more than an hour was reported for up to 40 and 35 mm in September and October 2013 respectively. Based on these cases, we investigated the water vapour, rainfall, surface meteorological data (surface pressure, relative humidity and temperature) and river water level. The precipitable water vapour (PWV) derived from Global Positioning System (GPS) was used to indicate the impact of the flash floods on the rainfall. We found that PWV dropped by 4 mm at 2 h before the rainfall reached 40 mm and dropped by 3 mm at 3 h before 35 mm of rainfall in the respective cases. The variation of PWV was higher for September as compared to October by about 2 mm. We suggest that rainfall phenomena can disturb GPS propagation and hence, the impact of PWV before, during and after the flash flood events at the three selected GPS stations in Klang Valley should be investigated for possible mitigation in the future.

Keywords: *Water vapour; flash flood; Global Positioning System (GPS); Klang Valley; local wind variability.*

1. INTRODUCTION

Klang Valley is a focal area of Malaysia where many activities are located and local weather condition plays an important role. Information on weather variability has significant effect on economic activities, including communications, services and utilities as well as the local community (Lazo *et al.*, 2011). As Klang Valley is the main economic area, it is very upsetting for the area to be affected by flash floods every year. Hence, more studies need to be carried out to provide basic information in setting up a mitigation plan against the disaster. The National Oceanic and Atmospheric Administration (NOAA) has defined flash floods occurring less than 6 h as a result of excessive rainfall within a short period of time, while the Department of Irrigation and Drainage Malaysia (DIDM) has defined flash floods as unexpected floods due to heavy rainfall in local and surrounding areas. DIDM monitors floods based on daily total rainfall and river water level along nationwide river streams, and has classified the water level of a particular station into four categories, normal, alert, warning and danger, depending on its cross sectional area. Daily total rainfall is also classified into four categories; light (1-10 mm), moderate (11-30 mm), heavy (31-60 mm) and very heavy (>60 mm). Information on local flood status is currently being spread online through an integrated system that monitors river water level and total daily rainfall (Wardah *et al.,* 2008).

Several studies on hydrographical factors, such as by Toriman *et al.* (2009), have been carried out, but studies on the meteorological component need to be improvised as proposed by Chan (1997). The Storm Water Management and Road Tunnel (SMART) System was built to solve issues on flash floods and peak traffic jam hours in Klang Valley, but it has become less effective due to uncontrolled development and economic activities in the area. A study by Low (2007) found that the rapid constructions of buildings and public facilities may cause changes in the meteorology and geology of a focal area. Global Positioning System (GPS) meteorology is widely used in weather nowcasting and in the study extreme of weather events, such as severe floods, storms and typhoons. A research in China (Xie *et al*., 2010) during a two-day observation found that the trend of precipitable water vapour (PWV) from GPS is high before heavy rainfall, while Rongzhen *et al*. (2013) found that PWV remains at a high level during stratiform rainfall. Previous studies have shown that the variation of GPS PWV in Peninsular Malaysia is highly correlated with daily total rainfall (Musa *et al*., 2011; Suparta *et al*., 2012).

The main purpose of this study is to monitor the variability of GPS PWV, total daily rainfall and surface meteorological data during short-term local weather nowcasting. Two incidents of flash floods that occurred in Klang Valley in September and October 2013, during the inter-monsoon season, were investigated.

2. METHODOLOGY

2.1 Dataset and Location

The main parameters used in this study were GPS and meteorological datasets. The GPS data was supplied by the Department of Survey and Mapping Malaysia (DSMM) via its RTKnet website (http://www.rtknet.gov.my), while the meteorological dataset (pressure, mean surface temperature and relative humidity) was obtained from the Malaysian Meteorological Department (MMD) and Weather Underground, a flight-meteorology website (http://www.wunderground.com). The supporting dataset consisted of total daily rainfall and water levels, which was obtained via DIDM's *infobanjir* website (http://infobanjir.water.gov.my). This study considered all the DID stations located along the Klang River within the Federal Territories of Kuala Lumpur. Figure 1 shows the locations of the GPS and meteorological stations which are located less than 60 km from the flash flood prone area as marked by the red pentagon, with the details tabulated in Table 1.

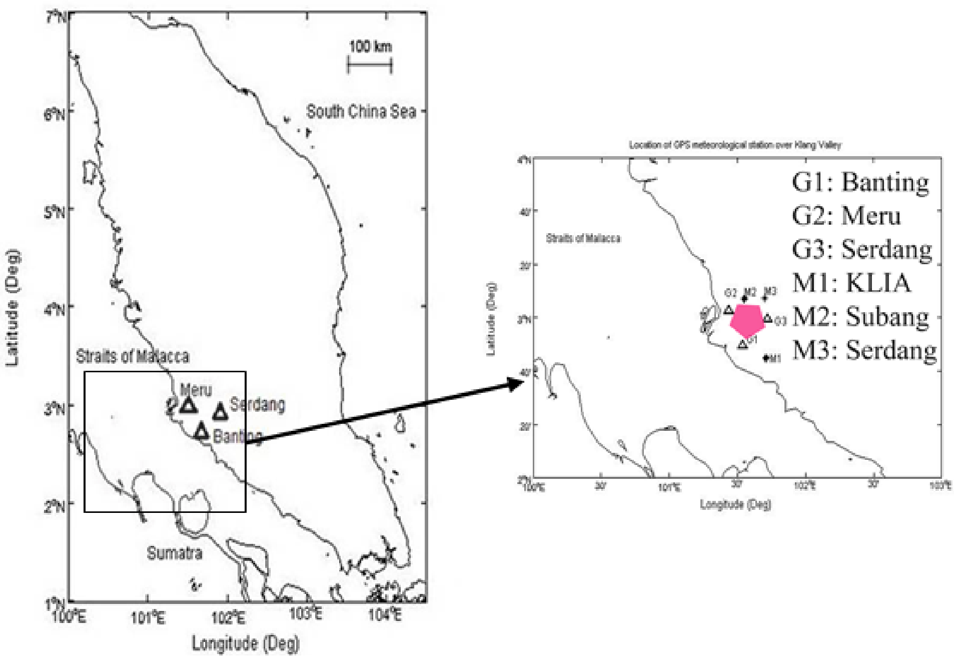

Figure 1: Locations of the GPS and meteorogical stations. The red pentagon indicates the flash flood prone area.

Table 1: Locations of the GPS stations and their distances from the point of incident.

GPS Station	Latitude (°N)	Longitude (°E)	Height (m)	Distance (km)
Banting (BANT)	2.83	101.54	8.83	57
Meru (MERU)	3.14	101.41	6.43	27
Serdang (UPMS)	2.99	101.72	100.38	28

The Tropical Rainfall Measuring Mission (TRMM) precipitation data archive was used to determine the association of accumulated precipitation and rainfall. The data was freely obtained from http://gdata1.sci.gsfc.nasa.gov, which was limited to 3 h daily measurements. The data was selected over Peninsular Malaysia within latitude of 0 to 8 ˚N and longitude of 99 to 105 ˚E.

2.2 Data Processing

The GPS and meteorological data at every GPS station needs to be cleaned before they can be processed to determine the PWV. The useful noise of GPS readings as a result of neutral atmospheric delay in identifying PWV has been explained in detail by Suparta *et al*. (2008). The processing of the PWV was done using a Matlab program called TroWav 2.0. This process used the regional mean weighted temperature T_m (Equation 1) instead of using the global mean weighted temperature (Suparta & Iskandar, 2013).

$$T_m = 0.83663T_s + 48.103 \quad (1)$$

where T_s is the measured surface temperature at the sample sites of study.

The main purpose of GPS station availability at particular places in Malaysia is for mapping and geodetic studies. Hence, all the GPS stations in the studied area are not equipped with meteorological sensors. Therefore, the meteorological parameters at the GPS positions were determined using an interpolation technique (Bai & Feng, 2003). The patterns of PWV from the GPS stations for the five day duration of the pre-, during and post-flash flood events were studied. This step was also applied to study the variability of rainfall, water level and meteorological parameters. The TRMM data was compared temporally and spatially to the heavy rainfall events to indicate the occurrence of flash floods.

3. RESULTS & DISCUSSION

The daily variations of GPS PWV, total rainfall and river water level for the flash flood events on 1 September and 10 October 2013 are depicted in Figures 2 and 3 respectively. The five day mean of rainfall in September was 2 mm higher than in October. Meanwhile, the mean standard deviation (STD) of PWV in September was doubled of October. We also identified that rainfall occurred every day for the five days in September, and three days in October.

Simple statistical analyses, such as mean and STD of PWV and rainfall, were carried out. Both variations were compared with the river water levels, meteorological parameters and TRMM precipitation images.

3.1 Case 1: GPS PWV Variation during the Flash Flood in September 2013

Figure 2 shows the GPS PWV variability at the three GPS stations with respect to the total rainfall and water level changes. The flash flood incident occurred specifically at 18:00 LT, causing havoc in Klang Valley as shown by the shaded area. In the figure, Phases 1, 2 and 3 are indicated for the pre-, during and post-flash flood events respectively. Figure 2(a) shows the peaks of PWV that correlated with the peaks of rainfall and water level. DIDM classified the water level into four levels: normal (14 m), alert (17 m), warning (18 m) and danger (19 m). By referring to the figure, the first light rainfall was recorded in the late evening on 30 August **(i)** due to a drop in PWV at all the GPS stations (Figure 2(b)). It caused the river water level to rise 0.5 m higher than the normal level for 2 h (Figure 2(c)). A similar trend of PWV occurred repeatedly on the following day **(ii)** with moderate rainfall (11 mm), resulting in the rise of river water level by 1.5 m over the normal level for a few hours. This 9 h of rainfall caused a 3 mm drop of PWV at UPMS and BANT and a 1 mm drop at MERU, but the drop at BANT occurred earlier than at UPMS and MERU.

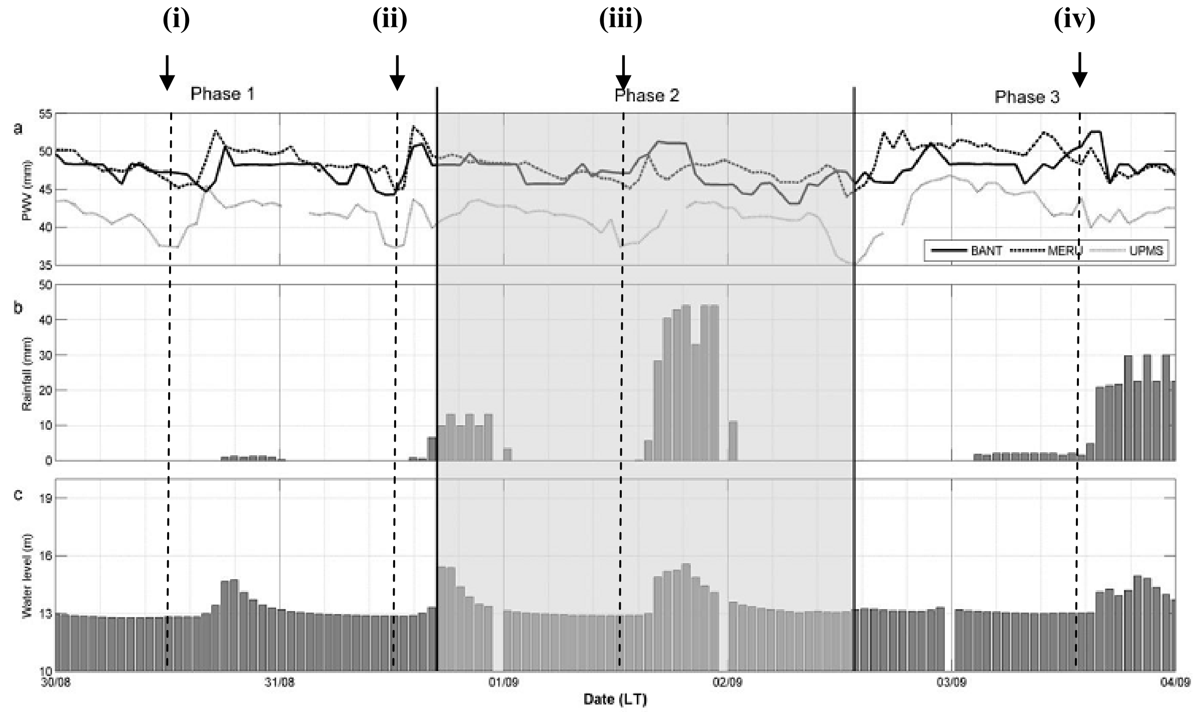

Figure 2: Variation of (a) PWV at the three GPS stations, (b) rainfall and (c) river water level for the five day period from 30 August to 4 September 2013, where the flash flood event occurred on 1 September.

The next episode of rainfall that caused the flash flood event was in the evening of 1 September **(iii).** The rainfall was recorded to be 40 mm as a result of a 6 mm PWV drop at UPMS and a 2 mm PWV drop at Klang at 2 h before the heavy rainfall event. However, the PWV at BANT did not show a similar trend as at UPMS and Klang. The PWV at BANT varied normally, where it dropped early in the morning and became highest in the afternoon and later decreased in the evening. This phenomenon may be due to normal water evaporation from the earth's surface during sun rise and sunset. The heavy rainfall resulted in a 1.5 m rise of river water level that sustained until the midnight of 1 September. This was also another factor that contributed to the flash incident in the flood-prone areas.

After the occurrence of heavy rainfall on 1 September, there was no rainfall recorded on 2 September except for an hour in the early morning. We found that all the PWV reached their minimum peaks on 2 September followed by light and moderate rainfall on 3 September **(iv)**. It seemed that the circulation of evaporation occurred on 2 September, which resulted in a whole day rainfall on the following day. For the case of the flash flood, we found that the PWV decreased by almost 4 mm at 2 h before the heavy rainfall.

The PWV was found to be higher at MERU and UPMS within 40 h of the flash flood event (shaded area). It was an increase of as much as 1 mm of mean PWV at both stations. However, it did not happen at BANT where the mean PWV at the same event was 1 mm lower as compared to Phase 1. The mean PWV at MERU and UPMS decreased by 1 mm in Phase 3, where they were similar before the flash flood event. It also did not happen at BANT, where the mean PWV continuously increased by 1 mm in the following phase. Overall, PWV was highest during the phase of the flash flood event by 0.33 mm as compared to the pre- and post-events.

Table 2 shows the mean and STD of PWV and rainfall during the five days of the pre-, during and post-flash flood events. The variation of GPS PWV was highest at UPMS during Phases 1 and 2 followed by MERU and BANT. The PWV varied by less than 2 mm in Phase 1. In Phase 2, the PWV variation was recorded to be more than 2 mm and less than 3 mm as compared to Phase 1. This showed that GPS detected the atmospheric disturbances in Phase 2 that could be a result of atmospheric water vapour and later on caused the flash flood. The STD of PWV decreased by 1 mm in Phase 3. Individually, PWV varied the most in BANT and the least in UPMS. Rainfall was recorded to be the highest during Phase 2, which was 5 mm more than the pre-event and 1 mm more than the post-event. The highest variation trend of the rainfall was also similar to the trend of the PWV.

Table 2: Statistical values of GPS PWV and rainfall for the five days of observations in Figure 2.

Phase	Station		GPS (mm)		Rainfall (mm)	
	GPS	Rainfall*	Mean	STD	Mean	STD
1	Banting		47.90	1.59	2.09	4.21
	Meru		48.00	1.70		
	Serdang		41.10	1.86		
2	Banting	Jambatan Petaling	47.02	2.04	7.42	15.30
	Meru		48.67	2.16		
	Serdang		42.32	3.16		
3	Banting		48.03	1.98	6.39	10.19
	Meru		47.94	1.65		
	Serdang		41.61	1.36		

*Rainfall data only recorded at Jambatan Petaling.

3.2 Case 2: GPS PWV Variation during the Flash Flood in October 2013

Another flash flood that hit Klang Valley was on 10 October after 3 h of rainfall at 1700 LT. Figure 3 shows the variation of GPS PWV at the three GPS stations as well as the total rainfall and changes of river water level. DIDM classified the water level into four levels: normal (24 m), alert (28 m), warning (29 m) and danger (30 m).

Similar to Figure 2, Figure 3(a) shows that the variation of PWV at the three nearest stations correlated to the total rainfall and changes of river water level. The PWV at UPMS was recorded to be the lowest, while it was the highest at BANT. During the five consecutive days of monitoring, the PWV reached a minimum peak in the afternoon, with 2 minimum peaks at UPMS in the evening of 9 October. The first rainfall was recorded in the evening of 10 October **(i)** as shown in Figure 3(b), which caused the flash flood at several parts of Klang Valley. From our observation, rainfall occurred later after the PWV dropped at all the stations. Before the rainfall, we identified a 4 mm drop of PWV at UPMS, and 4 and 9 mm drops at BANT and MERU respectively. The PWV at BANT and MERU dropped later than in UPMS with lead times of 3 and 4 h respectively. The other two rainfall events were in the evenings of 11 and 12 October as indicated by **(ii)** and **(iii)**, which led to drops of PWV at all the stations. The most PWV response with decreasing trend on 11 October before light rainfall can be seen at UPMS, while the least PWV occurred at MERU. On 12 October, the PWV at all the stations showed a decreasing trend before the light rainfall with lead time of 2 h. The river water level in Figure 3(c) increased drastically above the warning level in the evening of 10 October, which is believed to have caused the flash flood in the surrounding areas. The river water level then continued to rise on the following day and only declined to the normal level on 12 October. However, the light rainfall in the evening of 12 October caused a 1 m rise of river water level. Before that, we observed that the river water level increased drastically, reaching the alert level on 9 October even though no rainfall was recorded. It could be that the rainfall in the surrounding areas was not recorded at the Leboh Pasar DID station.

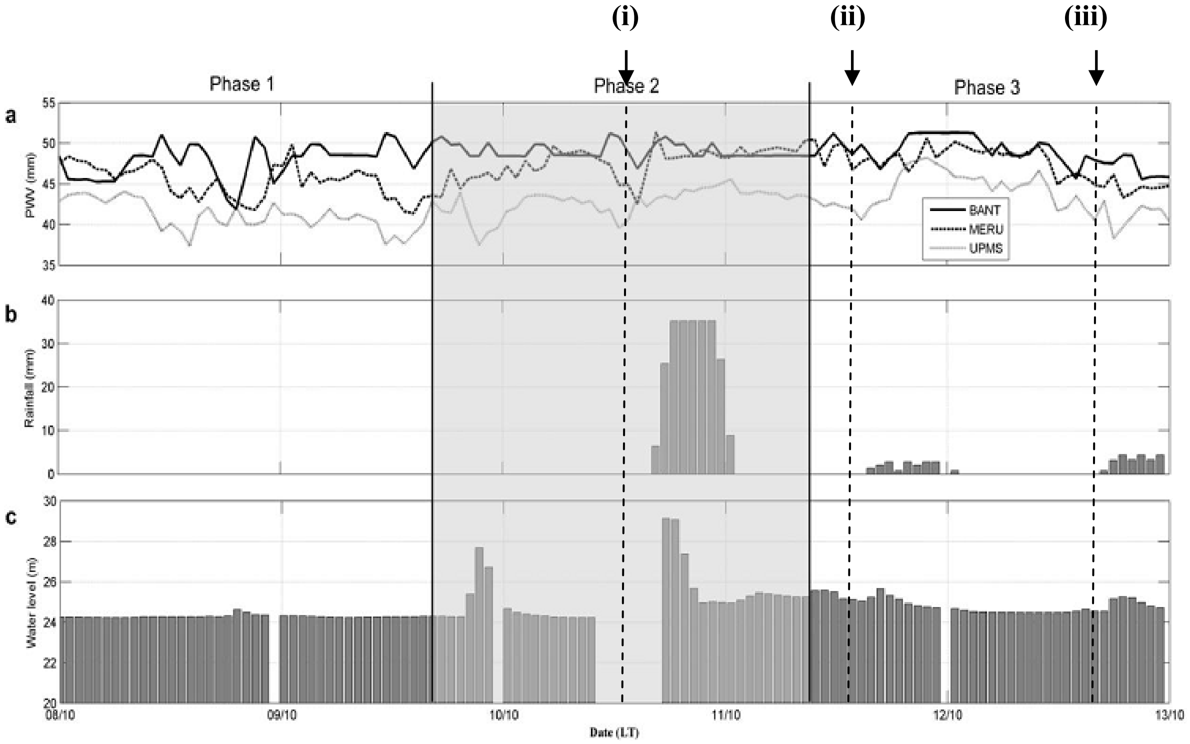

Figure 3: Variation of (a) PWV at the three GPS stations, (b) rainfall and (c) river water level for the five day period from 8 to 13 October 2013, where the flash flood event occurred on 10 October.

As shown in Table 3, we found that the mean PWV at all the three stations was the highest within 40 h (Phase 2) of the event, which is 1 mm higher as compared to Phases 1 and 3. This indicates that Phase 2 was wetter than Phases 1 and 3, where the increasing PWV trend (Figure 3(a)) in the evening of 9 October was maintained at a high level until the morning of 12 October. The STD of PWV at every GPS station was almost 2 mm before and after the flash flood incident, but lowest in Phase 2. The STD decreased by 1 mm from Phases 1 to 2 and increased by 1 mm when entering Phase 3. This pattern was opposite from the pattern of the flash flood in September.

As mentioned before, there was no rainfall recorded in Phase 1, resulting in no variation of rainfall in this phase. The first occurrence of rainfall in Phase 2 was in the evening of 10 October, which was recorded at 35 mm with STD of 13 mm. The light rainfall event repeatedly occurred in the evening of the following day and another day which caused deviation of 1.52 mm.

Table 2: Statistical values of GPS PWV and rainfall for the five days of observations in Figure 3.

Phase	Station		GPS (mm)		Rainfall (mm)	
	GPS	Rainfall*	Mean	STD	Mean	STD
1	Banting		48.11	1.92	0.00	0.00
	Meru		47.23	1.92		
	Serdang		46.51	1.89		
2	Banting	Leboh Pasar	48.79	0.89	6.11	12.57
	Meru		48.80	0.89		
	Serdang		48.02	0.88		
3	Banting		47.52	1.53	1.04	1.52
	Meru		47.53	1.53		
	Serdang		46.78	1.51		

*Rainfall data only recorded at Leboh Pasar. All values are in mm.

3.3 Variation of Local Wind Activity

The variation of local wind activity in the three phases of the flash flood for Cases 1 and 2 is shown in Figure 4. There are five descriptions of the wind, namely calm (<0.5 m/s) and light (0.5-1.7 m/s) air, and light (1.7-3.3 m/s), gentle (3.3-5.6 m/s) and moderate (5.6-8.3 m/s) breezes. According to Beaufort Wind Force Scale (Beer, 2013), the wind description indicates the strength of the wind force creates the local weather condition. In this study, the Beaufort Force ranged between Forces 0 to 4.

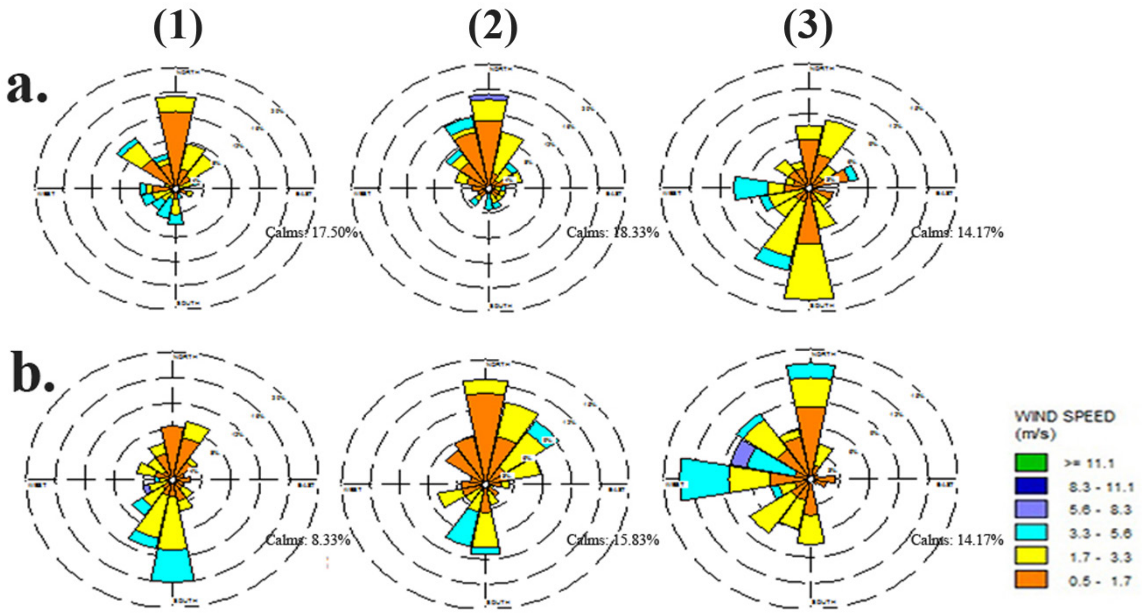

Figure 4: Average local wind variability for Cases (a) 1 and (b) 2, where each case is divided into three phases.

For Phase 1 of the flash floods, for Case 1, 30% of the wind prevailed from the north of the region, consisting mostly of light air and almost 30% of light breeze (Figure 4(a, 1)), while for Case 2, the wind gusted from the south (Figure 4(b, 1)), consisting of gentle and light breezes as well as some light air. The total frequency of the calm and light air that blew in this phase was 58% and 54% for Cases 1 and 2 respectively. For Phase 2, most of the wind distributed from the north (Figures 4(a, 2) and 4(b, 2)), which consisted mostly of light air and light breeze. Some of the wind in Case 2 (about 25%) blew from the south. More than 60% of calm and light air was recorded in this phase for both cases. In Phase 3, for Case 1, the highest distribution of wind prevailed from the southwest and north in the first case (Figure 4 (a, 3)), while for Case 2, the wind mostly prevailed from the southwest and northwest (Figure 4 (b, 3). The distribution for both cases mostly consisted of light and gentle breezes as well as some moderate breeze in Case 2. A total of about 55% of calm and light air was recorded in this phase at both cases.

Wind direction and speed are the important factors to determine the movement of clouds from one area to another. They are also crucial factors in forecasting the event of rainfall, and thus predicting weather related circumstances at flood prone areas such as Klang Valley. Based on both cases of flash floods, the highest distribution of calm and light air was identified in Phase 2, where the flash flood hazards were reported. These were related to the water cycle activities, where during Phase 1, the net wind force was able to transport the convective clouds from Klang Valley. However, the high amount of calm and light air in Phase 2 was not adequate to produce enough force to transport the convective clouds from Klang Valley. Hence, the convective clouds were sustained longer over the Klang Valley and the evaporation occurred until a certain level of precipitation. As a result, the rainfalls occurred frequently, which contributed to the flash flood hazards. Later on in Phase 3, the wind distribution consisted of light, gentle and moderate breezes that produced adequate force to transport the remaining clouds from Klang Valley.

3.4 Association of PWV Variations with Accumulated Precipitations from TRMM

From our analysis of the TRMM images, specifically at latitude of 2 to 3 ˚N and longitude of 101.5 to 200.0 ˚E, where the three GPS stations are located (triangle), we found that the accumulated precipitation was greatest in the evening during the 1 September and 10 October flash flood events. As shown in Figure 5(a), the accumulated precipitation was less than 15 mm in the afternoon of 1 September. Precipitation of less than 60 mm occurred at MERU. All the stations did not receive rainfall during this time until 14:00 LT. At this point, the stations in UPMS and BANT received 40 mm of rainfall, while the station in MERU received less than 20 mm of rainfall or none as shown in Figure 4(b). At this time (Figure 5(b)), North Malaysia (Kedah and Perlis) received more precipitation. For the three stations, heavy rainfall occurred in the evening on 1 September.

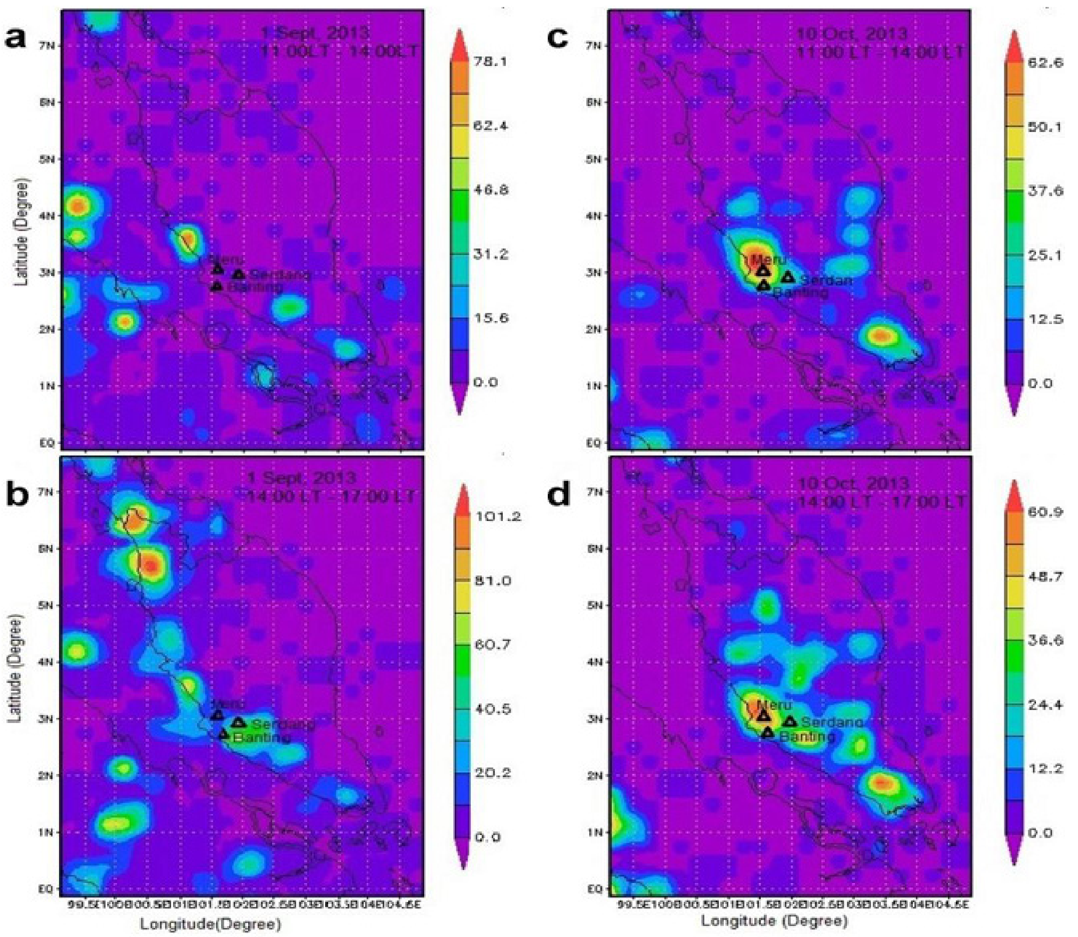

Figure 5: Accumulated precipitation (mm) from TRMM for: (a) 1100 to 1400 LT, 1 September (b) 1400 to 1700 LT, 1 September (c) 1100 to 1400 LT, 10 October (d) 1400 until 1700 LT, 10 October.

Figure 5(c) shows the accumulated precipitation in the afternoon on 10 October, where it was higher than 30 mm at all the stations. The accumulated precipitation then increased to more than 35 mm in the evening as shown in Figure 5(d). It was similar to the heavy rainfall recorded at this time, amounting to 35 mm hourly. As shown in the contour image, the accumulated precipitation in October was higher than in September. Based on Figure 5, the accumulated precipitation within 6 h in October was 15 mm greater as compared to September. The accumulation of precipitation in September was less than 15 mm, which occurred in the afternoon. On the other hand, in these flash flood cases, the accumulated precipitation in Figure 5 was linearly correlated with the amount of GPS PWV in Figures 2 and 3.

4. CONCLUSION

In this paper, the monitoring of the variation of GPS PWV for the pre-, during and post-flash flood events in Klang Valley in September and October 2013 was reported. These flash flood events occurred during the early northeast monsoon season, with the heavy rainfall investigated by studying the increasing trend of PWV. Specifically, heavy rainfall in the evening during a flash flood can be detected earlier by looking at its decreasing trend of approximately 3 mm within 2 h before the rainfall event. Furthermore, the PWV varies slowly in the afternoon of a flash flood event. During the flash floods, the PWV in October was higher with lower STD as compared to in September, which contrasts with the amount of rainfall, where the mean and STD of rainfall in September was higher than in October. This indicates that the variation of PWV was influenced by the annual winter monsoon. The variability of PWV is also associated with wind properties, whereby higher frequency of calm and light air can be associated with higher level of PWV and weather related hazards such as flash floods.

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COMPARISON OF THREE CHLOROPHYLL-A ESTIMATION APPROACHES USING ASTER DATA ACQUIRED OVER SRI LANKAN COASTAL WATER BODIES

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ABSTRACT

In the present study, we compare the following Chlorophyll–a (Chl-a) estimation algorithms using ASTER data acquired over Sri Lankan coastal water bodies: (1) the simple band-ratio algorithm with simple atmospheric correction using dark object subtraction (DOS); (2) the single band-ratio algorithm with radiative transfer-based atmospheric correction using ENVI's FLAASH software including MODTRAN; and (3) our previously proposed algorithm based on combinations of ASTER and corrected MODIS Ocean Color-3 (OC3) data. First, several ASTER band ratios were regressively analyzed with in-situ Chl-a data acquired from the Negombo estuary and Puttalam lagoon in the west coast of Sri Lanka, and the band ratio with the highest correlation was selected. Then, time-series Chl-a distribution maps with the spatial resolution of ASTER/VNIR (15 m) were generated using the above three methods, and compared with the in-situ Chl-a data. Based on the result obtained, the FLAASH and ASTER/OC3 based methods showed high correlation with the in-situ Chl-a values (R^2 = 0.96 and 0.92 respectively), while the DOS based method showed low correlation (R^2 = 0.61), which indicates that the ASTER/OC3 based method will give equivalent performance to the FLAASH based method even though it does not need user-based atmospheric correction like the DOS and the FLAASH based methods.

Keywords: *Chlorophyll-a (Chl-a); ASTER; MODIS OC3; atmospheric correction; coastal water bodies.*

1. INTRODUCTION

Since chlorophyll-a (Chl-a) concentration depends on nutrients availability, it is a good indicator of the trophic status of water bodies. Satellite remote sensing is an effective monitoring tool for Chl-a concentration, which allows us to know Chl-a distributions widely and repeatedly for investigated areas (Pattiaratchi *et al.*, 1994), and also to study past trends even when in-situ data is not available (Dahdouh-Guebas, 2002). As Chl-a in coastal regions serves as an indicator of the ambient ocean optical environment, temporal changes in Chl-a can be potentially linked to terrestrial and human interactions in an estuarine watershed (Strange *et al.*, 1998), and remote sensing is the most effective monitoring tool for such changes in Chl-a. In remote sensing for Chl-a, typical target water bodies are oceanic waters, called Case 1 waters, which have color characteristics dominated by chlorophyll and have little suspended sediments or dissolved color substances. On the other hand, estuarine and coastal waters are generally called Case 2 waters, where sediments and dissolved substances also contribute to a color and interface with the spectral signal of Chl-a in a water body. Even though not many studies have been undertaken on Chl-a monitoring for Case 2 waters, such as tropical lagoons, because of its optical complexity, some investigators have been developing bio-optical algorithms suitable for these waters, where dissolved and particulate marine and terrigenous substances affect the surface color (Pattiaratchi *et al.*, 1994). Furthermore Chl-a estimation and monitoring with remote sensing data are strongly affected by the accuracy of atmospheric effect correction (Gabriele & Emanuele, 2010).

Based on this, we developed a Chl-a estimation algorithm particularly focusing on coastal lagoons in Sri Lanka, and analyzed long-term changes in Chl-a concentrations for two lagoons mainly in order to understand the impacts of human activities to their environments (Dahanayaka *et al.*, 2013). This method has been designed for estimating Chl-a from a simple band ratio of a higher spatial resolution sensor without any specific atmospheric correction, by combining Moderate Resolution Imaging Spectroradiometer (MODIS) Ocean Color 3 (OC3) Chl-a products which are produced using MODIS's standard chlorophyll algorithm, called OC3, incorporating the 443, 488 and 547 nm bands (O'Reilly *et al.*, 2000). For a higher resolution sensor, we used the Advanced Spaceborne Thermal Emission and Reflectance Radiometer (ASTER), which has three spectral bands with spatial resolution of 15 m and swath width of 60 km in the visible and near-infrared (VNIR) spectral regions (Yamaguchi *et al.*, 1998). Even though the spectral positions of ASTER/VNIR have not been designed for ocean color observations, several investigators have performed Chl-a estimation using ASTER data (Kishino *et al.*, 2000; Motoi *et al.*, 2002; Sakuno & Matsunaga, 2002; Sakuno *et al.*, 2002; Kishino *et al.*, 2005; Nas *et al.*, 2009), partly because ASTER data is not very expensive but has spatial resolution that is sufficiently high to target smaller water bodies, such as lagoons and estuaries.

An advantage of our ASTER/OC3 based method is that it does not need user-based atmospheric correction for ASTER data, but this method has not been fully validated through comparisons with traditional approaches, including atmospheric correction. In the present study, the ASTER/OC3 based method is therefore compared with band ratio methods combined with two different atmospheric correction approaches; dark object subtraction (DOS) and radiative transfer calculation using ENVI's Fast Line of Sight Atmospheric Analysis of Spectral Hypercubes (FLAASH) software (Cooleya *et al.*, 2002), including the Moderate Resolution Atmospheric Transmission (MODTRAN) code (Berk *et al.*, 1989).

2. METHODOLOGY

2. 1 Band Ratio Method With DOS

DOS is a simple but widely-used image-based atmospheric correction method (Lathrop *et al.*, 1991; Lavery *et al.*, 1993; Ekstrand, 1994; Huguenin *et al.*, 1997). The at-sensor radiance $L_T(\lambda)$ in the wavelength λ is given by:

$$L_T(\lambda) = L_W(\lambda) + L_A(\lambda) \quad (1)$$

where $L_W(\lambda)$ is the water leaving radiance attenuated by the atmosphere, and $L_A(\lambda)$ is the path radiance due to additive scattering effects. In the DOS method, $L_T(\lambda)$ for the darkest pixel within the scene is used as $L_A(\lambda)$, assuming that the incoming radiation to the darkest pixel's surface is perfectly absorbed by the surface and the radiance recorded by the sensor is due to $L_A(\lambda)$ alone, and $L_A(\lambda)$ remains constant for the whole image.

2.2 Band Ratio Method With FLAASH

More accurate retrieval of Chl-a from remote sensing data will require more accurate estimation of surface reflectance through modeling of atmospheric absorption and scattering. The FLAASH software (Cooleya *et al*., 2002), provided by Exelis Visual Information Solutions Inc., can be used as one of the solutions for such purpose. FLAASH is one of the modules mounted on the ENVI software, which is one of popular software products for remote sensing users, and allows physics-based atmospheric correction with support of the radiative transfer code, MODTRAN (Berk *et al*., 1989). FLAASH is designed to obtain surface reflectances from at-sensor radiances of various multi- and hyper-spectral sensors by eliminating atmospheric scattering and absorption effects through MODTRAN's radiative transfer modeling, water vapor and aerosol retrieval, and other features (Cooleya *et al*., 2002).

2.3 ASTER/OC3-Based Method

This method is basically a traditional Chl-a estimation with a band ratio in the VNIR spectral region, but user-based atmospheric correction is not required by combining another Chl-a product simultaneously observed. An atmospherically-uncorrected ASTER/VNIR image and a MODIS OC3 Chl-a product simultaneously observed are combined, and a Chl-a image with the spatial resolution of ASTER/VNIR (15 m) is generated. In the present paper, we refer to this as the ASTER/OC3 based method.

In our previous paper (Dahanayaka *et al*., 2013), three ASTER/VNIR band ratios, such as B1/B2, were regressively analyzed with a corrected MODIS Chl-a product observed at each ASTER observation time for the Negombo estuary and Puttalam lagoon, Sri Lanka. The MODIS Chl-a correction was performed using an equation obtained by the regression analysis between the MODIS and in-situ Chl-a data, because the OC3 algorithm would overestimate the results for tropical coastal waters (Brando *et al*., 2006). Finally, the ASTER band ratio with highest correlation with the corrected MODIS Chl-a was selected and its regression equation was used for generating high-resolution Chl-a distribution maps for all the ASTER observation dates. Due to the low resolution of MODIS for monitoring Sri Lankan lagoons, comparison between in-situ and MODIS OC3 was a somewhat difficult task. Hence, we depended on adjacent ocean locations for the comparison between ASTER and MODIS OC3. This extrapolation of the closest ocean condition to the lagoon environment is one of the limitations of the ASTER/OC3 based method, which uses MODIS OC3 products which have been validated by the MODIS Ocean Team.

3. EVALUATION STUDY

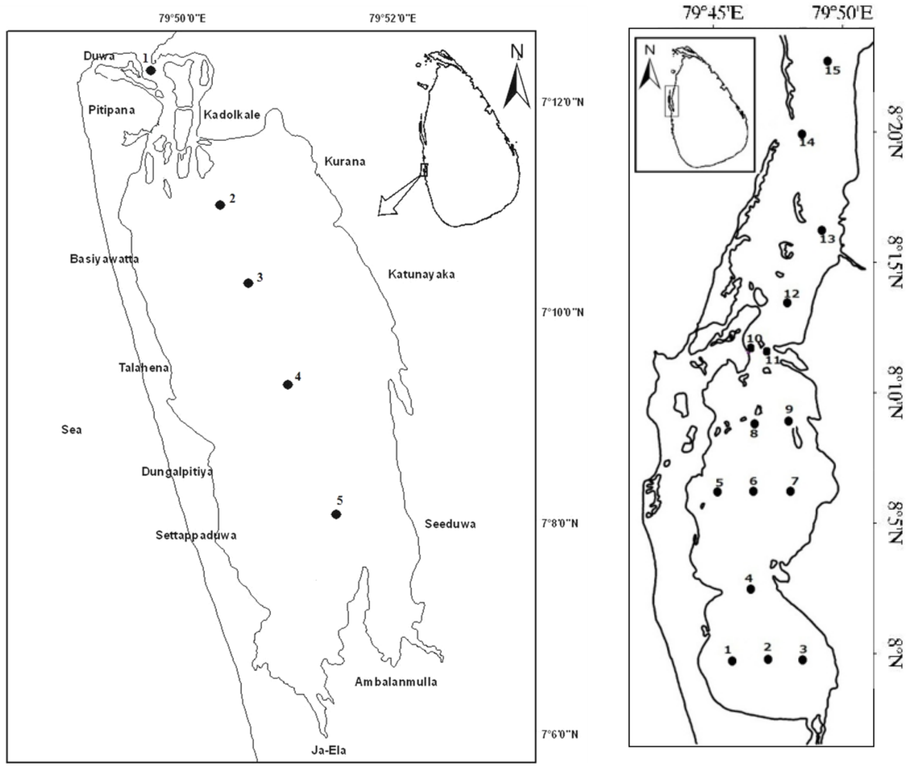
3.1 Sites

The west coast of Sri Lanka has been considerably developing with increases of population and investment opportunities for the past few centuries, but it has been putting pressure on estuarine environments. In addition, remote sensing has not almost been applied for Sri Lankan coastal water bodies, especially for water quality assessment (Dahanayaka *et al*., 2013). Considering these circumstances, two coastal water bodies were selected for the present study as representatives of highly productive fisheries with great significance for the local population. The Negombo estuary (7^o 6' - 7^o 12' N; 79^o 40' - 79^o 53' E) is a shallow basin estuary in the Western coastal region of Sri Lanka (Figure 1(a)). The surface area of the estuary is around 35 km², and approximately 10 km in length, 3.5 km in width at its widest point and has a mean depth of about 1.2 m (Dahanayaka *et al.*, 2013). The Puttalam lagoon (7º 45' – 8º 25' N; 79º 40' –79º 50'E) is the second largest lagoon in Sri Lanka, and located in the north-western coastal belt (Figure 1(b)). It covers an area of 230 km².

3.2 Data Used

3.2.1 In-situ Data

From January to December 2001, water samples were collected once per month at several points (Figure 1) in each water body, and Chl-a of each sample was measured using a laboratory spectrophotometer, as described by Richards & Thompson (1952). From March to June 2011, and in March 2012, Chl-a values were measured on site at several points in each lagoon using a handheld Chlorophyll meter (KRK CHL-30) based on Chl fluorescence.



(a) (b)

Figure 1: Maps of the (a) Negombo estuary and (b) Puttalam lagoon indicating the in-situ Chl-a sampling locations.

3.2.2 ASTER Data

ASTER scenes acquired for each water body under clear sky conditions were collected for Chl-a estimation. The number of scenes is ten for the Negombo estuary and eight for the Puttalam lagoon. Their observation dates are listed in Table 1. In all cases, ASTER level-1B products (registered radiance at the sensor product) were used as input data for the processing described below.

Table 1: ASTER observation dates for the Negombo estuary and Puttalam lagoon.

Negombo estuary		Puttalam lagoon	
2000/10/28	2011/3/17	2008/2/21	2011/5/13
2005/2/12	2011/4/11	2009/01/31	2011/5/20
2007/2/18	2011/5/20	2011/3/10	2012/3/12
2007/12/3	2012/3/3	2011/3/17	2012/3/19
2009/2/16	2012/3/19	2011/3/26	

3.3 Data Processing

First, all the ASTER images were atmospherically corrected using DOS and FLAASH. In DOS, pixels in open ocean (~30 km offshore) with very low productivity were selected for determination of dark pixel characteristics (assumed to be pixels with chlorophyll concentrations < 0.3 μg^{-1}) (Pattiaratchi *et al.*, 1990). In FLAASH, the tropical atmospheric and maritime aerosol models were used. Then, the ASTER band ratios for three band pairs were calculated from the atmospherically corrected images and regressively analyzed with the in-situ Chl-a data, so that the ratio of green (B1) to red (B2) bands with the highest correlation (R^2 = 0.68 and 0.57 for FLAASH and DOS respectively) was used for generation of Chl-a distribution maps. The reflectance ratio of B1 to B2 is generally a robust parameter to estimate the Chl-a content (Dahanayaka *et al.*, 2013).

On the other hand, the ASTER/OC3 based method was applied to each ASTER image as follows. First, the MODIS OC3 product simultaneously observed with each ASTER image was corrected using the following equation:

$$Chl\_corr = (Chl\_org - 0.5453) / 1.1027 \qquad (2)$$

where *Chl_corr* is the corrected MODIS OC3 Chl-a and *Chl_org* is the original MODIS OC3 Chl-a. This equation was obtained using regression analysis with the in-situ data. Next, three ASTER band ratios were regressively analyzed with the corrected OC3 Chl-a values on a day-by-day basis, and the ratio of B1 to B2 with the highest correlation (R^2 = 0.71) was used for generation of Chl-a distribution maps. Thus, Chl-a distribution maps with a spatial resolution of 15 m for the Negombo estuary and Puttalam lagoon were obtained for each ASTER observation date using the three approaches (DOS, FLAASH, and ASTER/OC3), and were compared with the in-situ measurements.

4. RESULTS AND DISCUSSION

Figure 2 shows the plots between the corrected MODIS OC3 Chl-a and the ASTER band ratio of B1 to B2. As shown, their correlation is high (R^2 = 0.71), while the middle range of Chl-a indicates somewhat larger scatters. This regression equation was used for Chl-a map generation using the ASTER/OC3 based method. Figure 3 shows the plots of the in-situ Chl-a and ASTER based Chl-a for the three approaches (DOS, FLAASH, and ASTER/OC3), which indicates higher correlations for FLAASH (R^2 = 0.96) and ASTER/OC3 (R^2 = 0.92), and lower correlation for DOS (R^2 = 0.61). This indicates that the ASTER/OC3 based method can work well even though it does not require user-based atmospheric correction like DOS and FLAASH.

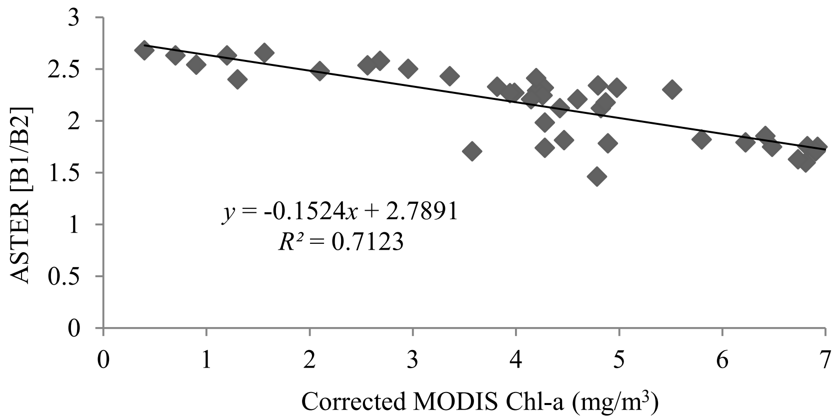


Figure 2: Correlation between the corrected MODIS Chl-a and ASTER [B1/B2].

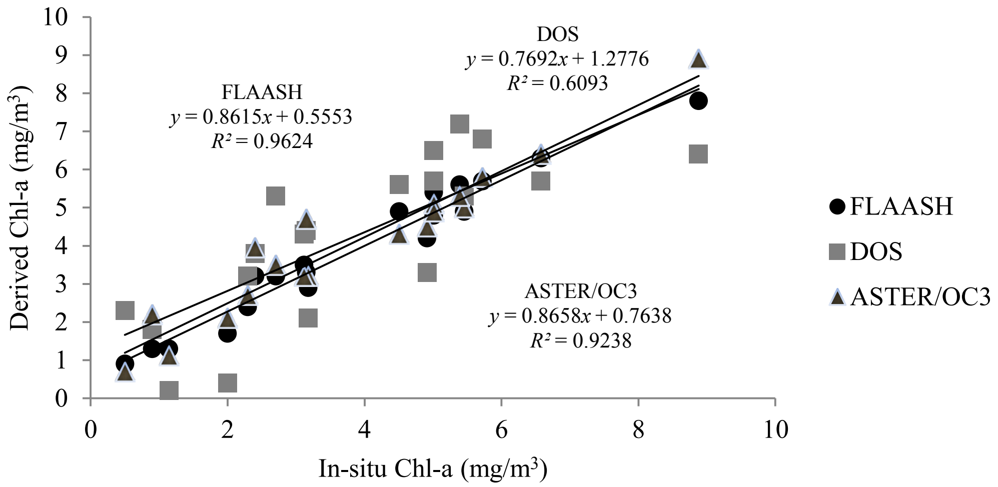
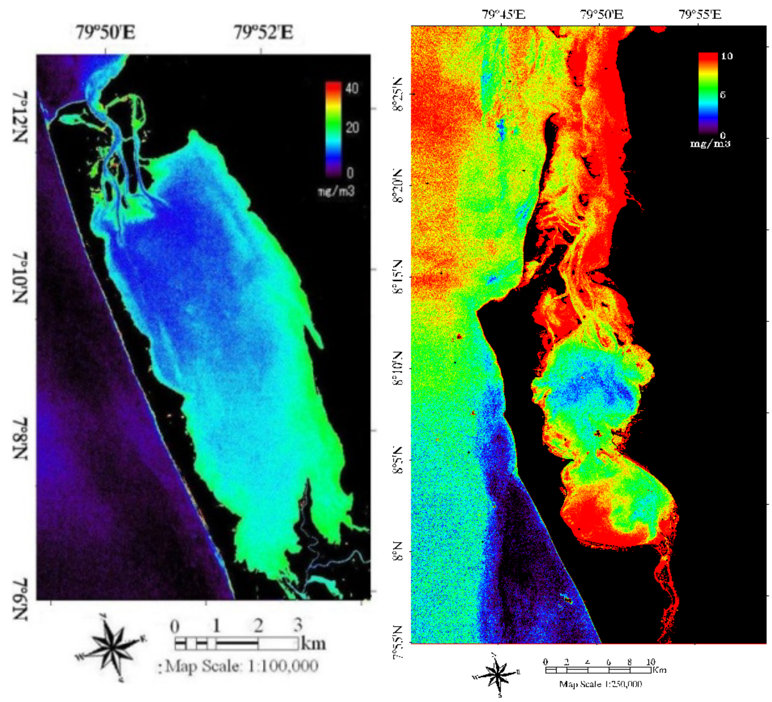


Figure 3: Comparison between estimated Chl-a using the DOS, FLAASH and ASTER/OC3 based methods with in-situ Chl-a.

Figure 4 shows examples of the Chl-a distribution maps obtained for the Negombo estuary and Puttalam lagoon using the ASTER/OC3 based method. These images are basically similar to each other for DOS, FLAASH and ASTER/OC3 in their spatial patterns, but the images for DOS show some biases from those by FLAASH and ASTER/OC3 on a day-by-day basis as predicted by Figure 3, indicating that FLAASH and ASTER/OC3 are better for higher accuracy and stability.



(a) **(b)**

Figure 4: Chl-a distribution maps derived using the ASTER/OC3 based method: (a) Negombo estuary on Feb 16, 2009. (b) Puttalam lagoon on Jan 31, 2009.

5. CONCLUSION

The DOS based Chl-a values showed much larger variance than the FLAASH and ASTER/OC3 based Chl-a values. This indicates that the DOS based method is less stable or less robust than the other methods. The FLAASH and ASTER/OC3 based method showed similar performance, which indicates that they are more applicable for Sri Lankan lagoons. In the comparison between these two methods, the ASTER/OC3 based method has an advantage in that it does not require any user-based atmospheric correction like the FLAASH based method. This will make it easier to develop a Chl-a database for tropical lagoons in the future. At present, the stability of the OC3 correction equation used in the ASTER/OC3 based method has not fully been validated. Therefore, we will focus on this study as the next step.

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LANDFORM CLASSIFICATION OF ZAGROS MOUNTAINS USING MULTISCALE ANALYSIS OF DIGITAL ELEVATION MODELS

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ABSTRACT

This study is aimed at performing landform classification using multiscale analysis, which is implemented on Shuttle Radar Topography Mission (SRTM) digital elevation models (DEMs) with spatial resolution of 90 m using quadratic parameterization and the lifting scheme. Multiscale DEMs with scales of 5 to 55 cells are prepared using the two methods. Based on the landform classification method of topographic position index (TPI), landform maps are generated for each multiscale DEM. The study is conducted for Zagros Mountains, Iran to evaluate the effectiveness of the classification and to determine the characteristic scale for landform classification in the study area. Through comparisons with geology maps of the study area, the results obtained show that the lifting scheme provides higher accuracy than quadratic parameterization. This is due to its ability to preserve accurate surface profiles, in terms of waveform, shape and amplitude, without causing boundary destruction.

Keywords: Landform classification; multiscale digital elevation models (DEMs); lifting scheme; quadratic parameterization; topographic position index (TPI).

1. INTRODUCTION

The effects of common geological and geomorphological processes generate different types of landforms, with the term used being morphometrically homogeneous land-surface regions (Crevenna *et al*., 2005). Geomorphometry is a sub-discipline of geomorphology, which provides quantitative description and measurement of landforms (Pike & Dikau, 1995; Dehn *et al*., 2001; Pike, 2002; Crevenna *et al*., 2005). The main feature of geomorphometry is that there exists a relationship between relief forms and terrain parameters, and processes related to its evolution (Crevenna *et al*., 2005). Morphometric studies usually start with the extraction of terrain parameters of relief, such as slope, aspect, elevation. Wood (1996) suggested a group of algorithms for describing relief as morphometric classes.

The input data for landform classification consists of topographic maps, aerial stereophotos, satellite imagery and digital elevation models (DEMs). A number of studies have employed DEMs for the automated mapping of landforms (MacMillan *et al*., 2000; Burrough *et al*., 2000; Meybeck *et al*., 2001; Schmidt & Hewitt, 2004; Saadat *et al*., 2008; Verhagen & Drăguţ, 2010; Migon *et al*., 2013). There are several approaches for derivation of landforms, including classification of terrain parameters (Dikau *et al*., 1995; Dikau, 1989), filter techniques (Sulebak *et al*., 1997), cluster analysis (Sulebak *et al*., 1997; Dikau et al., 1995) and multivariate statistics

(Adediran *et al*., 2004). Landforms are formed by small and simple elements which are topologically and structurally related. Using complex terrain parameters calculated from simple ones, such as topographic wetness index (Moore & Nieber, 1989), stream power index (Moore *et al*., 1993a), and aggradation and degradation indices (Moore *et al*., 1993b), more complete landforms can be described. In geomorphologic studies, DEMs are the information base for extracting basic components and terrain parameters.

Geometric characteristics, such as terrain parameters, of topographic forms of the earth surface vary with different spatial scales. Hence, changing the scale can result in representation of patterns or processes that are different from those intended, including loss of detail, and variations in terrain parameters and landforms (Lam *et al*., 2004; Summerfield, 2005; Drăguţ *et al*., 2011; Goodchild, 2011). Hence, in various studies, feature detection often needs to be performed at different scales of measurement. In order to extract greater amount of information from a DEM about the spatial characteristics of a feature, analysis of a location at multiple scales is required (Wood, 2009; Drăguţ *et al*., 2009, 2011; Poulos *et al*., 2012).

This paper focuses on landform classification via multiscale analysis of DEMs. For landform classification, the determination of the appropriate scale for analysis is important. According to Wood (1996, 2009), this clearly depends on the extent of the nature of the application and the inherent scale of the features under study. This may be determined as the characteristic scale of the study of interest. Size and spacing of landforms often show clustering around characteristic scales (Evans, 2003).

In this study, in order to determine characteristic scales for landform classification, multiscale DEMs are generated using quadratic parameterization (Wood, 1996) and the lifting scheme (Sweldens, 1996, 1997). Landform classification is then performed using topographic position index (TPI). The generated landform maps via quadratic parameterization and the lifting scheme are compared, and the characteristic scales for preparing the landform maps are selected for the study area, which is Zagros Mountains, Iran. Comparisons with geology maps of the study area are used to determine the accuracy of the landform maps.

2. MATERIALS AND METHODS

2.1 Study Area

The study area consists of three different case areas of Zagros Mountains (Figure 1), which are:

- Case 1 (Grain Mountain) is located at 33° 49′ 15″ to 33° 58′ 17″ N and 48° 39′ 12″ to 48° 52′ 03″ E, with area of 315.35 km^2
- Case 2 (Oshtorankooh Mountain) is located at 32° 46′ 27″ to 32° 55′ 18″ N and 43° 27′ 24″to 49° 15′ 30″ E, with area of 288.02 km^2
- Case 3 (Zardkooh Mountain) is located at 32° 30′ 04″ to 32° 39′ 25″ N and 49° 54′ 24″ to 50° 06′ 50″ E, with area of 318.46 km^2.

The highest elevation for these cases is 4,102 m for Case 3, which is located in the north of the area, while the lowest elevation is 815 m for Case 2, which is located in the southwest of area. The dataset for the area originates from a Shuttle Radar Topography Mission (SRTM) DEM with resolution of 90 m, which was downloaded from http://srtm.csi.cgiar.org.

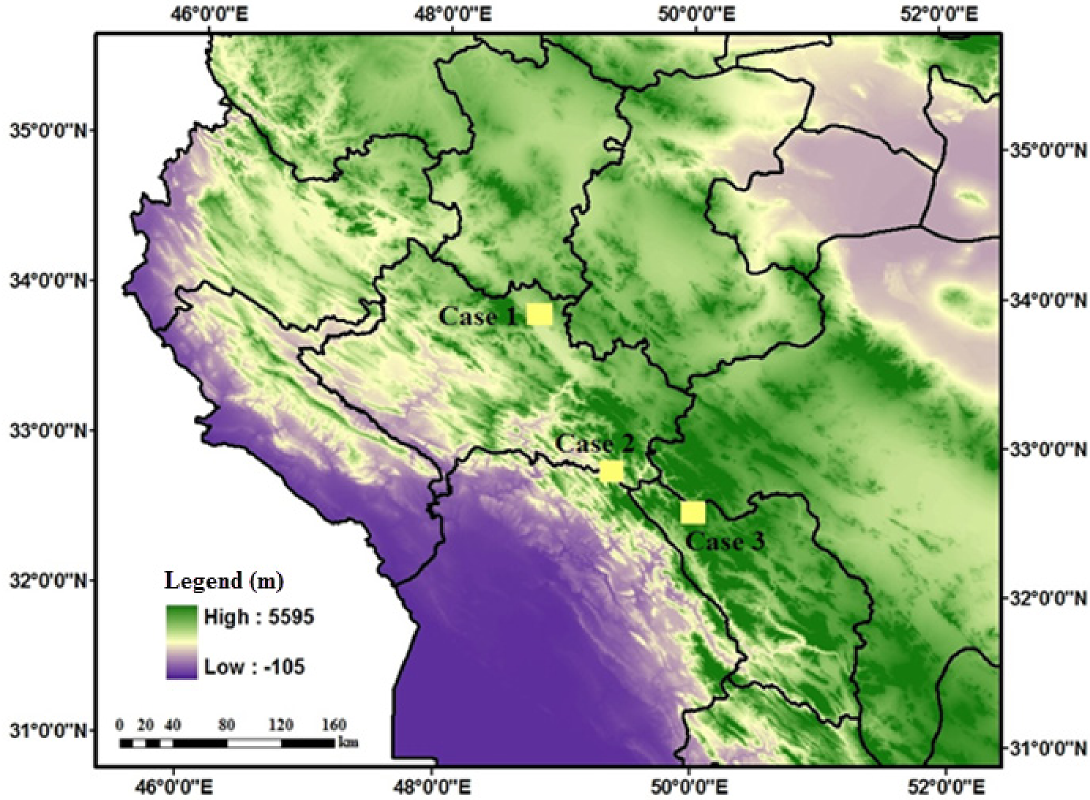


Figure 1: Location of the study area.

2.2 Generation of Multiscale DEMs

2.2.1 Quadratic Parameterization

Consider the derivation of the six coefficients (Equation 1) that define a quadratic trend surface with a local window passed over the DEM and the change in gradient of a central point in relation to its neighbors, which is derived by a second degree polynomial function (Evans, 1972):

$$z = ax^2 + by^2 + cxy + dx + ey + f \tag{1}$$

where:

Slope = arctan (sqrt $(d^2 + e^2)$)
Cross-sectional curvature = $n * g\ (b * d^2 + a * e^2 - c * d * e) / (d^2 + e^2)$
Maximum curvature = $n * g\ (-a - b + \text{sqrt}\ ((a-b))) * (a-b) + c^2$
Minimum curvature = $n * g\ (-a - b - \text{sqrt}\ ((a-b))) * (a-b) + c^2$

with:

g: Grid resolution of the DEM
n: Size of window
a to f: Quadratic coefficient
x, y: Local coordinates
z: Elevation.

This is more conventionally expressed as a specific case of a more general polynomial expression (Equation 2) (Unwin, 1975; Unwin & Wrigley, 1987):

$$z_i = b_0 + b_1 x_i + b_2 y_i + b_3 {x_i}^2 + b_4 x_i y_i + b_5 {y_i}^2 \quad (2)$$

To solve this expression, the number of points sampled i must be at least 6. If we limit the sample of elevation values to a square window centered around the point of interest, i will be 9, 16, 25, ... n^2 as the local window increases from the smallest size (3 x 3 cells) to the largest size (n x n). The resultant quadratic expression will be identical to Evans' quadratic derivation (Evans, 1979).

2.2.2 Lifting Scheme

A powerful multiscale analysis tool in image and signal processing is the lifting scheme (Claypoole & Baraniuk, 2000; Starck, 2002; Guo *et al*., 2008; Abdul-Rahman *et al*., 2013), which was proposed by Sweldens (1996, 1997). Recently, it has received attention in geospatial analysis (Hayat *et al*., 2008; Yang *et al*., 2009; Ahmad Fadzil *et al*., 2011; Chiao *et al*., 2012), due to its ability to preserve accurate surface profiles, form and amplitude, without causing boundary destruction (Jiang *et al*., 2001a, b; Nonomura *et al*., 2010). It is used to separate a basic dataset into low and high frequency subsets using the following three steps:

Step 1: Split

The original dataset $x[n]$ is decomposed into two subsets, even $x_e[n]$ and odd $x_o[n]$ indexed point.

Step 2: Predict

There is often high correlation between the odd and even subsets. As this relationship structure is typically local, one subset can be used to predict the other subset. Hence, the even indexed subset is used to predict the odd indexed subset using the predict operator P (Equation 3). The high frequency subset $d[n]$ is the difference between the predicted and original odd indexed subsets (Equation 4). The input for the next step is the even indexed subset that is left unchanged.

$$P(x_o[n]) = 1/2(x_e[n] + x_e[n+1]) \quad (3)$$

$$d[n] = x_o[n] - P(x_o[n]) \quad (4)$$

Step 3: Update

The even indexed subset is replaced with an average by applying the update operator U to $d[n]$ (Equation 5) and adding it to the even indexed subset (Equation 6). This gives the low frequency subset $c[n]$, which is a smoother output that shows a coarse estimation to the original dataset.

$$U(d[n]) = 1/4(d[n-1] + d[n+1]) \quad (5)$$

$$c[n] = x_e[n] + U(d[n]) \quad (6)$$

An iteration of the lifting scheme produces a complete set of multiscale DEMs $c_s[n]$ and the elevation loss caused by the change of scale $d_s[n]$. As $c_s[n]$ at each iteration only contains half of the points of the input for the iteration, the spatial resolution of the generated multiscale DEM is reduced by half.

2.3 Landform Classification

TPI compares the elevation of each cell in a DEM to the mean elevation of a specified vicinity of the cell. Positive TPI values indicate locations that are higher than the average of their neighborhoods, as determined by the surroundings (ridges). On the other hand, negative TPI values indicate locations that are lower than their neighborhoods (valleys). TPI values near zero are either plain areas (where the slope is near zero) or areas of stable slope (where the slope of the cell is mainly greater than zero). Mean elevation is subtracted from the elevation value at the center of the neighborhood (Weiss, 2001):

$$TPI_i = Z_0 - \sum_{n-1} Z_n / n \qquad (7)$$

where:

Z_0= elevation of the model cell under evaluation
Z_n= elevation values of grid cells defining the neighborhood
n = cells in the neighborhood

Incorporating TPI using small and large neighborhoods allows for a variety of landforms to be classified (Table 1). To classify very small features like small streams or drainages, a small square neighborhood (5 cells) is used, while to identify large canyons and mountains, a large square neighborhood (45 cells) is used. High and low TPI values are distinguished by setting a threshold of ±1 SD (standard deviation).

$$SD = \sqrt{\frac{\sum_{i=1}^{n} x_i - \bar{x}}{n}} \qquad (8)$$

where:

x_i: Elevation at cell i
$\bar{x}$: Average elevation
n: Number of the neighborhood points.

In the cases where TPI values from both neighborhood sizes are between -1 and 1, small plains and midslope areas are distinguished by using a threshold slope value of 5°. A full description of each morphological classification can be found in Weiss (2001) and Jenness (2006). The precise breakpoints among classes can be manually chosen to optimize the classification for different landscapes. Additional topographic metrics, such as variances of elevation, slope and aspect within the surroundings, can increase the accuracy of the classification (Weiss, 2001; Tagil & Jenness, 2008).

The classes of canyons, deeply incised streams, midslope and upland drainages, and shallow valleys tend to have strongly negative plane form curvature values. On the other hand, local ridges/hills in valleys, midslope ridges, small hills in plains and mountain tops, and high ridges have strongly positive plane form curvature values (Weiss, 2001; Tagil & Jenness, 2008). For this study, the implementation of TPI was done using ArcsGIS' Topographic Tools 9.3 extension.

Table 1: Landform classification based on TPI .
(Source: Weiss, 2001)

Classes	Description
Canyons, deeply incised streams	Small Neighborhood: TPI ≤ -1 SD Large Neighborhood: TPI ≤ -1 SD
Midslope drainages, shallow valleys	Small Neighborhood: TPI ≤ -1 SD Large Neighborhood: -1 SD < TPI < 1 SD
Upland drainages, headwaters	Small Neighborhood: TPI ≤ -1 SD Large Neighborhood: TPI ≥ 1 SD
U-shaped valleys	Small Neighborhood: -1 SD< TPI < 1SD Large Neighborhood: TPI ≤ -1 SD
Plains small	Neighborhood: -1 SD < TPI < 1 SD Large Neighborhood: -1 SD < TPI < 1 SD Slope ≤ 5°
Open slopes	Small Neighborhood: -1 SD < TPI < 1 SD Large Neighborhood: -1 SD < TPI < 1 SD Slope > 5°
Upper slopes, mesas	Small Neighborhood: -1 SD < TPI < 1 SD Large Neighborhood: TPI ≥ 1 SD
Local ridges/hills in valleys	Small Neighborhood: TPI ≥ 1 SD Large Neighborhood: TPI ≤ -1 SD
Midslope ridges, small hills in plains	Small Neighborhood: TPI ≥ 1 SD Large Neighborhood: -1 SD < TPI < 1 SD
Mountain tops, high ridges	Small Neighborhood: TPI ≥ 1 SD Large Neighborhood: TPI ≥ 1 SD

3. RESULTS AND DISCUSSION

Multiscale DEMs of the study area were generated by implementing quadratic parameterization and the lifting scheme on the DEMs using scales of 5 to 55 cells. As shown in Figure 2, due to decreasing spatial resolution with increasing scale, the smaller the scale (cell size), the more detail that is shown as compared to the larger scales.

The TPI maps generated using small and large neighborhoods are shown in Figures 3 and 4 respectively. For the lifting scheme and quadratic parameterization, the maximum and minimum values of TPI obtained are shown in Table 2.

The landform maps generated based on the TPI values are shown in Figure 5. Based on the comparison of landforms extracted using the two methods (Figures 6-8), it is observed that with increasing scale, due to the decreasing spatial resolution, less details of the region are visible. It is also observed that the maximum difference of classes between the two methods is related to scale. In order to determine the accuracy of the methods, scales of 15, 35 and 55 should be analyzed for Cases 1, 2 and 3 respectively, as these are the characteristic scales with the most details shown (Figure 9).

For comparison of landform classification using the two methods, 30 points are randomly selected for Cases 1, 2 and 3 (Figure 10) to check the landforms at the selected characteristic scales with the geology maps of the case areas (Figure 11) based on the relationships between landforms and geology classes (Table 3). It was found that landform classification using the lifting scheme (95 %) provided higher accuracy than using quadratic parameterization (73 %) (Table 4).

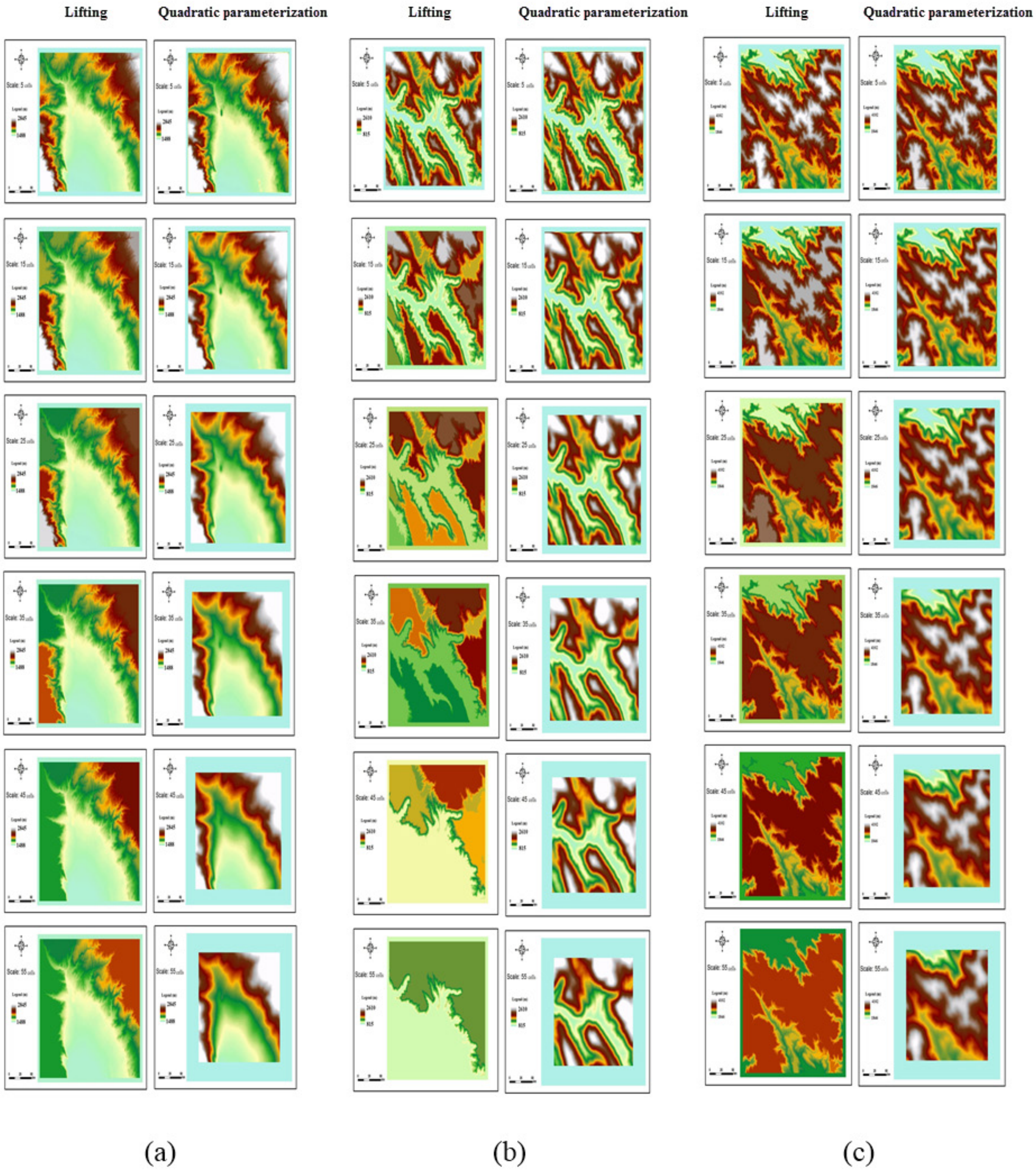


Figure 2: Relief shapes of the generated multiscale DEMs for: (a) Case 1 (b) Case 2 (c) Case 3.

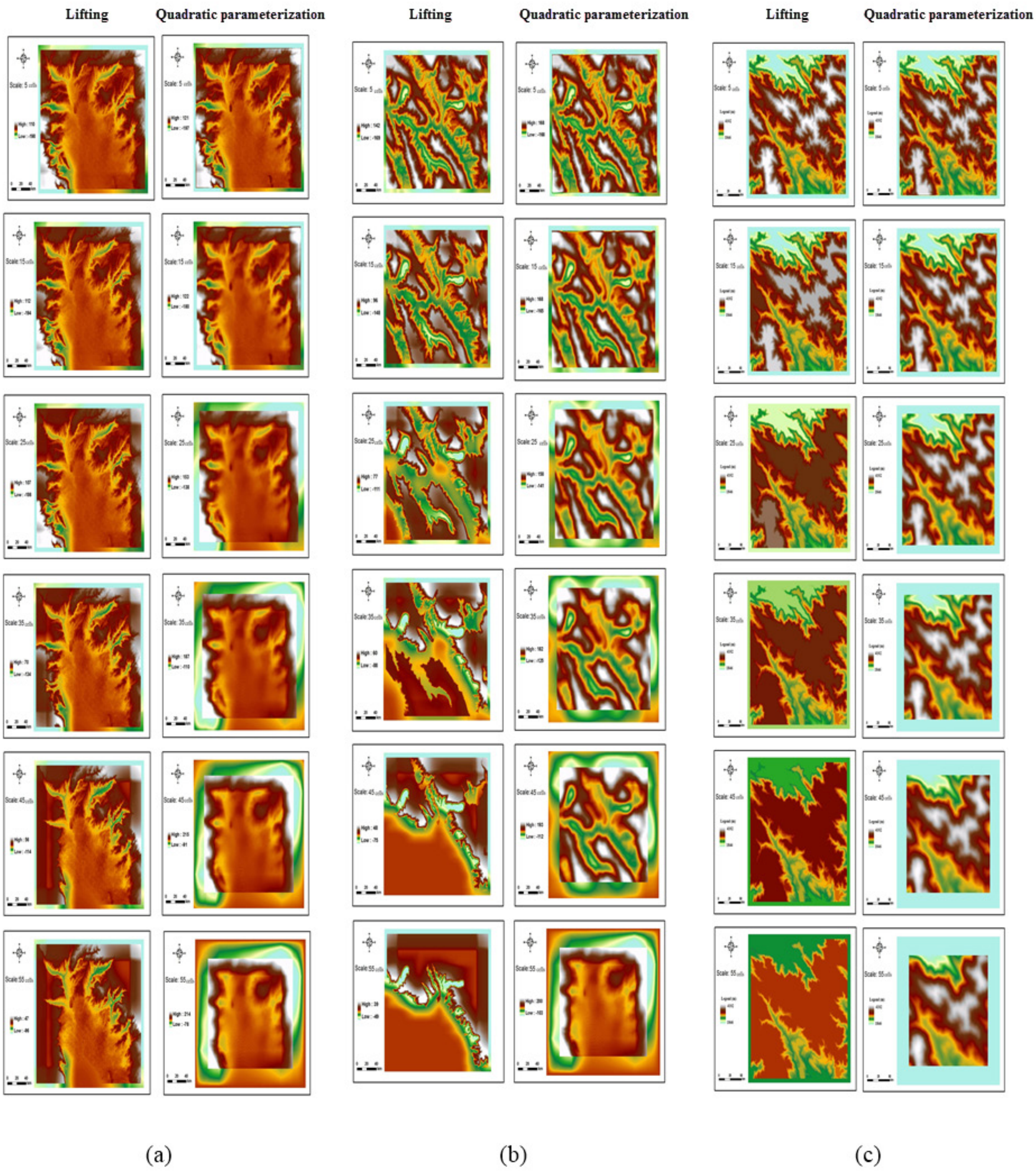
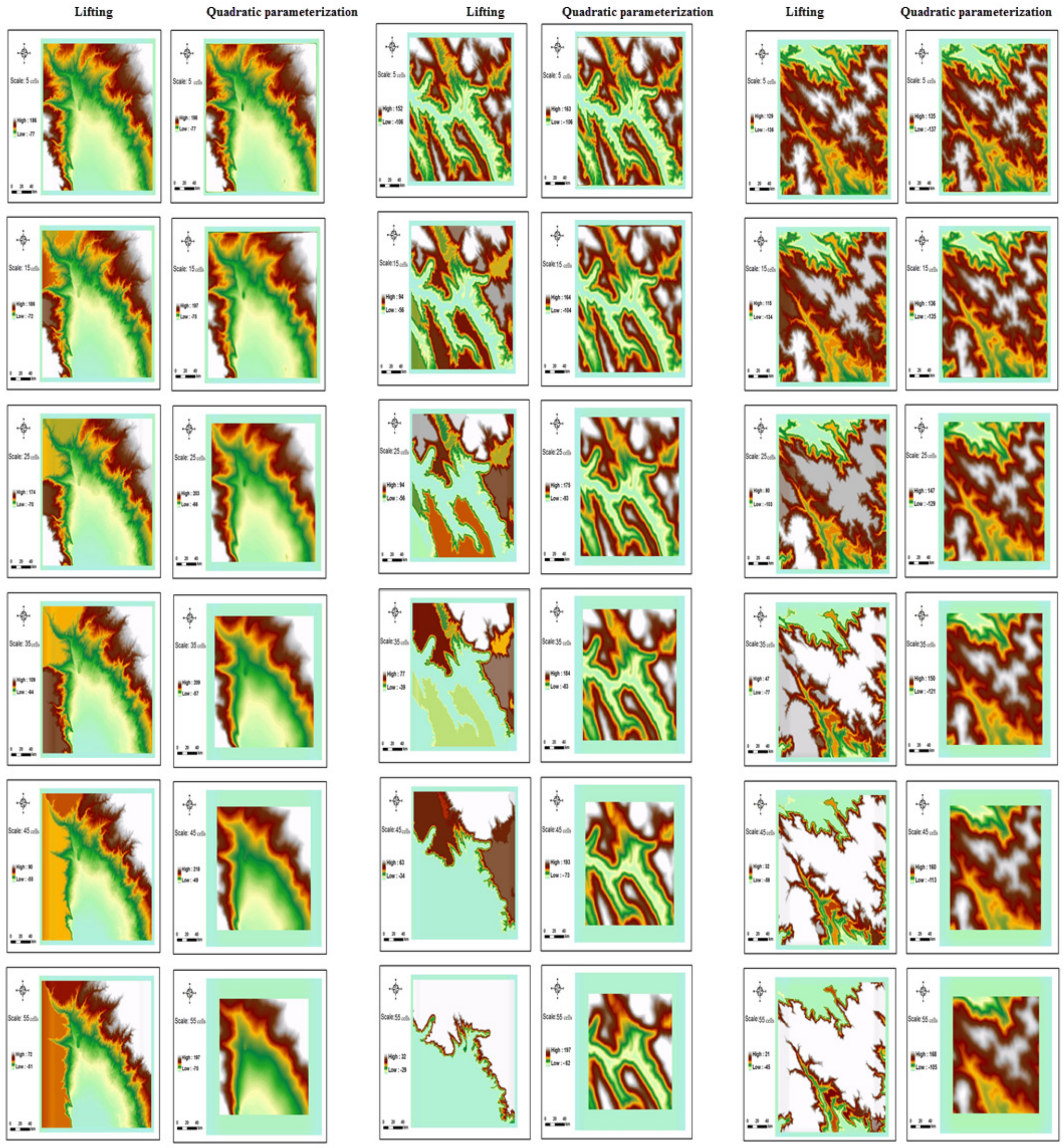


Figure 3: TPI maps generated using small neighborhood (5 cells) for the multiscale DEMs for: (a) Case 1 (b) Case 2 (c) Case 3.



(a) (b) (c)

Figure 4: TPI maps generated using large neighborhood (45 cells) for the multiscale DEMs for: (a) Case 1 (b) Case 2 (c) Case 3.

Table 2: Maximum and minimum TPI values for the study area.

Method	Study area	Neighborhood (cells)	TPI value	Scale
Lifting scheme	Case 1	5	Max: 112	15
			Min: -198	5
		45	Max: 186	5, 15
			Min: -77	5
	Case 2	5	Max: 142	5
			Min: -169	5
		45	Max:152	5
			Min: -156	5
	Case 3	5	Max: 99	5, 15
			Min: -172	5
		45	Max: 129	5
			Min: -136	5
Quadratic parameterization	Case 1	5	Max: 215	45
			Min: -197	5
		45	Max:218	45
			Min: -77	5
	Case 2	5	Max:200	55
			Min: -169	5
		45	Max: 197	55
			Min: -106	5
	Case 3	5	Max: 155	55
			Min: -178	5
		45	Max:168	55
			Min: -137	5

The main feature of the lifting scheme is that all of its constructions are derived in the spatial domain. This method uses a simple relationship between all resolutions with the same scaling function and has received recent attention in geospatial analysis. This is due to its ability to preserve accurate surface profiles, in terms of waveform, shape and amplitude, without causing boundary destruction. On the other hand, for quadratic parameterization, very small windows are heavily influenced by errors in DEM elevations, especially if the error has very low spatial autocorrelation. Furthermore, if the DEM grid used in the analysis is produced through interpolation from sparser elevation points or contour lines at very small scales, the grid surface shape is more likely to represent the shape of the specific interpolator used than the real topographic surface and thus, is subject to the effect of interpolation artefacts. In addition, as the evaluation window gets larger, it is less likely that the quadratic equation will be a good descriptor of the topographic surface in the neighborhood of the evaluation point.

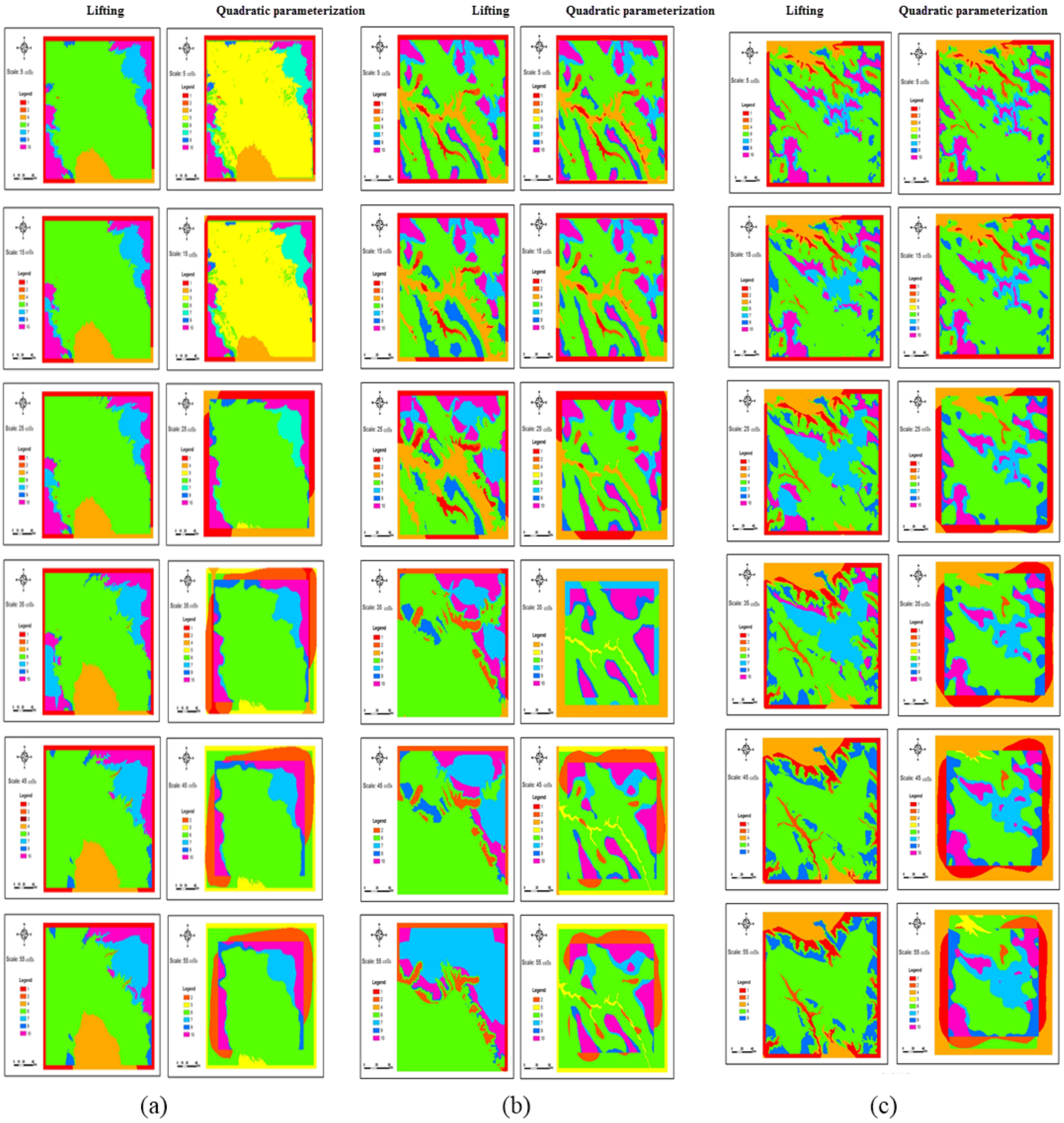


Figure 5: Landform classification for the multiscale DEMs for: (a) Case 1 (b) Case 2 (c): Case 3. 1: Canyons, deeply incised streams, 2: Midslope drainages, shallow valleys, 3: upland drainages, headwaters, 4: U-shaped valleys, 5: Plains small, 6: Open slopes, 7: Upper slopes, mesas, 8: Local ridges/hills in valleys, 9: Midslope ridges, small hills in plains, 10: Mountain tops, high ridges

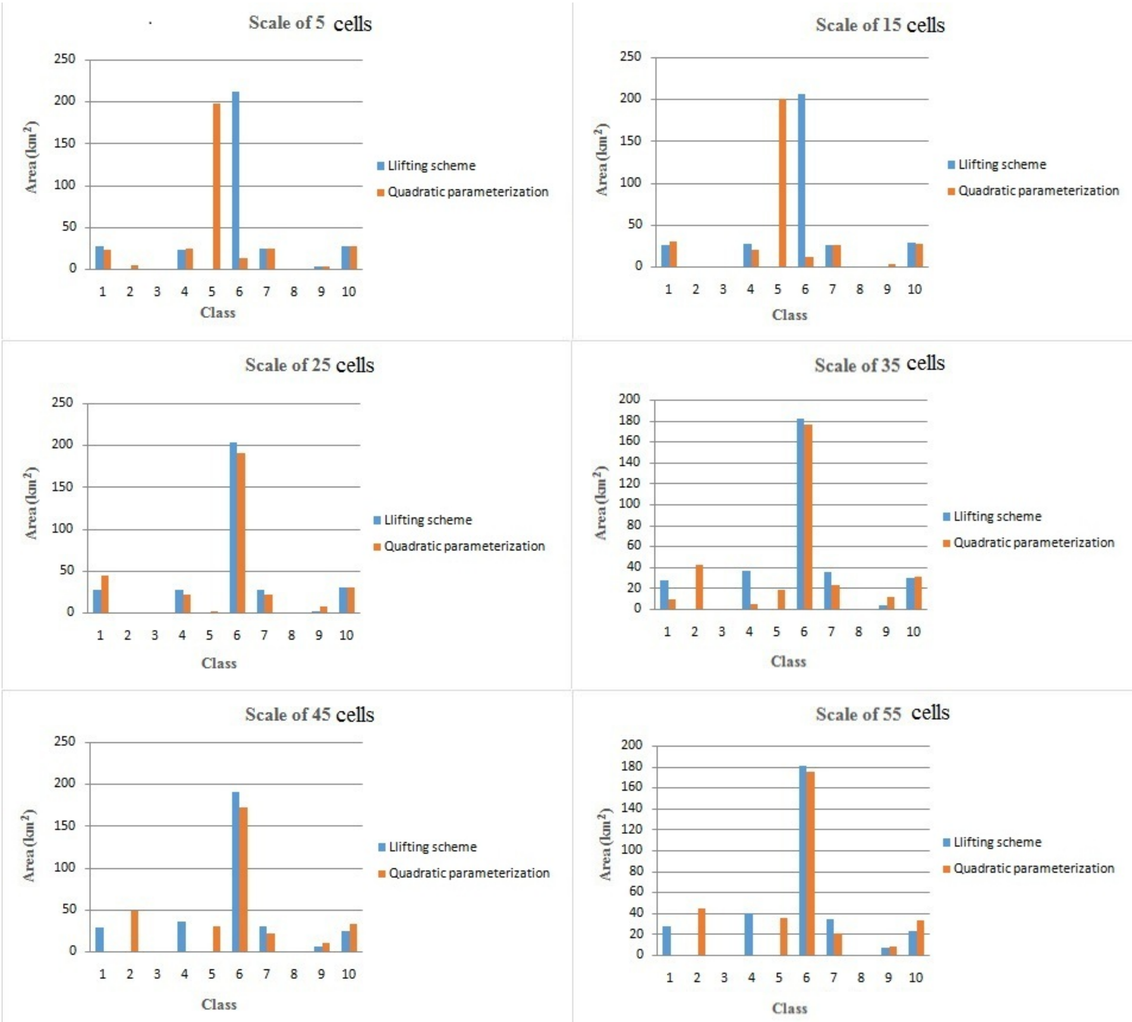


Figure 6: Comparison of landforms extracted using the two methods (Case 1).
1: Canyons, deeply incised streams, 2: Midslope drainages, shallow valleys, 3: upland drainages, headwaters, 4: U-shaped valleys, 5: Plains small, 6: Open slopes, 7: Upper slopes, mesas, 8: Local ridges/hills in valleys, 9: Midslope ridges, small hills in plains, 10: Mountain tops, high ridges

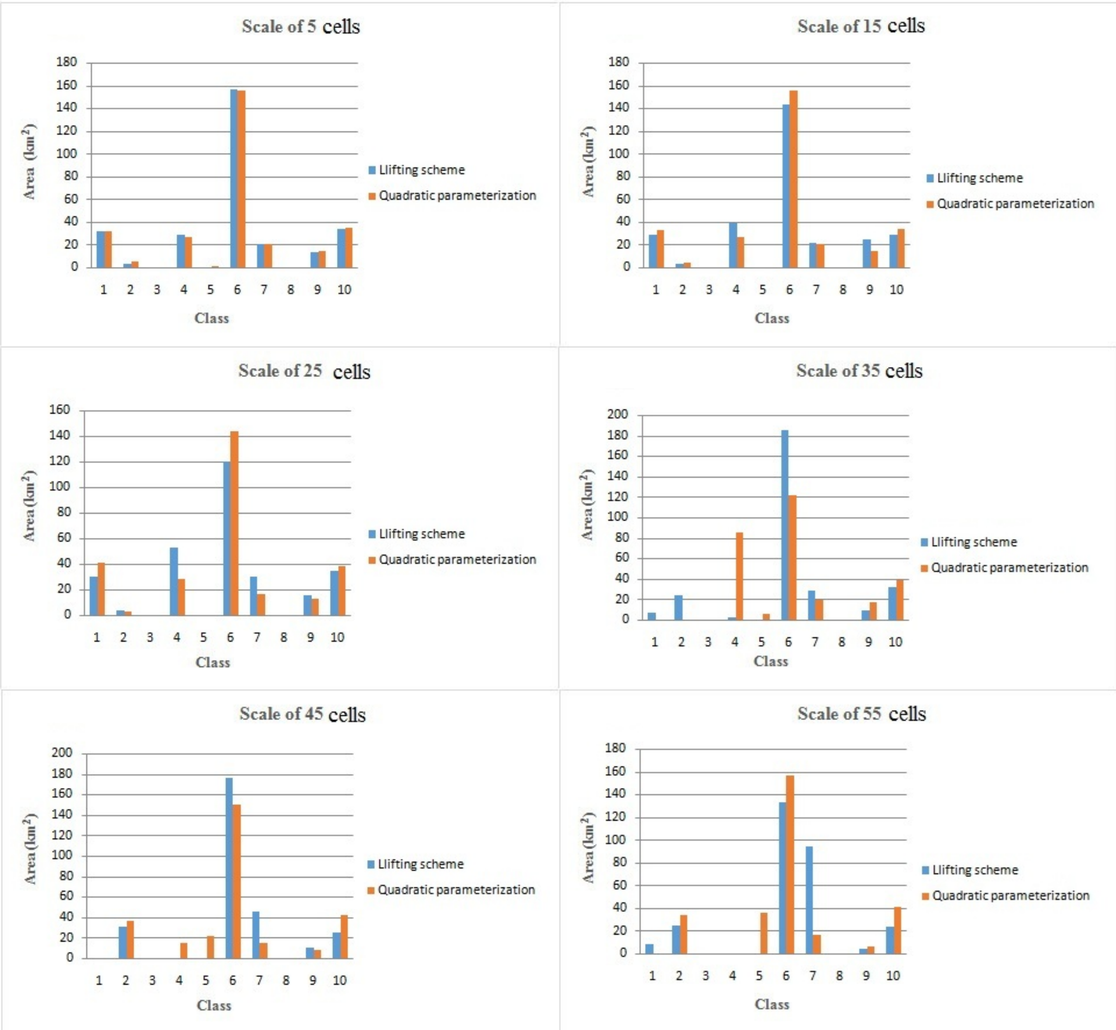


Figure 7: Comparison of landforms extracted using the two methods (Case 2).
1: Canyons, deeply incised streams, 2: Midslope drainages, shallow valleys, 3: upland drainages, headwaters, 4: U-shaped valleys, 5: Plains small, 6: Open slopes, 7: Upper slopes, mesas, 8: Local ridges/hills in valleys, 9: Midslope ridges, small hills in plains, 10: Mountain tops, high ridges.

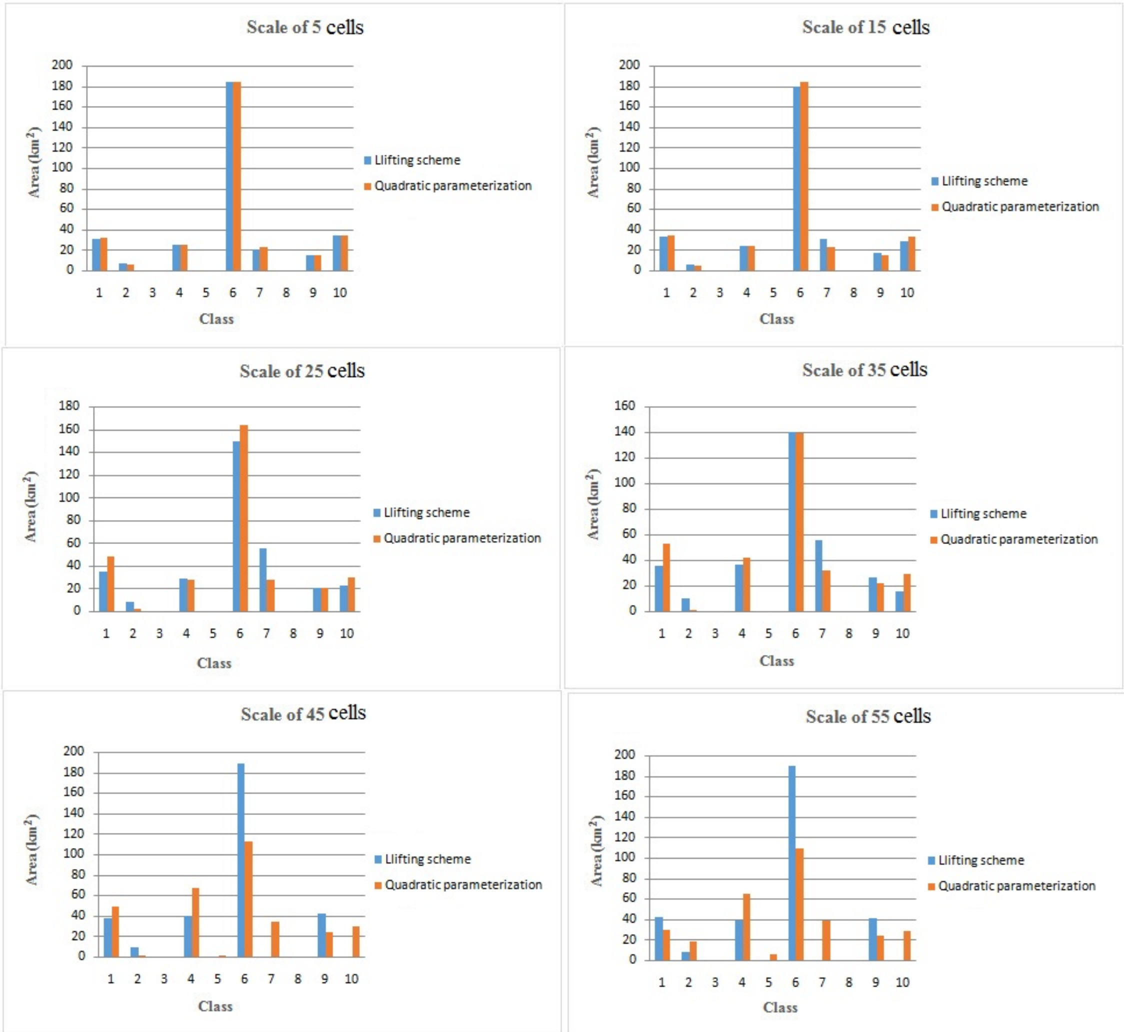


Figure 8: Comparison of landforms extracted using the two methods (Case 3).
1: Canyons, deeply incised streams, 2: Midslope drainages, shallow valleys, 3: upland drainages, headwaters, 4: U-shaped valleys, 5: Plains small, 6: Open slopes, 7: Upper slopes, mesas, 8: Local ridges/hills in valleys, 9: Midslope ridges, small hills in plains, 10: Mountain tops, high ridges.

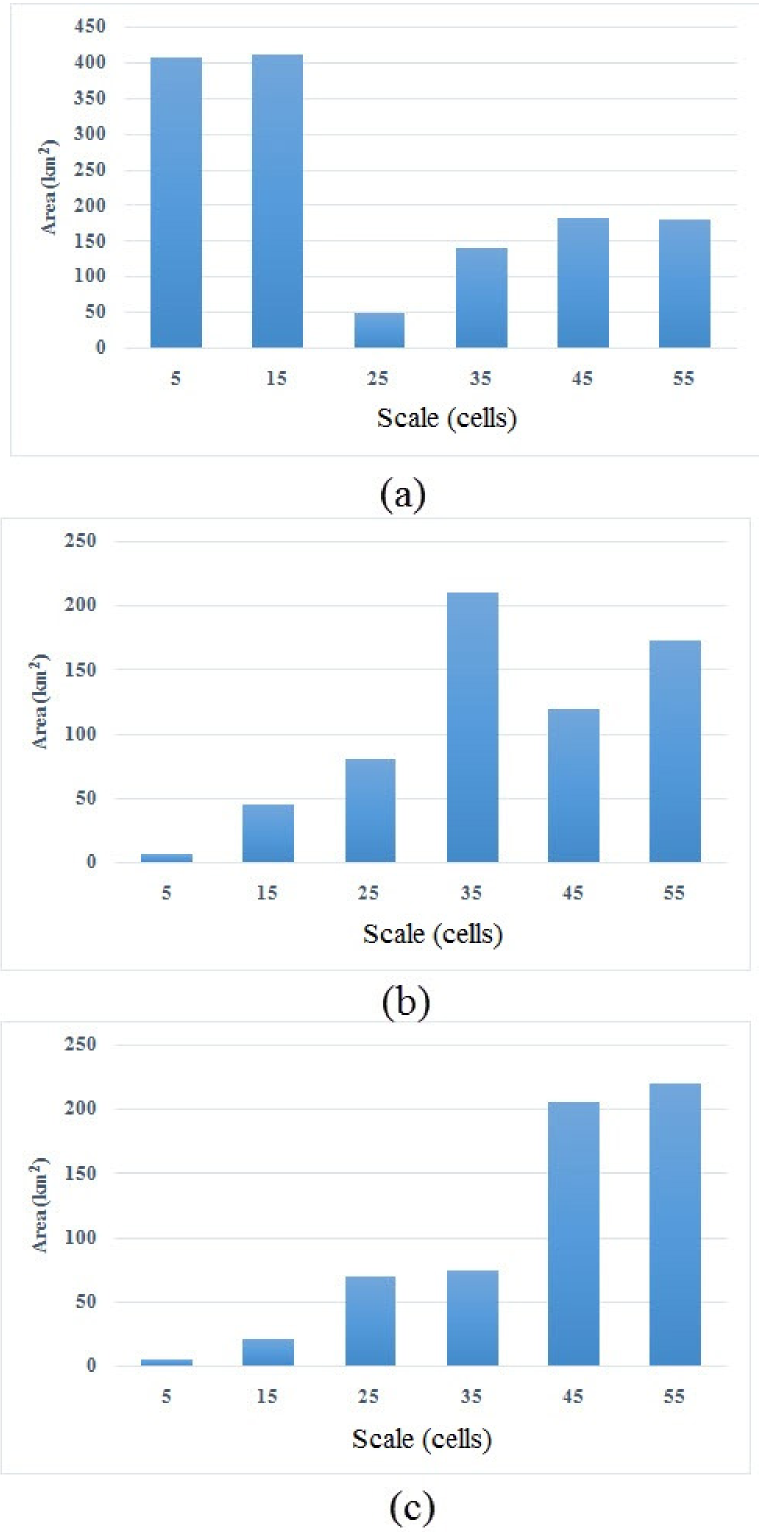
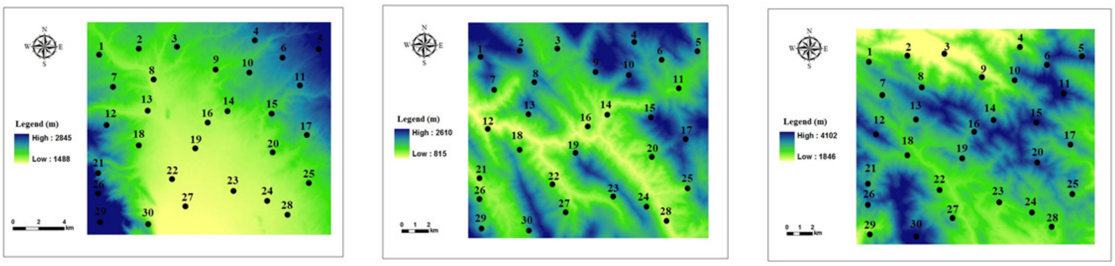


Figure 9: Difference of classes for the two methods according to scale for: (a) Case 1 (b) Case 2 (c) Case 3.



(a) (b) (c)

Figure 10: Randomly selected points for: (a) Case 1 (b) Case 2 (c) Case 3.

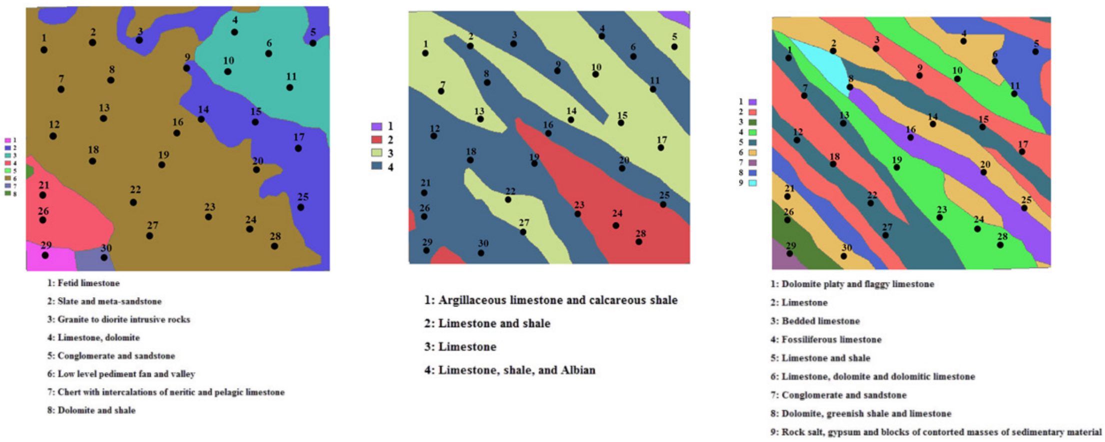


Figure 11: Geology map of the study area for: (a) Case 1 (b) Case 2 (c) Case 3.

Table 3: Relationships between landforms and geology classes.
Source: Tagil & Jenness (2008)

Type of geology units	Landform classes
Limestone	Open slopes, upland drainages, headwaters, mountain tops, high ridges, upper slopes, mesas
Alluvial	U-shaped valleys, open slopes, plains small
Sandstones , mudstones and agglomerates	Open slopes, upper slopes, mountain tops peak, local ridges / hills in valleys

Table 4: Summary of the accuracies of the methods for the different classes.

Class	Geology units	Number	Correct classifications	
			Lifting scheme	Quadratic parameterization
Open slopes, upland drainages, headwaters, mountain tops, high ridges, upper slopes, mesas	Limestone	61	58	45
U-shaped valleys- Open slopes- Plains small	Alluvial	15	14	14
Open slopes, upper slopes, mountain tops peak, local ridges / hills in valleys, Midslope ridges, small hills in plains	Sandstones , mudstones, and agglomerates	14	14	7

4. CONCLUSION

In this paper, landform classification of multiscale DEMs was performed for quadratic parameterization and the lifting scheme. Based on the results obtained, it was determined that the lifting scheme produced higher accuracy than quadratic parameterization for selecting the characteristic scale for landform classification, due to its ability to preserve accurate surface profiles, in terms of waveform, shape and amplitude, without causing boundary destruction.

The TPI method used in this paper compares the elevation of each cell in a DEM to the mean elevation of a specified neighborhood around that cell, which is then used for landform classification. On the other hand, slope is very dependent on the scale at which it is measured, and hence, the characteristics of landforms derived using slope are also scale-dependent. Furthermore, landform classification using other methods, such as fuzzy classification, can allow for more effective gathering of information content from different scales.

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