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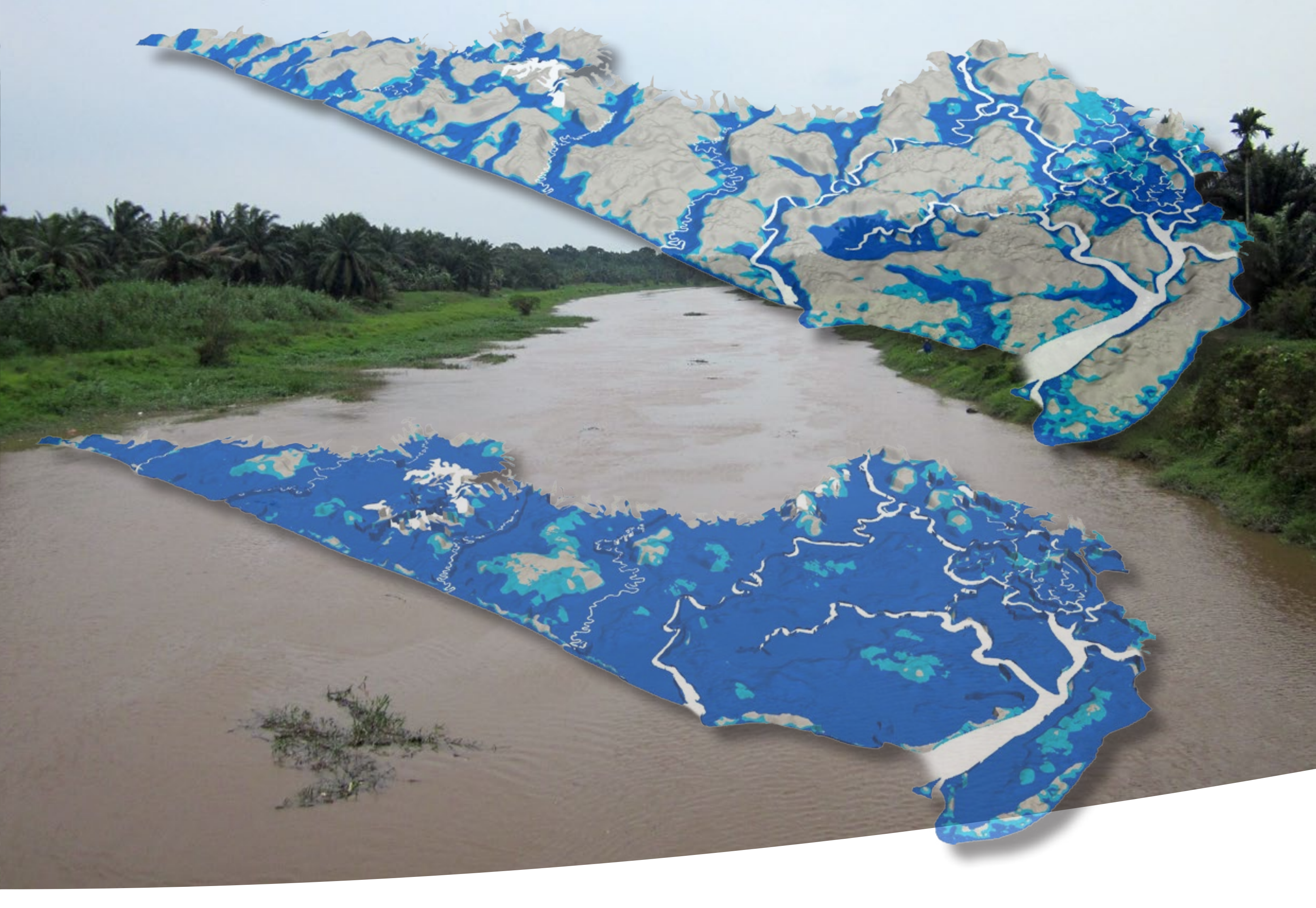
Flooding projections from elevation and subsidence models for oil palm plantations in the Rajang Delta peatlands, Sarawak, Malaysia



Flooding projections from elevation and subsidence models for oil palm plantations in the Rajang Delta peatlands, Sarawak, Malaysia

Report 1207384

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List of Abbreviations

DID	Drainage and Irrigation Department of Malaysia
DTM	Digital Terrain Model – *a 3D representation of the ground surface*
FAO	Food and Agriculture Organization
FDL	Free Drainage Limit – *elevation below which drainage by gravity is impeded*
GHG	Greenhouse gas
HWL	High Water Level – *elevation of extreme floods*
IFSAR	airborne InteroFerometric Synthetic Aperture Radar elevation data
IPCC	International Panel on Climate Change
MSL	Mean Sea Level – *the average sea surface level, between low and high tide*
Norad	Norwegian Agency for Development Cooperation
RBL	River Bank Level – *elevation of the river side that is known to flood frequently*
RSPO	Roundtable for Sustainable Palm Oil
SLR	Sea Level Rise
SRTM	Shuttle Radar Topography Mission - *Space Shuttle radar elevation data*

Preface

Peat swamp forests in SE Asia have been subject to rapid conversion to drained land-uses, especially oil palm and *Acacia* plantations. Over the last decade increasing concerns have been raised about environmental issues linked to this development. These include loss of biodiversity and the very high CO_2 emissions related to the oxidation of the carbon stored in the peat. However, another environmental impact, soil subsidence, has received little attention so far in SE Asia, even though it has been well known from other peatland regions in the world since the 19th century. This is especially of concern in lowland regions where land subsidence can bring the soil surface down to levels at which drainability and flooding become critical issues.

Wetlands International has been advocating against unsustainable land-use developments in peatlands worldwide and for alternative sustainable peatland management, including the conservation and restoration of peatlands. We are particularly concerned about the degradation of the peatlands in SE Asia in view of their high biodiversity as well as the disproportionately high GHG emissions. Our advocacy has resulted in increased awareness on these issues and over the last years resulted in significant steps by key players in the plantations industry including the RSPO and by the Indonesian government. These steps include commitments to halt expansion on peat and the adoption of more stringent policies for peatland management including best management practices for existing plantations on peat. However, even under best management practice peatland drainage is often unsustainable as it results in continued peat loss and thus carbon emissions and soil subsidence.

Wetlands International believes that the issue of peatland subsidence and related flood risks will only be taken seriously if policy makers and land-use planners have access to appropriate science-based information. We have therefore commissioned Deltares to carry out this case study to provide a scientific assessment of future subsidence and flood risk in the Rajang Delta peatlands in Sarawak, an area that has seen rapid expansion of drainage-based agriculture in recent years.

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Wetlands International

Summary

This report presents a detailed study of the impact of agricultural development on tropical coastal lowland peatlands, specifically the impact of drainage on peat subsidence and flood risk. The landscape morphology of the Rajang Delta peatland study area in Sarawak (Malaysia) is quantified and an assessment made of the future lowering of the land surface and associated flood risk resulting from recent drainage.

Background

As peatland is not really ‘land’ in the common sense but an unstable mix of water (over 90 %) and organic matter from partly decomposed plant material, peatland drainage for agriculture inevitably leads to rapid land surface subsidence and carbon loss. Inundation and loss of agricultural production is common in such areas. This land loss is the reason that expansion of peatland drainage for agriculture was ended in Europe and the USA by the mid 20th century. In Malaysia and Indonesia, however, large scale development of peatlands for agriculture (mostly oil palm and *Acacia* plantations) has only started recently.

In SE Asia, the dominant peatland landscapes are the so-called peat domes that have a raised topography some meters above the rivers that traverse the lowland plains. In most peatlands, as in the Rajang Delta, the peat bottom (i.e. the surface of the mineral substrate below the peat) is located below the flood level of rivers and the sea. Continued land surface subsidence in these areas will therefore cause a steady decline in drainability, resulting in increased flooding. Drainability is defined here as the opportunity to prevent flooding and waterlogging by making use of natural runoff of rainfall by gravity only.

The pattern of agricultural development and failure has been recognized in peatlands worldwide. Following an initial phase of physical compaction and consolidation of the peat after drainage, peat loss and subsidence are largely driven by biological decomposition of the peat by microorganisms (bacteria and fungi), which is highly temperature dependent. It is well understood that these processes operate at much higher rates in tropical climates and will therefore lead to problems sooner, and more severely, than in temperate climates. However, despite this obvious and major risk to forestry plantations and agriculture on drained peatland in the tropics, there have been no studies to date in SE Asia that quantify the likely timeframe in which subsidence will result in flooding at the landscape scale.

Results

We have investigated at what rate the process of steadily increasing flood risk following peatland drainage proceeds in a study area of 850,000 hectares of peatland in the Rajang Delta of Sarawak, Malaysia. From 2000 to 2014, the cover of industrial oil palm plantations increased from 6 % to 47 %, while the area of swamp forest decreased from 56 % to less than 16 %. The remaining area consisted of drained cropland, possibly including smallholder oil palm plantations, and degraded forest, that are also largely drained (Section 2.3).

An elevation model for the area was constructed from airborne IFSAR data collected in 2009 by filtering out vegetation and canal effects (Chapter 3). Elevations corresponding to thresholds for drainability and flooding were defined following earlier assessments of the area (Section 4.1). A subsidence rate of 3.5 cm per year was applied, which is a relatively

conservative figure and in line with the latest science and IPCC and FAO estimates of carbon emissions from plantations and cropland on drained tropical peatland (Section 2.4).

Industrial oil palm plantations generally occupy the highest parts of the peat domes in the Rajang Delta, illustrating the importance for plantations of being on high ground above flood levels as oil palm is known to have limited tolerance to flooding. By being on the highest areas of peatland, these plantation areas maximise the time before flooding problems will arise. For the 50 % of peatland that was still outside of industrial plantations in 2014, flooding projections are therefore even more dire than for existing plantations. This suggests that further expansion of oil palm area is likely to result in these new plantations being located in areas that are even more vulnerable to flooding.

Model results suggest that in 2009, 29 % of existing plantations suffered from reduced drainability characterised by the peat surface being below the Free Drainage Limit, see Figure 20; Section 4.1). Assuming no further oil palm expansion beyond 2014 in the area, we find that 42 % of current industrial plantations will experience problems associated with reduced drainability by 2034, 56 % by 2059 and 82 % by 2109. For areas that are frequently flooded with river water, where the peat surface has subsided to below the High Water Level, the corresponding figures are 18 % by 2009, 27 % by 2034, 39 % by 2059 and 64 % by 2109 (Section 4.2). These areas are likely to experience significantly reduced productivity associated with first groundwater table depths less than those that are optimal for crop growth, and eventually floods. It is expected that agricultural production will be lost long before flooding becomes near-permanent. **Eventually, nearly all peatland in the area is expected to be lost for production, much of it within decades and most within the next 100 years**.

We consider these projections to be conservative because subsidence rates and therefore the onset of flood problems may be higher than what we have applied, while surface elevations may be lower and flood levels may be higher. Indeed, a field survey showed considerably more flooding in oil palm plantations than was predicted by the model (Annex E). Moreover, we have not accounted for rising sea and river water levels (Section 5.2).

The study confirms earlier assessments of the agronomic potential of these peatlands by Malaysian Government organizations, completed before and during the 1990s, prior to oil palm plantation development (Section 2.1). These assessments, which are well documented in maps and reports (Figure 3, Figure 6), considered these peatlands to be fundamentally unsuitable for agriculture. Such assessments are in accordance with similar assessments of agricultural suitability of peatlands in other parts of the world. Regardless, oil palm cultivation and the associated drainage infrastructure has expanded in Sarawak’s peatlands since the late 1990s against such existing assessments. This study has taken these assessments further and identified the potential timeframe of the impacts of subsidence on peatland drainability and crop production.

A comparison of peatland profiles for the study area with those from other localities throughout SE Asia shows the Sarawak case to be quite representative for the broader region (Annex C). The pattern of increased flooding and productivity loss that is predicted for the Rajang Delta, and is evident historically and globally, should also be expected in other peatland regions of Malaysia and Indonesia.

The analysis presented here has room for improvement regarding timing of flood risk projections. Further model improvement is possible, but this will not change conclusions regarding the end result of current developments. Land subsidence of drained peatland is inevitable. It is beyond doubt that the area will in coming years and decades suffer increasing loss of agricultural production similar to other coastal lowland peatlands after drainage, globally. The major difference is that being in a tropical climate, this process proceeds at a much faster rate in Sarawak than in temperate climates. Given that the study area accounts for 40 % of the current planted oil palm plantations area in Sarawak, and there are plans to double Sarawak's oil palm plantation area by 2020 including expansion in peatland areas, this issue has important implications for Sarawak's palm oil industry as a whole.

Recommendations

Specific recommendations of this assessment are:

1. All tropical coastal lowland peatlands require subsidence and flood analysis to be undertaken as part of land use and economic planning. While carbon emissions have been the focus of recent debates regarding peatland development, the flooding consequences of peatland drainage need to receive much more attention as they affect direct economic interests and the lives of people living in peatland regions.
2. Elevation models are one of the key data that have been lacking in spatial planning for peatlands throughout SE Asia. Our recommendation, is to develop accurate elevation models for all coastal lowland peatlands in SE Asia as a matter of urgency and use them in land use planning.
3. Pumping drainage is unlikely to be a solution considering the large areas, high rainfall intensities and low unit area revenues involved. However, a sound engineering study and cost-benefit analysis should be conducted into the feasibility of large scale mechanical pumping drainage of plantations in drained tropical peatland to evaluate options for businesses and governments.
4. Clearly peatland subsidence and flooding as a consequence of drainage needs to be considered as part of economic and land use planning in Sarawak and other tropical regions with significant peatland area. For rational land use decision-making for the Rajang Delta and other peatlands in the region, we propose a classification of four categories of peatlands that distinguishes forested and deforested peatlands on the one hand, and areas with substantial and negligible future flood risk on the other (Table 7). Land use planning could take these criteria into consideration.
5. For a more sustainable future for the study area, a transition to an alternative use of the peatlands would be needed that can operate without artificial drainage. It is recommended to plan a transition to low-impact land uses well before flood risk has increased so severely that not only use as plantations but also regeneration of peat swamp forest will be impossible. The remaining degraded forests could be conserved and rehabilitated to form the core for the development of sustainable peatland production landscapes without drainage canals (Section 5.5).

1 Introduction

This study has been completed as part of the Sustainable Peatlands for People and Climate (SPPC) project, which is funded by Norad (Norwegian Agency for Development Cooperation) and managed by Wetlands International.

1.1 Land subsidence in peatlands

It has long been established that land subsidence is an inevitable consequence of the drainage of peatlands for agriculture (e.g. Stephens and Speir, 1969; Schothorst, 1977; Hutchinson, 1980; Andriesse, 1988; Wösten *et al.*, 1997; Deverel and Leighton, 2010; Hooijer *et al.*, 2012). This lowering of the land surface through subsidence occurs as a result of physical processes including consolidation and compaction, in particular immediately following drainage, but over the long-term is dominated by the decomposition of drained peat soils that is well publicized in recent years because of the associated carbon emissions (IPCC, 2013). A major consequence of land subsidence, that has received less attention in recent years, is that drained peatlands are often lowered to levels where they become vulnerable to flooding and are lost to production. This loss begins long before the surface is near river or sea levels, when surface gradients from the peatland towards natural rivers are diminished to the point that excess rainwater can no longer be removed by gravity drainage.

After learning from failures in Europe and the USA in the 19th and 20th centuries, the long term inevitability of peatland loss and surface subsidence following drained land-use is well understood. There is strong evidence indicating that both the speed and severity of these impacts will be higher in tropical peatland regions than in the temperate regions as a result of higher ambient temperature that produces higher rates of peat decomposition and, therefore, land subsidence and carbon emissions (Stephens *et al.*, 1984; Andriesse, 1988; Hooijer *et al.* 2012; IPCC, 2013; Page and Hooijer, 2014). The consequences of the subsequent flooding have been either a loss of production or the need for costly water management solutions such as dykes and pumps to keep the land suitable for agriculture and inhabitation (e.g. The Netherlands). By the mid to late 20th century, the conversion of peatland to farmland was therefore stopped in countries where these issues occurred at a large scale. Examples of areas where peatlands are being abandoned and rehabilitated, at huge cost, abound in Europe and the USA[1]. At present, only Malaysia and Indonesia are still attempting large scale agricultural expansion on peat.

1.2 Assessing land subsidence and flood risk in tropical peatlands

This report for the first time quantifies the effects of drainage on subsidence and future flooding in tropical peatlands in SE Asia, presenting a case from Sarawak, Malaysia. Peat loss and subsidence are largely driven by biological decomposition of the peat by micro-organisms (bacteria and fungi), which is highly temperature dependent. It is well understood that these processes operate at a much higher rates in tropical climates and will therefore lead to problems sooner, and more severely, than in temperate climates. However, despite

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[1] For examples of large peatland restoration initiatives, see the following: Florida Everglades (www.evergladesplan.org), Sacremento Delta (www.deltaconservancy.ca.gov) and Cris *et al.* (2014).

this obvious and major risk to agriculture on peatland in the tropics, there have been no studies to date that quantify the potential rate of increasing flood problems.

The greatest extent of tropical peatland is found in SE Asia, principally in Indonesia and Malaysia, which have two-thirds of the global tropical peatland resource (Page *et al.*, 2011). This case study covers the Rajang Delta peatlands in Sarawak (Figure 1), which have largely been cleared and drained for oil palm plantations in the last decades. The area was chosen because of several factors that reduce uncertainties in the analysis[2]. It consists almost entirely of peatland with a negligable area of mineral soil and is already largely drained by industrial oil palm plantations that can easily be mapped from Landsat satellite images. From literature sources the bottom of the peat is known to be flat and nearly always below river and high tide sea level, so that it is possible for nearly all the peatland to be flooded as subsidence progresses (see Annex C). Perhaps most importantly, recent airborne IFSAR data are available for the area, allowing construction of a reasonably accurate surface elevation model (Figure 2).

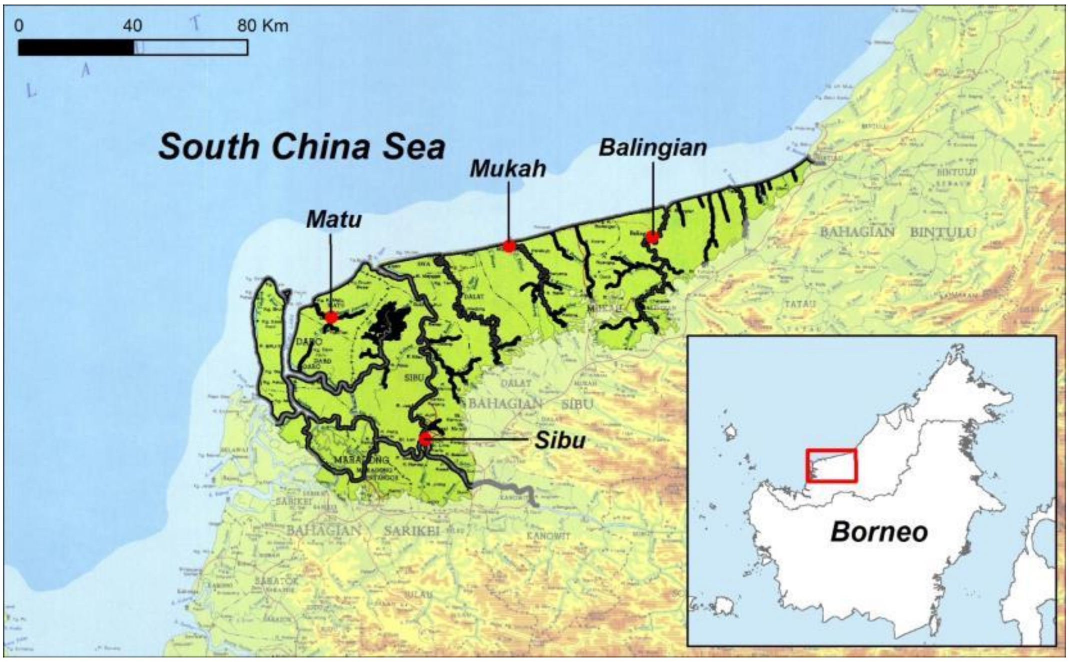

Figure 1 The Rajang Delta study area in Sarawak (Malaysia), on the island of Borneo.

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[2] Note that the Baram Delta was also investigated, but it proved impossible to create a DTM of similar accuracy as for the Rajang Delta, see Annex D.

1.3 This report

The study is presented as follows:

1. The study area is described and likely peat subsidence rates assessed (Chapter 2).
2. A digital terrain model (DTM) is constructed based on IFSAR data (Chapter 3).
3. Subsidence rates and DTM are combined and used to map land subsidence across the landscape. This produces a projection of likely loss of drainability and degree of increased flooding over the coming decades (Chapter 4).
   The results of this analysis are discussed along with their implications for future of oil palm production and what solutions may exist (Chapter 5).

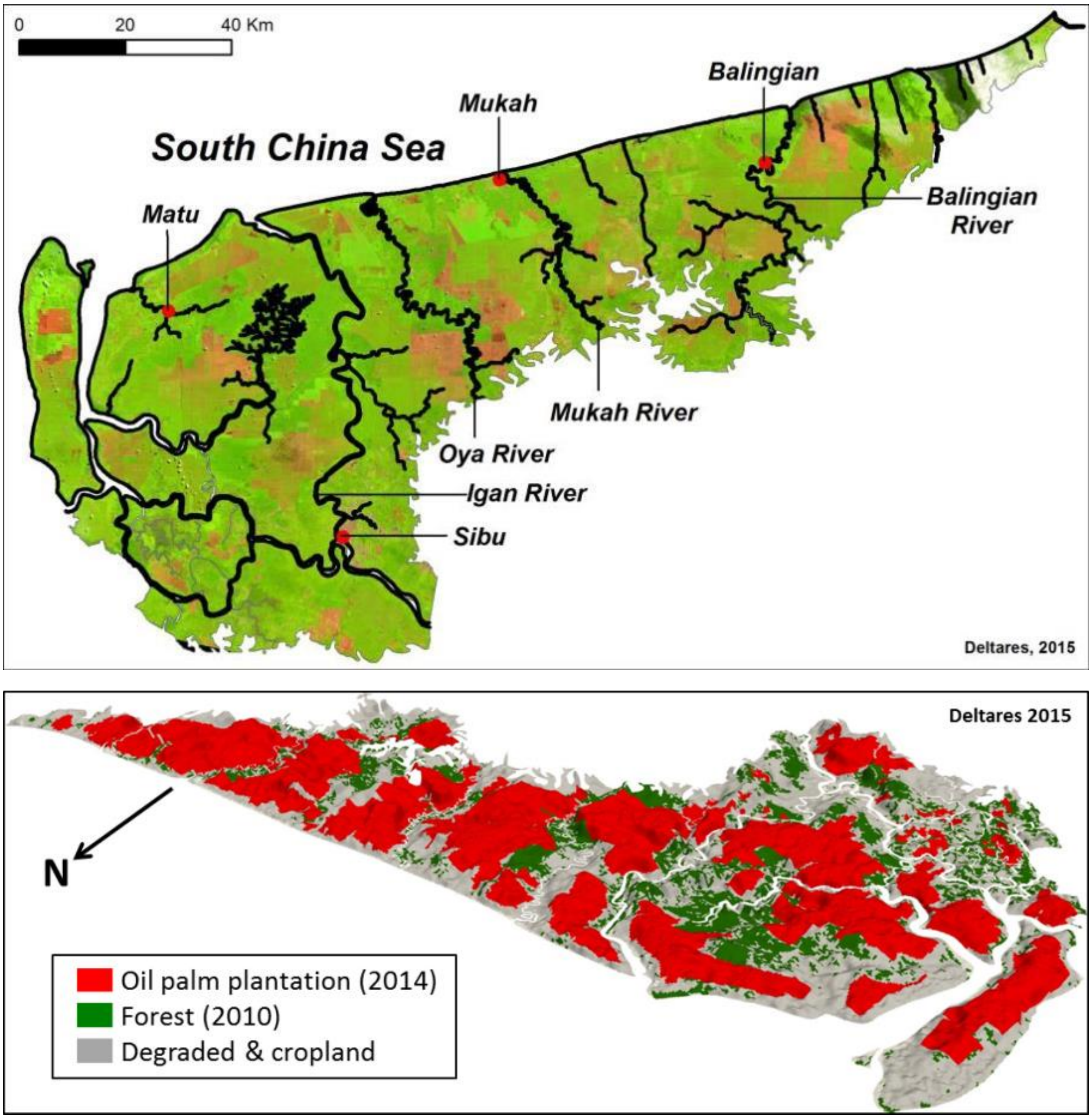

Figure 2 Images of the study region. **Top**: The Landsat 654 composite image from 27 June 2014 was used to identify industrial plantations. **Bottom**: Oblique 3D view of land cover map overlaying the vertically exaggerated DTM, towards the Sarawak coast from the South China Sea. See Chapter 3 for details of land cover map and elevation model.

2 The Rajang Delta - peat soils, plantations and subsidence

The Rajang Delta peatland study area of 848,000 ha is located in the central coastal area of Sarawak (Figure 1). The soil map of 1968 shows nearly the entire Rajang Delta plain to be covered with peat (Figure 3). Peat over 3 m in thickness (i.e. soil profile depth) makes up most of the study area (75.0 %; see also Figure 4), whereas less thick peaty soils ('shallow' and 'mixed') account for another 4.4 and 8.6 %, respectively. The remaining 11.9 % of the study area is non-peat and consists of Gleysols (frequently flooded, water-logged soils) that are found at the lowest elevations in river floodplains and coastal plains.

The peat domes in the area are the highest features in the coastal plain, but are nevertheless relatively low relief features. The land surface rarely exceeds 10 m above Mean Sea Level (+MSL) and remains mostly below 6 m +MSL (Figure 4; see also Chapter 3 and Annex C). The base of the peat and the contact surface with the mineral substrate underlying the peat, is usually around or below 1 m +MSL and nearly always below 2 m +MSL, as expected given the origin of peat development in tidal mangrove swamps and alluvial flood plains thousands of years ago (Staub and Gastaldo, 2003; Dommain *et al.*, 2011; see also Annex C). In peat areas further inland the peat bottom creeps up against pre-existing hill morphology; such land was excluded from the model assessments in order to reduce uncertainties.

Oil palm plantations in the area are found almost exclusively on peat of over 3 m thickness, whereas the Gleysols are rarely cultivated.

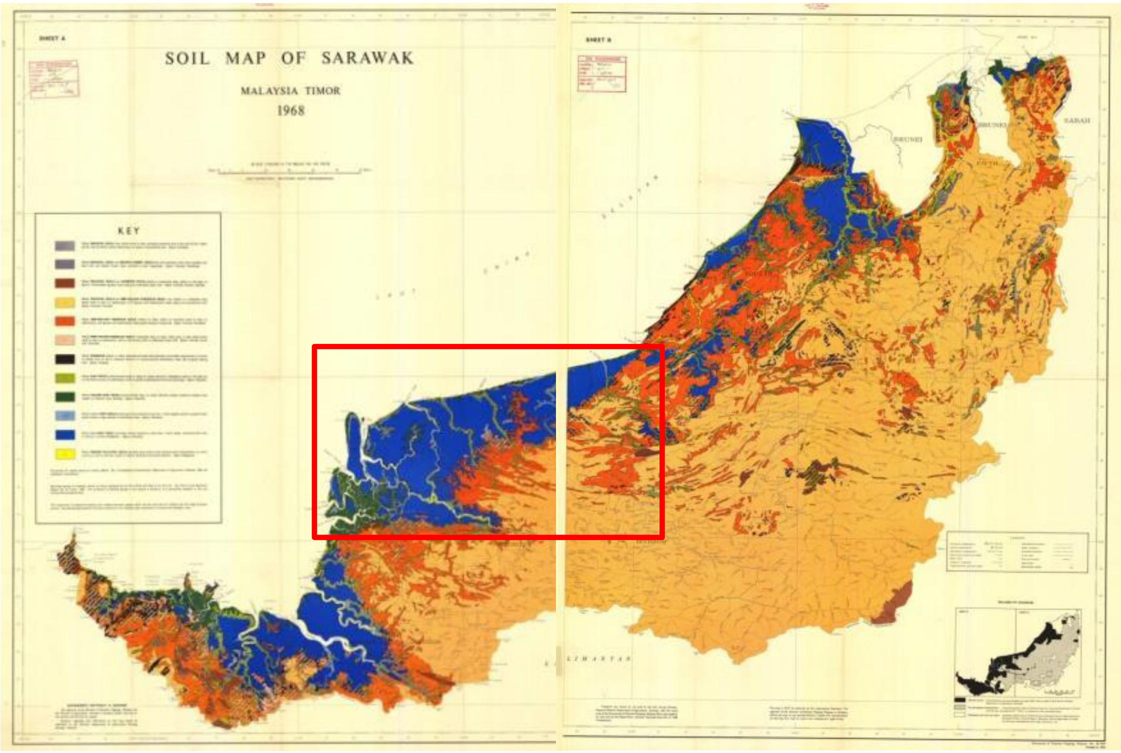

Figure 3 Soil map of Sarawak, published by the Department of Agriculture of Sarawak (1968). The dark blue area (class 11) presents "deep peat (commonly more than 3 m)". Red box indicates study area.

2.1 Past assessments of agricultural suitability of peatland in Sarawak

The dominance of peat and evidence of flooding problems along the Sarawak coast have lead to earlier land suitability assessments, that have generated useful concepts of drainability (Figure 5). According to such concepts, it has always been clear that the drainability of most Sarawak peatlands must be considered to be very poor. In line with this insight, the 1982 Sarawak Department of Agriculture map of ‘agriculture capability’ shows nearly all of the study area to be unsuitable for agriculture with the remainder being shallow peat or flooded mineral soils that were considered only marginally suitable with severe limitations (Figure 6). Apart from flooding issues, considerations of low fertility, high acidity and poor anchorage contributed to this negative assessment of agriculture potential for these areas. Such land has therefore long been used only for logging using light rail for access without the need for drainage canals, which has proven to be sustainable over decades. The issues of land subsidence and drainability were addressed by Sarawak state government’s Drainage and Irrigation Department in its comprehensive *‘Water Management Guidelines for Agricultural Development in Lowland Peat Swamps of Sarawak’* (DID Sarawak, 2001). These describe peatland subsidence as occurring at a constant rate of 5 cm yr^{-1}, following an initial surface drop of 1 m in the first 2 years after drainage. This translates to 3.4 m of subsidence in 50 years, a figure that is in the range presented by all thorough studies of the subject in tropical peatlands that have looked at large numbers of locations over long time periods following well described methods (Stephens *et al.*, 1984; Andriesse, 1988; Wösten *et al.*, 1997; Hooijer *et al.*, 2012). The DID guidelines also note that peat dome elevations range from around 4 m +MSL near the coast to 9 m +MSL furthest inland, and that the bottom of the peaty subsoil is typically found *below* the gravity drainage base, making flooding inevitable as pumping drainage is not an option in these areas. The publication concedes that in such cases, flooding is inevitable and the “land will have to be returned to nature”.[3]

However, despite this acceptance of sound science-based peatland subsidence principles, DID Sarawak (2001) then proceeds to state that “depending on peat thickness, [these problems can become acute] from 50 to more than 750 years”. That places the problem, and therefore the need to deal with it, in a more distant future than is justified by the evidence presented in the same publication. Indeed, existing flooding in drained peatland areas throughout SE Asia, including in urban areas on peat around Sibu at the boundary of the study area, indicate flooding to have become increasingly problematic in the last few decades. Observations by the authors and others across peatlands in SE Asia suggest that wet season flooding is already occuring in oil palm plantations on peat in many places, leading to responses such as mound planting and the effective abandonment of plantations.

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[3] It is also often noted that the mineral soils below the peat consist largely of unripe clays, often Potential Acid Sulphate Soils. Therefore, even in the limited areas where the mineral soil surface would be sufficiently high to remain drainable after all peat has disappeared, subsidence will continue - albeit at a far lower rate - when these clay soils get compacted as a result of drainage, and acid sulphate problems may develop.

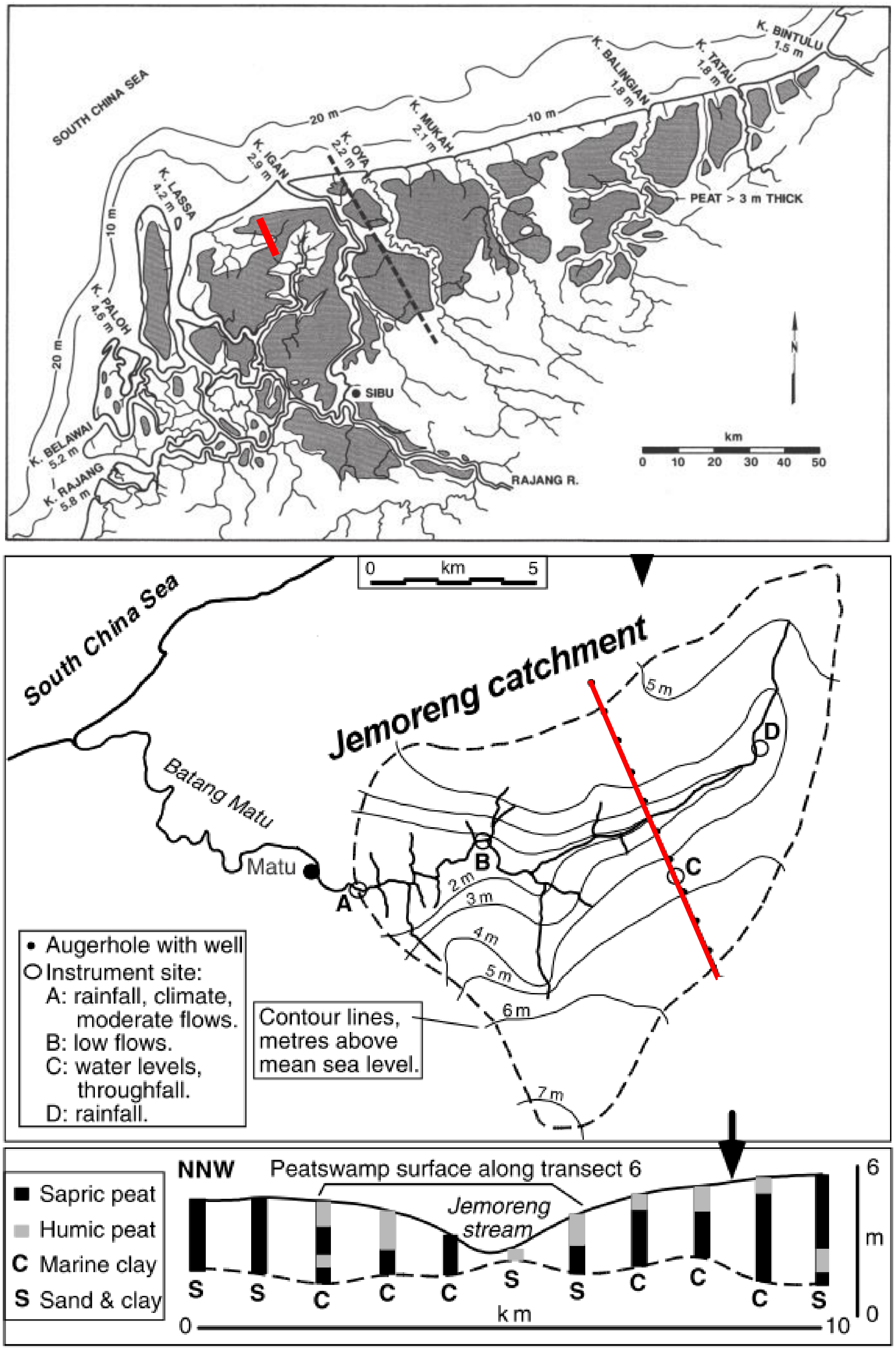
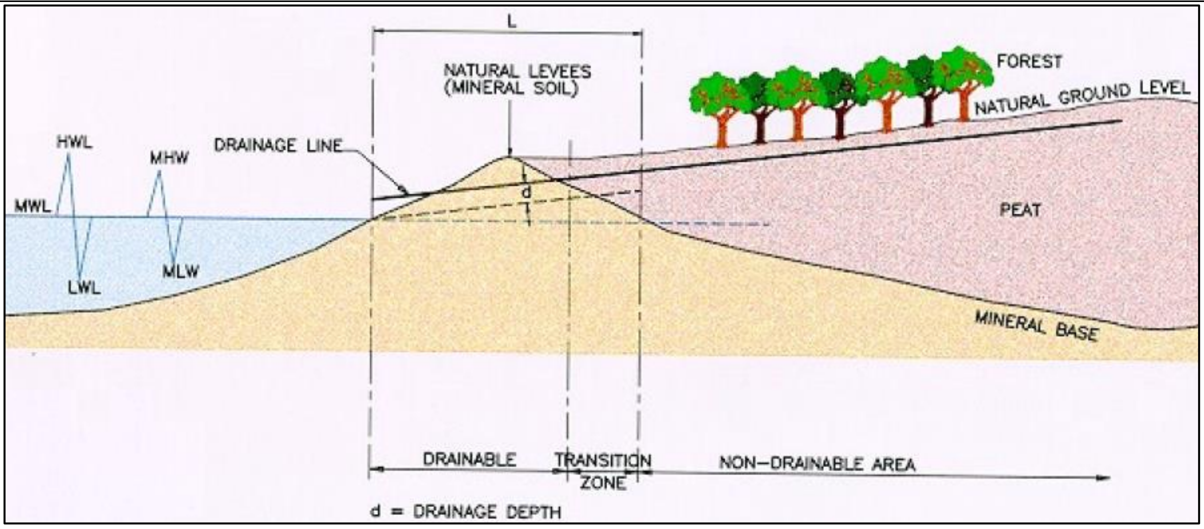


Figure 4 Peat soils in the Rajang Delta. **Top**: Full extent of peat with a thickness over 3 m (grey area) in and around the Rajang Delta. The black dotted line separates the Rajang Delta system in the West from the Coastal Plain system in the East. Also shown is the maximum spring tidal range (in metres) at the mouth of each of the delta distributaries and coastal-plain rivers. From Staub and Gastaldo (2003). **Middle/Bottom**: Elevation map and peat cross section through one peat dome in the study area (from Hooijer *et al.*, 1997; Hooijer 2005). The transect is indicated by the red line in the map. See Annex C for more profiles.



Drainability refers to drainage by gravity, thus drainage without the aid of mechanical devices such as pumps. Long-term drainability is assessed on the basis of the mineral subsoil level, rather than the present (peat) ground surface. The drainage base is defined as the water level in the adjacent river or stream, below which natural drainage by gravity cannot be achieved (conveyance losses add an additional hydraulic head of at least 20 cm per km). To assess drainability, the following classification is used:

Very good: *Mineral subsoil surface is above the drainage base established at High Water Level (HWL); therefore natural drainage can be achieved at all tide levels, including high tides.*

Good: *Mineral subsoil surface is between drainage base established at HWL and Mean Water Level (MWL).*

Moderate: *Mineral subsoil surface is between drainage base established at MWL and Low Water Level (LWL).*

Poor: *Mineral subsoil surface is below drainage base established at LWL; therefore natural drainage cannot be achieved at any tides, even low tides.*

Figure 5 Schematic concept of drainability classes (Agrosol, 1997). A very similar definition of drainability is applied in the current study (Figure 20; Section 4.1), including the conveyance gradient of 0.2 m km^{-1} that is also presented in DID Sarawak (2001). Note however that the definition of Low Water Level (LWL) presented here applies only to fully tidal areas. In deltas and coastal plains such as the study area, LWL is in fact controlled mostly by river levels which is a function of discharge as well as tide. In periods of high discharge, LWL is in fact well above Mean Sea Level. Therefore, very few if any peatlands in Sarawak (as in most of SE Asia) have a mineral base above LWL, which means that nearly all peatlands in the study area are ‘non drainable’ according to this classification.

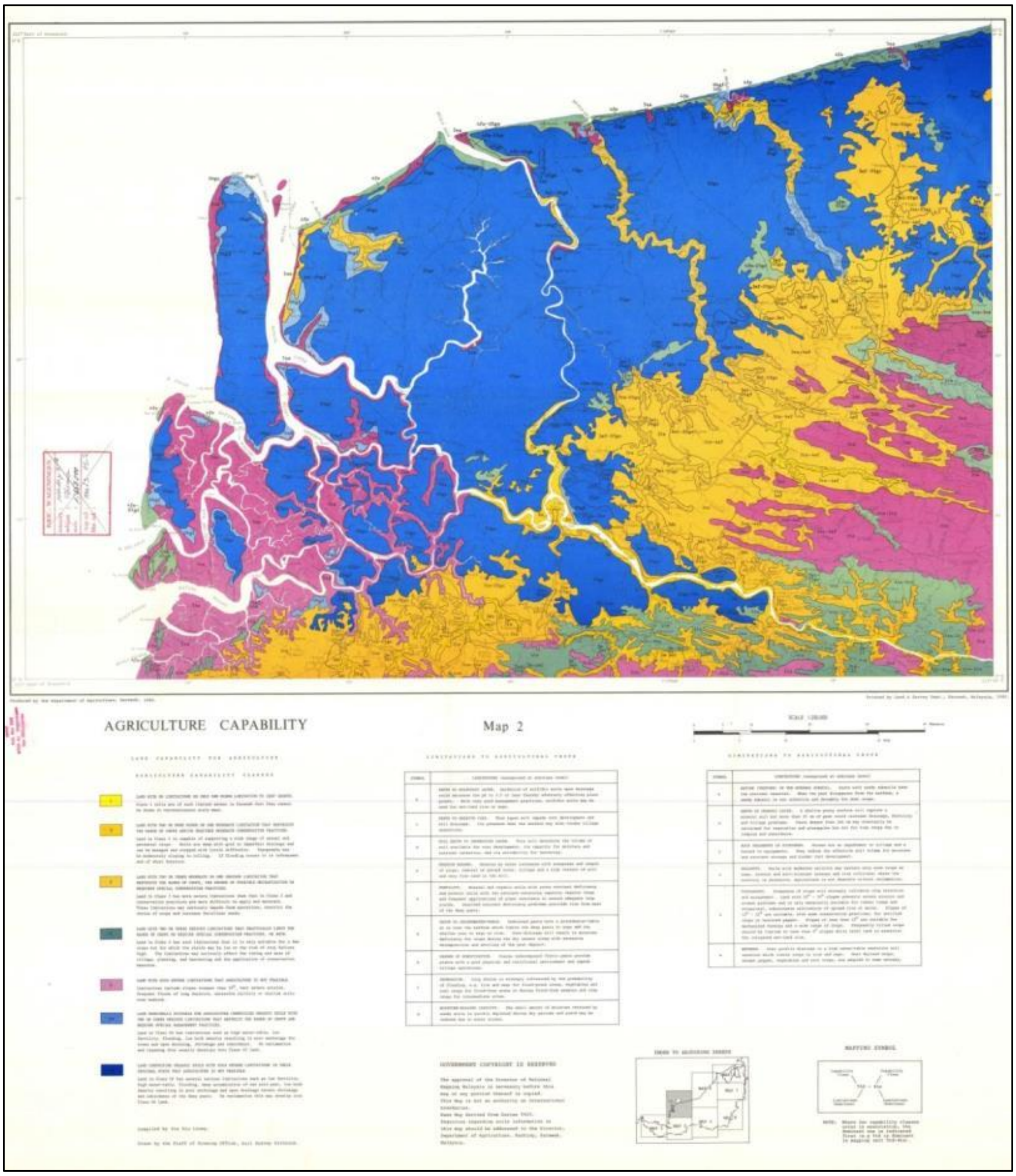


Figure 6 Map of ‘agriculture capability’ for part of the study area, as published by the Department of Agriculture of Sarawak (1982). The dark blue area (class O5) that is dominant in this map presents peat and is described as *‘Land comprising organic soils with such severe limitations that agriculture is not feasible*. *Land in class O5 has serious limitations such as low fertility, high water table, flooding, deep accumulation of raw acid peat, low bulk density resulting in poor anchorage and upon drainage severe shrinkage and subsidence of the deep peats. On reclamation this may develop into class O4 land.’* Class O4 land (lighter blue area at the margins of class O5) is described as ‘*Land marginally suitable for agriculture comprising organic soils*’, which suffers from these same limitations but to a lesser degree. The yellow areas along streams through the peatlands in the study area are class 3 with ‘*limitations that may seriously impede farm operations*’. In summary, no peatland in the study area is considered suitable for agriculture according to this Government map.

2.2 Current flooding along the Sarawak coast

The Sarawak coast, especially around the Rajang Delta, is well known to be exceptionally flood prone, as is evident in numerous reports in public media (Figure 7). This is due to a combination of five conditions. First, the land is very flat and low-lying even at large distances from the coast. Secondly, most of the land is peat, which is easily waterlogged in the wet season and provides little storage capacity for rainfall in such periods, resulting in rapid runoff to the lowest lying areas. Third, 10-year maximum rainfall values ranging from 326 mm in a week at Sibu to 628 mm at Mukah (DID Sarawak, 2001), which are high even for tropical conditions. Fourth, the Rajang River drains a large mountainous catchment covering 50,000 km^2 and can have peak discharges exceeding 25,000 m^3/s (Jeeps and Gates, 1963; Staub and Esterle, 1994). Large scale deforestation in the upstream catchment causes increased sediment influx and deposition in the Rajang Delta, which over time raises annual flood water levels, with inland parts of the river delta systems typically being the most sensitive (e.g. Klijn and Schweckendiek, 2012). Finally, there is a large astronomic tidal amplitude of up to 5 m in the western part of the area (DID Sarawak, 2001; see also Figure 4), and sea surface levels can be further pushed up by monsoon conditions that can increase water levels by 0.4 m and storm surges that can exceed 1.3 m high in the South China Sea (Bird, 2010).

Figure 7 Flooding in the Matu-Daro district, in the NW part of the study area near the coast, in 2011. Note that the water is mostly ‘tea coloured’, indicating it originates at least partly from the peatlands further inland but cannot be discharged quickly to the sea because of high river and sea levels. This situation has existed for many years, illustrating that flooding in the area is not easily mitigated (from http://www.theborneopost.com/2011/01/13/15000-affected-by-floods-in-matu-daro-district/; use of reproduction granted).

Traditional houses in coastal towns in the area such as Matu and Daro, and originally also Sibu, are built on high stilts to cope with the frequent flooding (Figure 7). Traditional crops such as sago were also flood tolerant. Despite these adaptations, there are news reports that flooding frequency has been increasing and even traditional flood-adapted houses are now sometimes flooded. It is also much publicized that newer houses that were built on lower or even no stilts are severely affected by flooding in the city of Sibu which is partly on peat, necessitating construction of major pumping stations in the area in the hope to reduce such problems. The scale of the ongoing Sibu Flood Mitigation Project, with a total cost that in 2010 was estimated to exceed RM 1 billion[4], is a measure of how serious this problem has become. However, the long-term effectiveness of pumping in peat areas, and other attempted solutions to reduce flooding in Sibu such as dredging the rivers is disputed[5].

2.3 Land cover developments and status

To assess the expansion of oil palm plantations, we investigated Landsat satellite images over a fourteen-year period in steps of about 5 years: 2000 (21 August 1999 and 1 April 2000), 2004 (10 August), 2009 (31 July) and 2014 (27 June) (see Figure 2 for 2014 image). Plantations were mapped through visual inspection and manual classification. Just two land use classes were distinguished: (1) industrial plantations that are easily distinguished by their drainage patterns and rectangular shapes; and (2) a broad class covering all other land covers including forest remnants, shrubland, smallholder cropland and probably also smaller oil palm plots. In the latter category, we further identified intact forest on the one hand and degraded forest plus cropland on the other from the 2000 and 2010 land cover maps by Miettinen *et al.* (2012) (Figure 9).

An NREB agricultural land use and forest type map was available for a large part of the study area (625,000 ha or 74 %), mainly covering the Mukah administrative division showing amongst others the licensed plantation areas (Figure 8). This map was digitized and licensed oil palm and sago plantations shown on this map were compared with current (2014) plantation extent (Figure 8; Table 1).

Table 1 Licensed (NREB) and existing (2014, Landsat) oil palm and sago plantation area within the part of the study area shown in Figure 8 (74 % of the total study area).

	Licensed (NREB)		Existing (2014)	
Landuse type	**ha**	**%**	**ha**	**%**
Oil palm	324968	83.7	261705	78.2
Sago	63211	16.3	21571	6.4
Industrial plantations (not in NREB licensed area)	n.a.	-	51473	15.4
Total	**388180**	**100.0**	**334749**	**100.0**

By June 2014, at least 47 % (4,018 km^2) of the study area had been converted to industrial plantations that started to appear since the early 1990s but were mostly developed after 2000 when their extent was 6 % (Figure 9). A small part of the existing plantations are sago plantations (6.4 %; Table 1) whereas the majority are oil palm plantations (93.6 %; Table 1). An unknown but probably substantial part of the remaining area is used for smallholder agriculture around settlements. The remaining forest areas are highly fragmented, and often crossed by canals (Figure 10).

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[4] http://bernama.com/bernama/v3/bm/news_lite.php?id=497313
NB 1 Billion Malaysian Ringgit is approximately 250 Million US $ at 2014 rates.

[5] http://www.theborneopost.com/2013/03/15/dredging-found-to-be-ineffective-in-flood-mitigation-uggah/

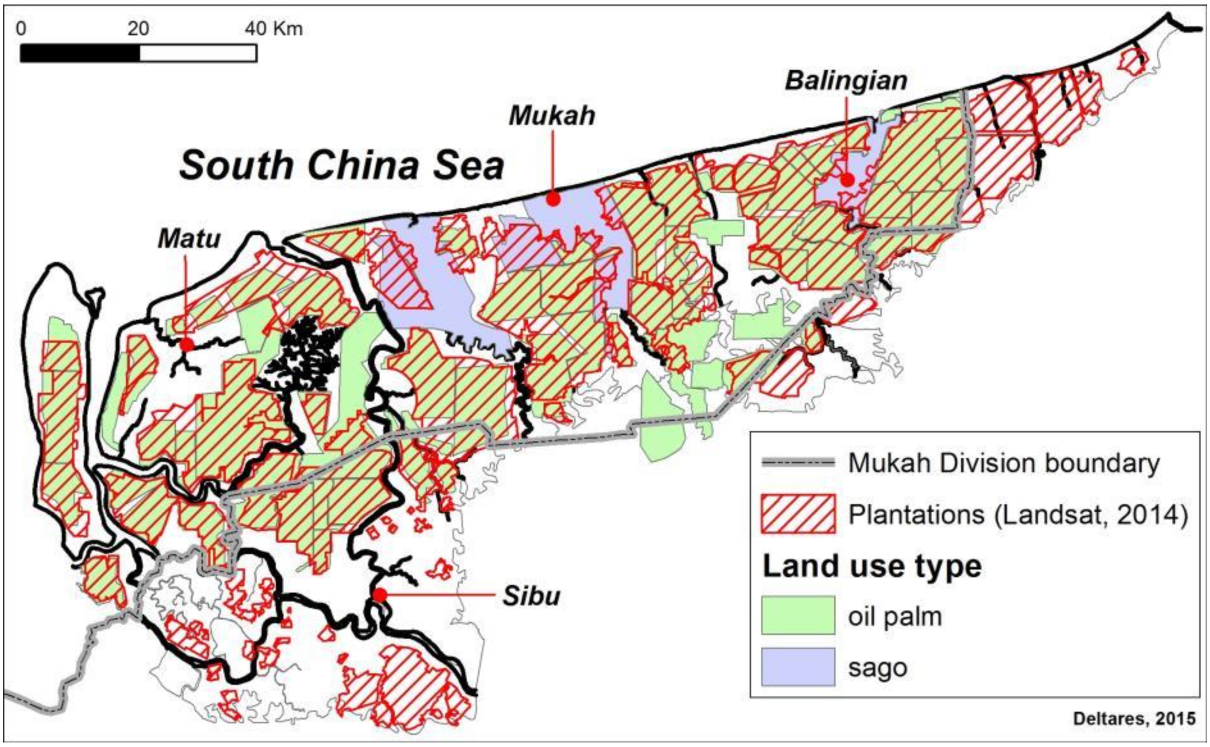

Figure 8 Licensed oil palm and sago plantations in and around Mukah Division (digitized from NREB map) and current (2014) plantation cover as determined from Landsat.

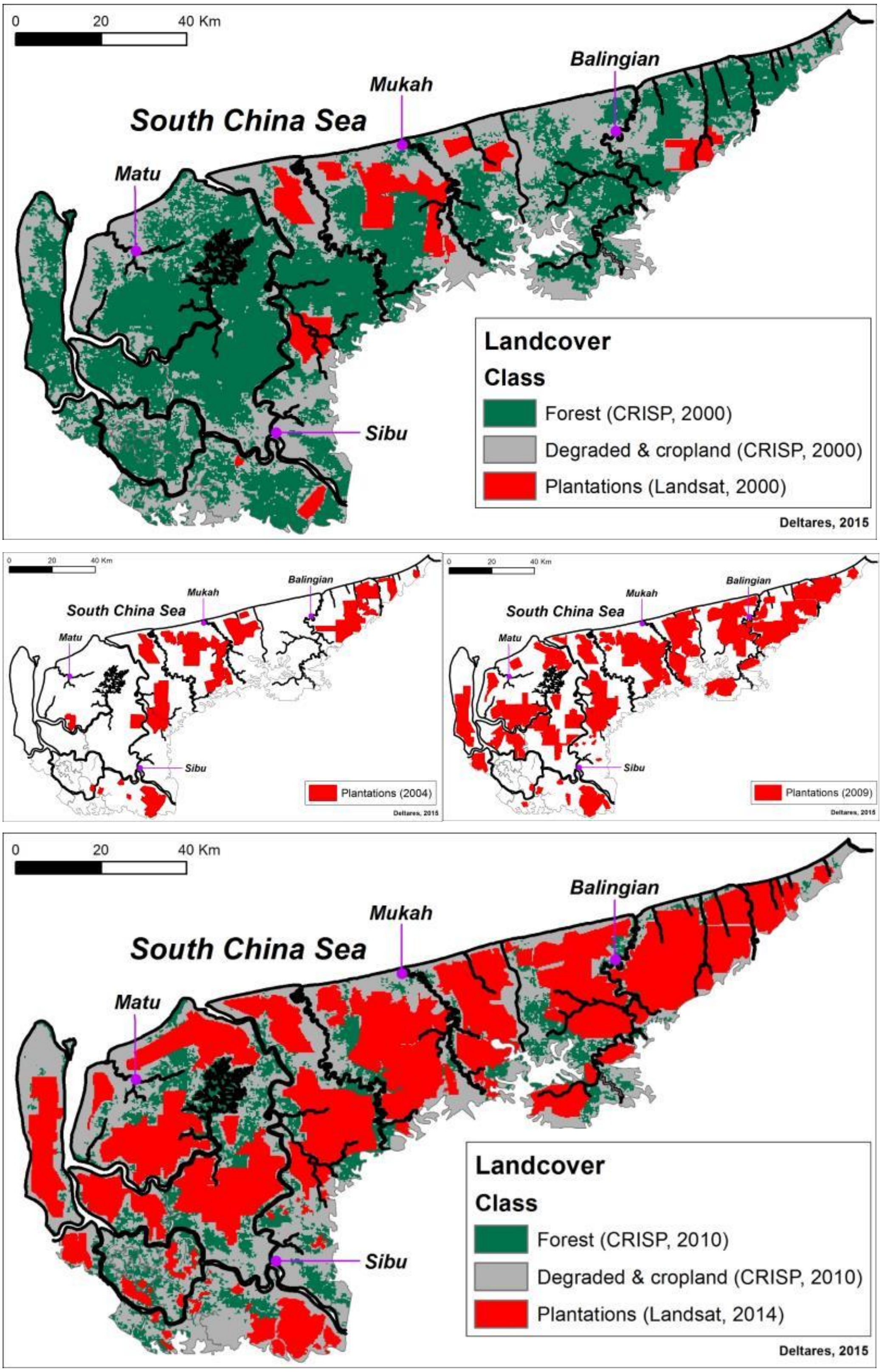

Figure 9 Reclassified CRISP land cover images (Miettinen *et al.*, 2012) with 2014 industrial plantation cover added as determined from Landsat from this study. **Top**: Land cover in 2000. **Middle**: Plantation extent in 2004 and 2009. **Bottom**: Land cover in 2014. A major decrease in forest cover (from 55.6 % to 15.6 % of the area from 2000 to 2010; Table 2) and increase in plantation cover (from 6.1 % to 47.4 % from 2000 to 2014) is evident.

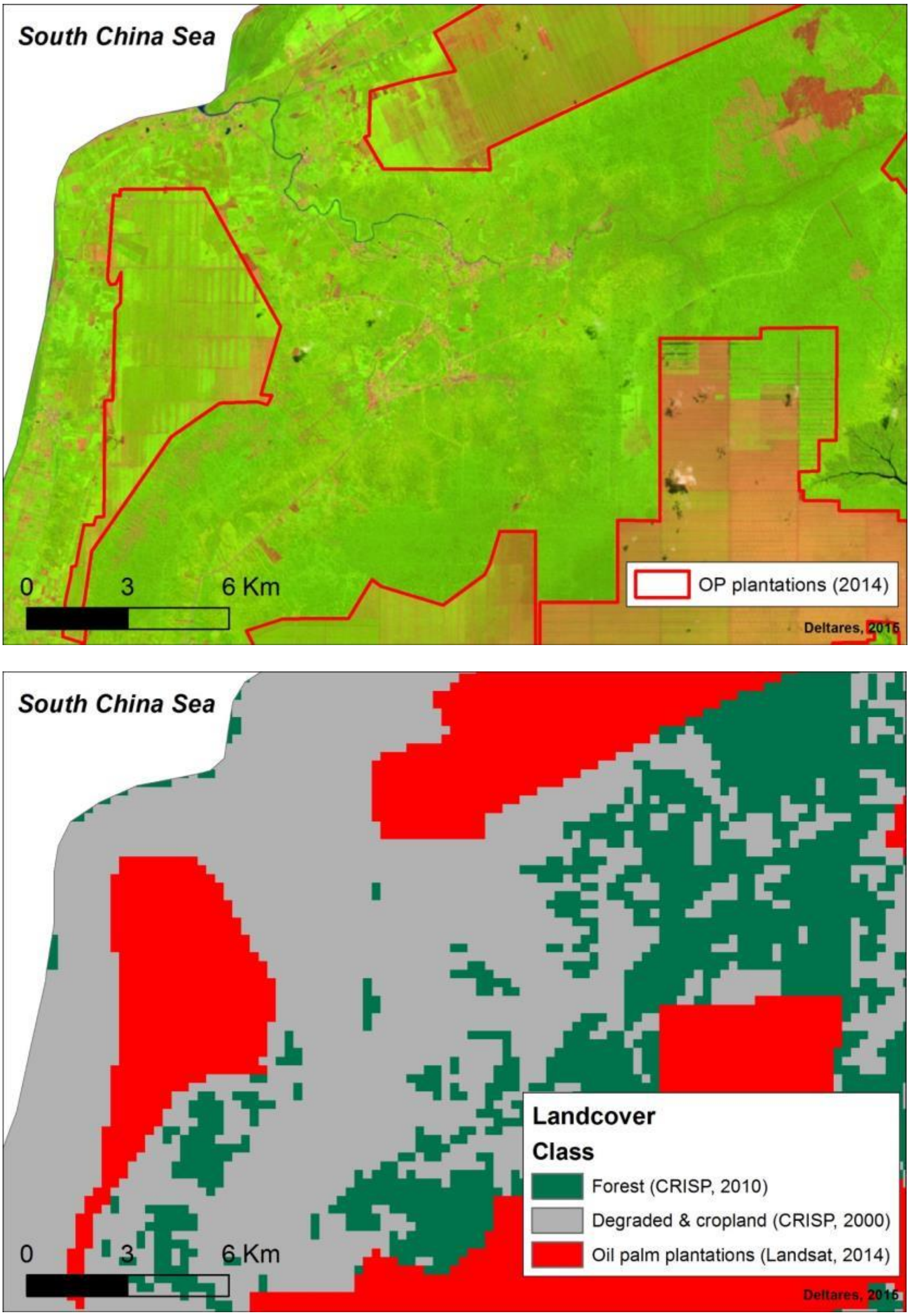

Figure 10 Non-plantation land in the study area is usually not intact forest but a mosaic of smallholder agricultural land and remnants of degraded forest. **Top**: Landsat 2014 image of the area around Matu with oil palm plantations identified as red lines. **Bottom**: CRISP 2010 image (Miettinen *et al.*, 2012) showing more or less intact forest, open land and degraded land in 2010, with the 2014 OP plantation extent superimposed.

Table 2 Extent of industrial plantations in 2000, 2004, 2009 and 2014 in the study area as determined from Landsat imagery. The forest, degraded/regrowth and open land cover classes are also included as determined from the CRISP 2000 and 2010 land cover maps (Miettinen *et al.*, 2012; Figure 9). Note that the plantation extent has almost quadrupled in the 10 years from 2004 and 2014.

Landcover class		2000	2004	2009	2014
forest	[ha]	463461	-	-	130393
	[% total area]	55.6	-	-	15.6
degraded & cropland	[ha]	318508	-	-	302379
	[% total area]	38.2	-	-	36.2
industrial plantation	[ha]	51901	108614	281355	401770
	[% total area]	6.1	12.8	33.2	47.4
Total	**[ha]**	**833871**	**-**	**-**	**834541**

2.3.1 Assessment of currently drained area extent

Given the recent dominance of oil palm plantations in this landscape (Table 1), the likelihood that oil palm plantations are still being expanded, the fact that drainage of deep peat can have an impact over several kilometres from canals (DID Sarawak, 2001; Hooijer *et al.*, 2012) and finally the presence of numerous drainage features also outside plantations, this entire peatland landscape may now be considered to be drained, albeit not necessarily always to the same intensity as in industrial plantations.

2.3.2 Occurrence of fires

Despite the fact that the study area receives more rainfall than most coastal areas in SE Asia, at 3,000-4,000 mm per year (DID Sarawak, 2001), and rarely experiences dry months, fires have occurred in the area at a large scale as shown in Figure 11. It is remarkable that fire hotspots have to date been concentrated almost entirely in plantation areas, and judging from the clear patterns with different groupings in different years they appear to be a regular and well-coordinated land clearing tool, not accidental occurrences.

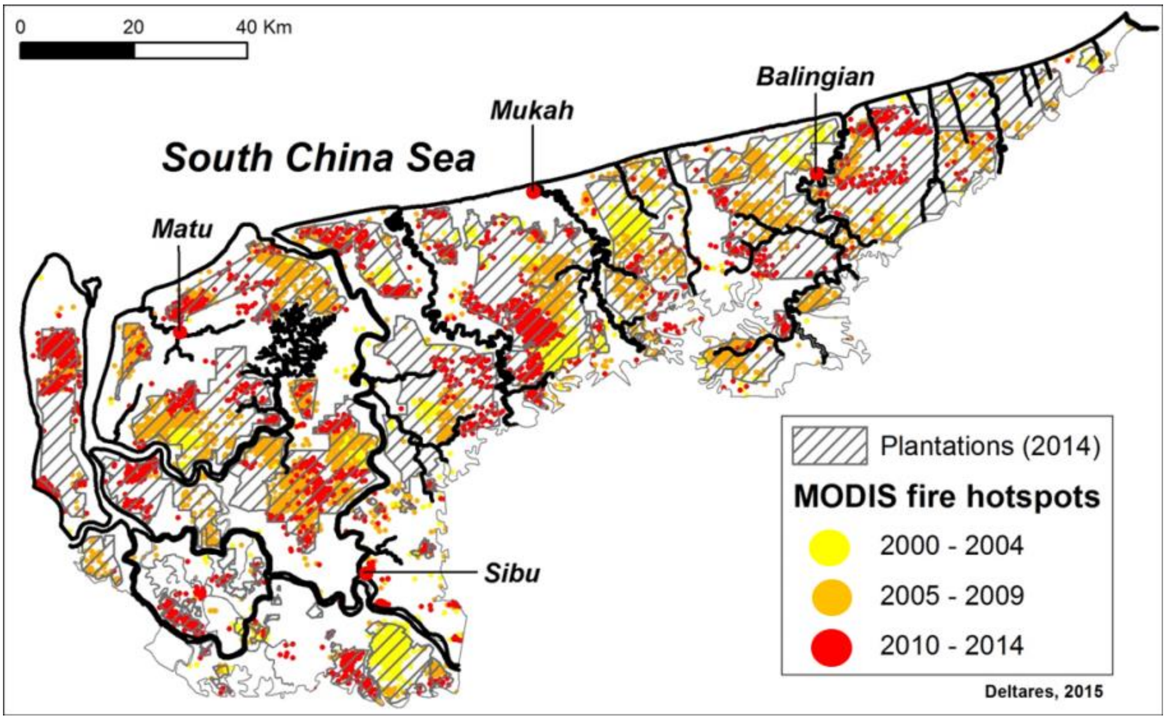

Figure 11 Extent of current (June 2014) industrial plantations and fires in the study area.

2.4 Subsidence rates in tropical peatlands

It is well known that the peat surface subsides following drainage due to compression and the loss of peat due to microbial decomposition when air enters the de-watered peat.[6] These processes have long been recognized in many parts of the world, but the biological component that causes peat loss and emissions is found to be most active in the tropics as microbial processes are highly temperature sensitive (Stephens and Speir, 1969; Andriesse 1988; Page and Hooijer, 2014).

The long-term subsidence rate for tropical peatland in the region and study area was estimated to be in the range of 3.5 to 5 cm yr^{-1}, based on numbers published for tropical peatland in SE Asia by Andriesse (1988), Wösten *et al.* (1997), DID Sarawak (2001), Othman *et al.* (2011), Hooijer *et al.* (2012) and Couwenberg and Hooijer (2014). Based on these studies, we defined three scenarios for this analysis: (1) a 'Maximum Impact' scenario, (2) a 'Conservative Impact' scenario and (3) a 'Minimum Impact' scenario.

For the 'Maximum Impact' scenario, a subsidence rate of 5 cm yr^{-1} (5 m in 100 years) is considered the most appropriate value based on the studies presented above. In reality, this value may be as realistic as the 'Conservative Impact' scenario given typical conditions in plantations on peat.

To be conservative we used the lower end subsidence rate of 3.5 cm yr^{-1} in our analysis for the 'Conservative Impact' scenario, which is consistent with the recently published average emission factor for cropland and plantations on tropical peatland as published by the Intergovernmental Panel on Climate Change (IPCC, 2013) and also the Food and Agriculture Organization (Page and Hooijer, 2014).[7] Subsidence rates in this range are also reported for op deep peat in Sarawak under 'Best Management' conditions, in experimental stations with raised water levels (Othman *et al.* 2011).

A 'Minimum Impact' subsidence rate was further defined based on the lowest reported subsidence rates for peatlands in SE Asia. One study in Peninsular Malaysia, extrapolating future subsidence in a peatland after 28 years of drainage, has predicted subsidence rates to reduce to 2 cm yr^{-1} (2 m over 100 years) in the long term (cumulative subsidence in the first 28 years was 2.8 m; Wösten *et al.*, 1997). However, actual measurements of subsidence rates below 3 cm yr^{-1} in general apply only to peat that is higher in mineral content than is the case in the ombrogenous peat typical of the region, including the peat in this study area. Othman *et al.* (2011) report a reduction to around 3 cm yr^{-1} (in peat of around 3 m thickness) and 1 cm yr^{-1} (in peat of around 1 m thickness) under best management practices with water tables kept constant between 0.3 and 0.4 m below the surface; however this was achieved only in small experimental plots and such optimum water management must be considered impossible at the large scale where resources will be limited and the priority will always be to prevent flooding by keeping water tables low.

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[6] Peat compression consists of compaction above the water table and consolidation below the water table. See Hooijer *et al.*, 2012 for further explanation.

[7] An average emission factor for industrial plantations on tropical peatlands of around 15 t C ha^{-1} yr^{-1} (55 t CO_2 ha^{-1} yr^{-1}) is now widely accepted , as is a similar value of 14 t C ha-1 yr^{-1} (51 t CO_2 ha^{-1} yr^{-1}) for smallholder cropland (IPCC, 2013; Page and Hooijer, 2014). At an average bulk density of the original (non-surface) peat of around 0.09 g cm^{-3} and a carbon content of around 55 %, as is applicable throughout most of SE Asia (Page *et al.*, 2011), this EF translates to an annual subsidence rate of 3.5 cm yr^{-1} or 3.5 m over 100 years assuming no compression of the peat takes place beyond the first few years after drainage, and no accounting for the spike in emissions and subsidence that is known to occur in the first few years after drainage.

Nevertheless, we apply a value of 2 cm yr^{-1} in a 'Minimum Impact' scenario that we consider to be least likely.

Subsidence rates in all scenarios applied in this study assume that the land has already undergone the initial subsidence spike that follows drainage at the start of the analysis period in 2009 (Figure 12). This initial rapid drop of the land surface is caused by the high peat compression rates and high oxidation rates that occur in the first few years following drainage, which has been reported as subsidence of 1 m in 2 years (DID Sarawak, 2001) and 1.42 m in 5 years (Hooijer *et al.*, 2012). Where this initial rapid subsidence has yet to take place, wholly or more likely partly as may be the case in some remaining pockets of relatively undrained peatland forest that may be left in the study area, this approach is conservative in that it underestimates potential future subsidence rates.

In this study, a subsidence rate is applied to model the change in surface elevation from land subsidence resulting from drainage over time. Most of the study area is peat or peaty, the entire area is considered to be drained and there is no information on local variations in peat type and management that may cause variations in subsidence rate. Therefore a uniform subsidence rate is applied over the entire model applied in this assessment. For areas outside industrial plantations, that are mostly deforested and drained but possibly less intensively, this may mean that subsidence rates are somewhat overestimated, and the subsidence and flooding projection may best be interpreted as if those areas were converted to plantations. However, this possible overestimation does not affect the projections for known oil palm plantation areas.

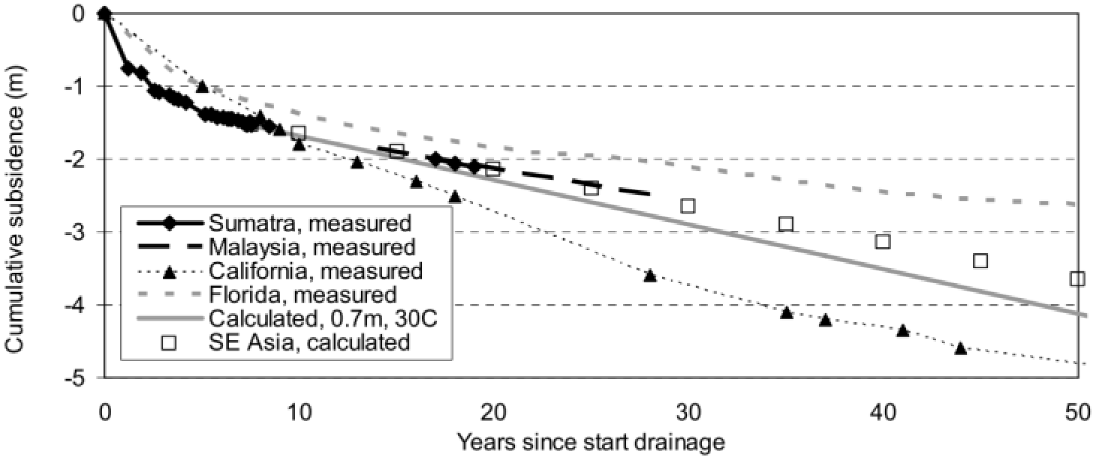

Figure 12 Subsidence rates as measured in warm and tropical climates (from Hooijer *et al.*, 2012).

3 Digitial Terrain Model of the Rajang Delta and coastal plain

An accurate digital terrain model (DTM) of the study area based on recent data is the starting point for the projection of peat subsidence completed in this study. As there is no existing DTM of the area available in the public domain, this study developed a novel approach for DTM creation in tropical coastal lowland peatlands using airborne interoferometric synthetic aperture radar data, also know as IFSAR.

3.1 General approach

An elevation model was created from IFSAR data that were collected by Intermap in 2009 for the study area[8] and are commercially available (Figure 13). These radar data were provided to the project team in raster format with each cell measuring 10 m by 10 m. These data represent the actual land surface elevation accurately in areas that are free of vegetation and buildings but are known to yield higher elevations in vegetated areas, as illustrated in Figure 14, and to have errors in areas with standing water. IFSAR data therefore need to be filtered in several steps before they can be used to create a model of the actual land surface elevation, commonly referred to as a Digital Terrain Model (DTM). The individual filtering steps are further explained below and presented in Figure 15 for a selected part of the study area. The validity of the resulting DTM was tested by comparing the overall elevation distribution with the distribution as derived from published field surveys, as explained in Section 3.7.2.

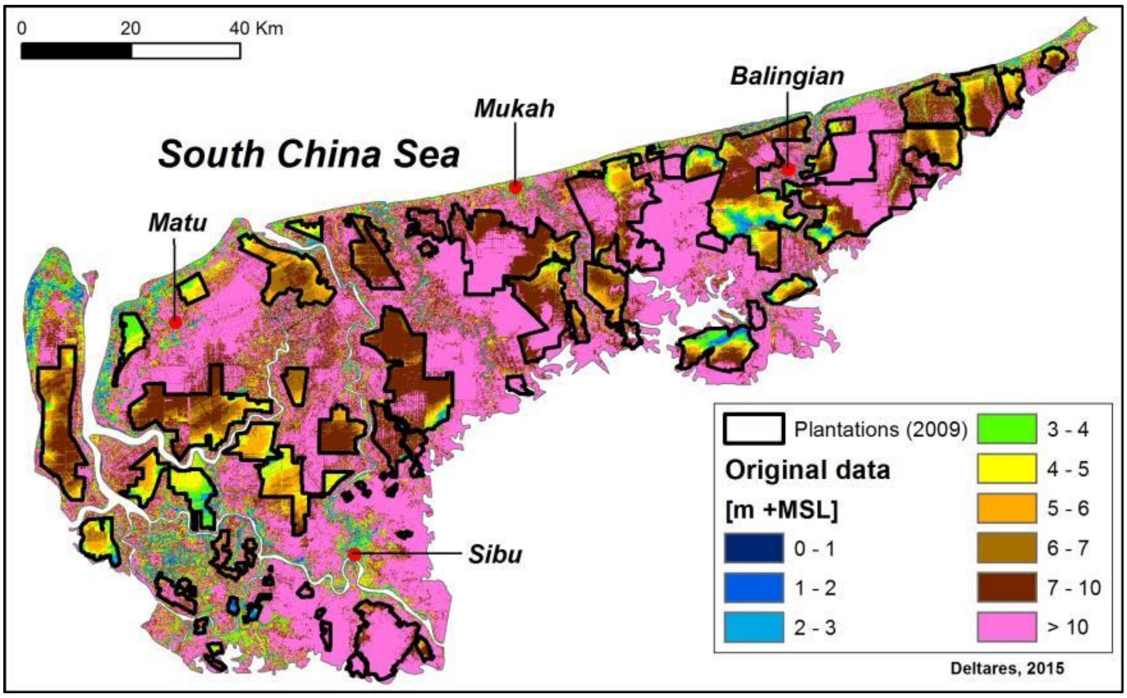

Figure 13 Original (resampled to 10*10 m by Intermap) IFSAR data for the study area, as collected in 2009. Extent (2009) of plantations is also shown. The filtering process applied is demonstrated in Figure 15 for an Island in the SE of the Rajang Delta.

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[8] http://www.mygeoportal.gov.my/sites/default/files/LAMPIRAN H_NEXTMap® Malaysia_071210.pdf

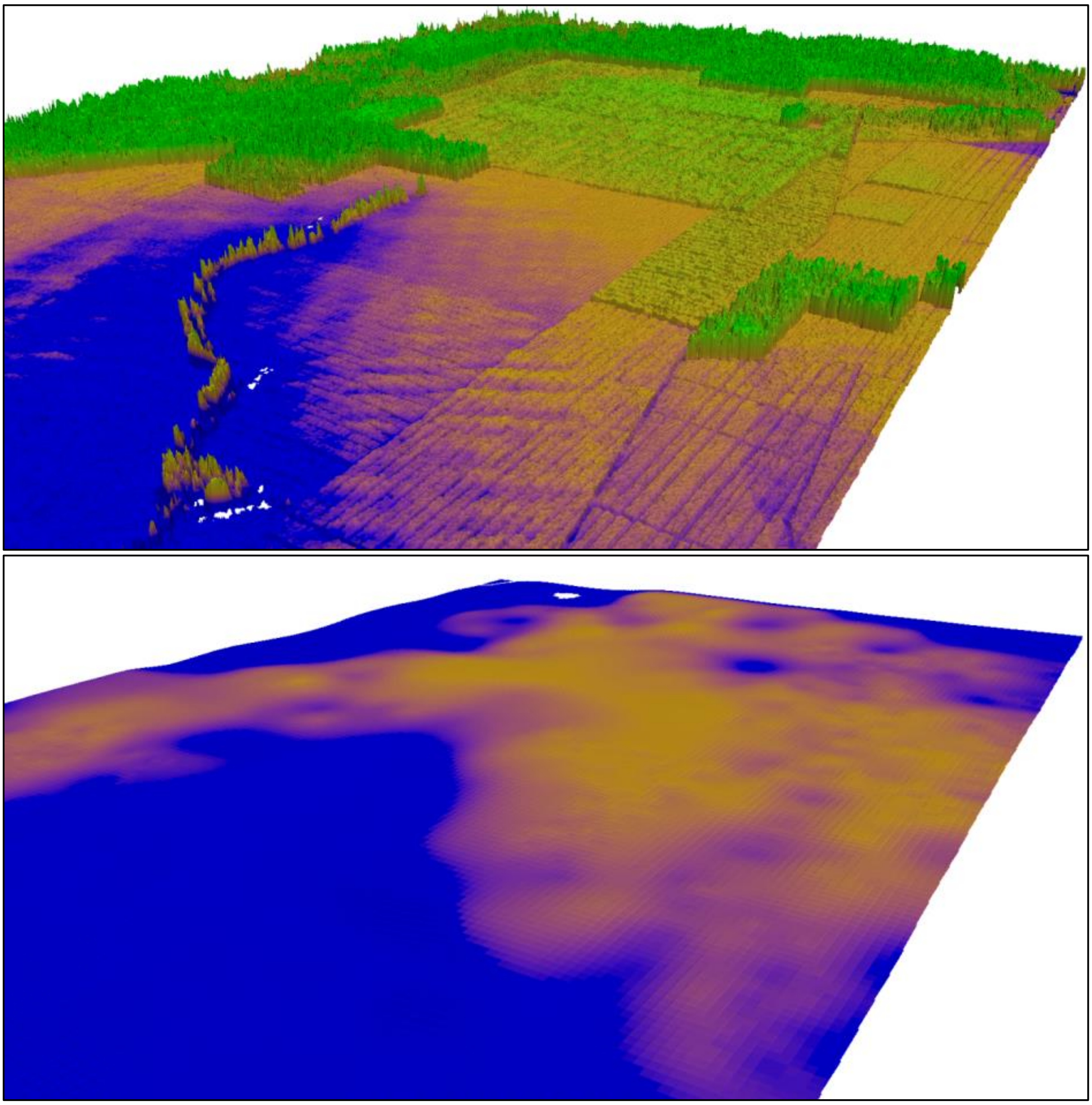

Figure 14 Top: 3D representation of original IFSAR data in an open oil palm plantation in the study area; clearly visible are the drainage canals as well as vegetation and **Bottom**: Same area after filtering steps as explained in the text. Vertical exaggeration is 3 times.

3.2 Removing vegetation effects from IFSAR data

Vegetation effects are largely removed in three steps. First, a ‘minimum filter’[9] is applied to the data, and set to select the lowest value in a 100*100 m^2 block of cells (10x10 cells). This block-size provided a visually better (smoother) result than applying block sizes of 50*50 m^2 (5x5 cells) or 250*250 m^2 (25x25 cells).

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[9] The minimum, median (canal) and slope (forest) filters have been programmed in the Julia scripting language (http://julialang.org/)

As part of the same step, visual inspection in areas known to be open from Landsat images revealed that none of the peat surface is above 10 m in the original IFSAR data for the study area. As this is the case in nearly all coastal lowland peatlands in SE Asia, all 100*100 m cell values above 10 m were therefore removed from the data.

The resulting elevation model after application of the minimum filter adequately represents the peat surface in open areas, but still does not always provide an accurate representation where dense vegetation occurs. Vegetation elevation in such areas is therefore further removed by applying a 'slope filter' that uses the peatland characteristic in the study area (as in the rest of SE Asia) of the surface slope being only rarely greater than 2 m km^{-1}. This removes all data points that are elevated above the general surface by more than this slope, and which are likely to represent vegetation. This filter is applied over a radius of 3 km (30 cells) around each point (cell).

3.3 Removing canal levels and 'open water' errors from IFSAR data

A dense network of canals is present in much of the study area at about 250 m intervals in the plantations. After application of the 'minimum filter', the IFSAR data are in some areas dominated not by the actual peat surface but by values that represent canal sides and canal water levels, which can be over a metre below the peat surface where water levels are low. Such 'canal' levels are largely removed by applying a filter that removes cell values that are more than 2 m below the median (most common) value in the surrounding 8 cells. This filter is applied before the 'slope or forest filter'. It was found that applying a threshold level of less than 2 m also removed larger low-lying areas not only canal sides. This filter step also removes the often very low erroneous values that occur in IFSAR data over open water.

3.4 Determining River Bank Level

River Bank Level (RBL; see also Figure 20) was determined for each river, which was first digitized from the 2014 Landsat image (Figure 2). The digitized rivers were cut into 100 m sections, after which the lowest elevation (using the remaining data points after application of the 'slope or forest filter') found in the vicinity of the river was attributed to the river section. As there were not always data points available near the river section, the elevation for the respective river section was derived from linear interpolation between the downstream and upstream elevation, following the principle that RBL elevation must go down in a downstream direction.

3.5 Filling in 'no data' points

The resulting data set after filtering combined with the River Bank Level data points has a large number of 'no data' points', as all point values that did not meet subsequent criteria were removed from the dataset. When projected on a 1 x 1 km grid, 63.1 % of the grid cells had at least 1 remaining value; this was 93.3 and 97.9 % when projected on a 2.5 x 2.5 and 5 x 5 km grid respectively. 'No data' model cells were subsequently filled by cell values generated by spline interpolation between remaining data points using ESRI ArcGIS software.

3.6 Correction of IFSAR DTM reference level with filtered SRTM-30

It was found that while the resulting DTM succeeded in presenting the typical peat dome shapes that are known to occur in the area, it had very low elevations along rivers of below 1 m +MSL at over 50 km from the coast. This is highly unlikely as such areas would be below high tide levels and normal river levels, and would be near-permanently flooded.

As a final step the resulting IFSAR DTM was therefore compared with SRTM-30 data (Space Shuttle Radar with a 30 m lateral resolution; 1 m vertical resolution (Farr *et al.*, 2007) from 2000, which has recently become available in the public domain for Sarawak. The SRTM-30 data were downloaded through the USGS Earth Explorer (http://earthexplorer.usgs.gov/). As with ‘raw’ IFSAR data, SRTM is not a DTM but a DSM that needs to be filtered to remove vegetation effects. To remove the vegetation effects the minimum value within a moving window of 33 x 33 grid cells (i.e. approximately 1 km) was used (Hooijer and Vernimmen, 2013).

The comparison of both DTMs was done only for those areas which were (i) considered ‘open’ i.e. free of tall vegetation in both 2000 and 2010 based on CRISP land cover classification, 250 m spatial resolution (Miettinen *et al.,* 2012; Figure 9), (ii) not on deep peat according to the 1968 Sarawak soil map to avoid issues of subsidence between the time of SRTM acquisition in 2000 and IFSAR of 2009 and (iii) were between 0 and 3 m + MSL to limit effect of incidental vegetation which may still be present in both filtered datasets.

In Figure 15 the different steps are shown in maps (the maps for the full study area are shown in Annex A). On average the difference between the IFSAR DTM and SRTM-30 is 1.6 m. The IFSAR DTM was therefore raised by 1.6 m to produce the final IFSAR DTM (Figure 16). It should be noted that this does not necessarily mean that the original IFSAR data are too low by 1.6 m, as it is possible that the filtering applied to remove vegetation has also lowered the ground elevation.

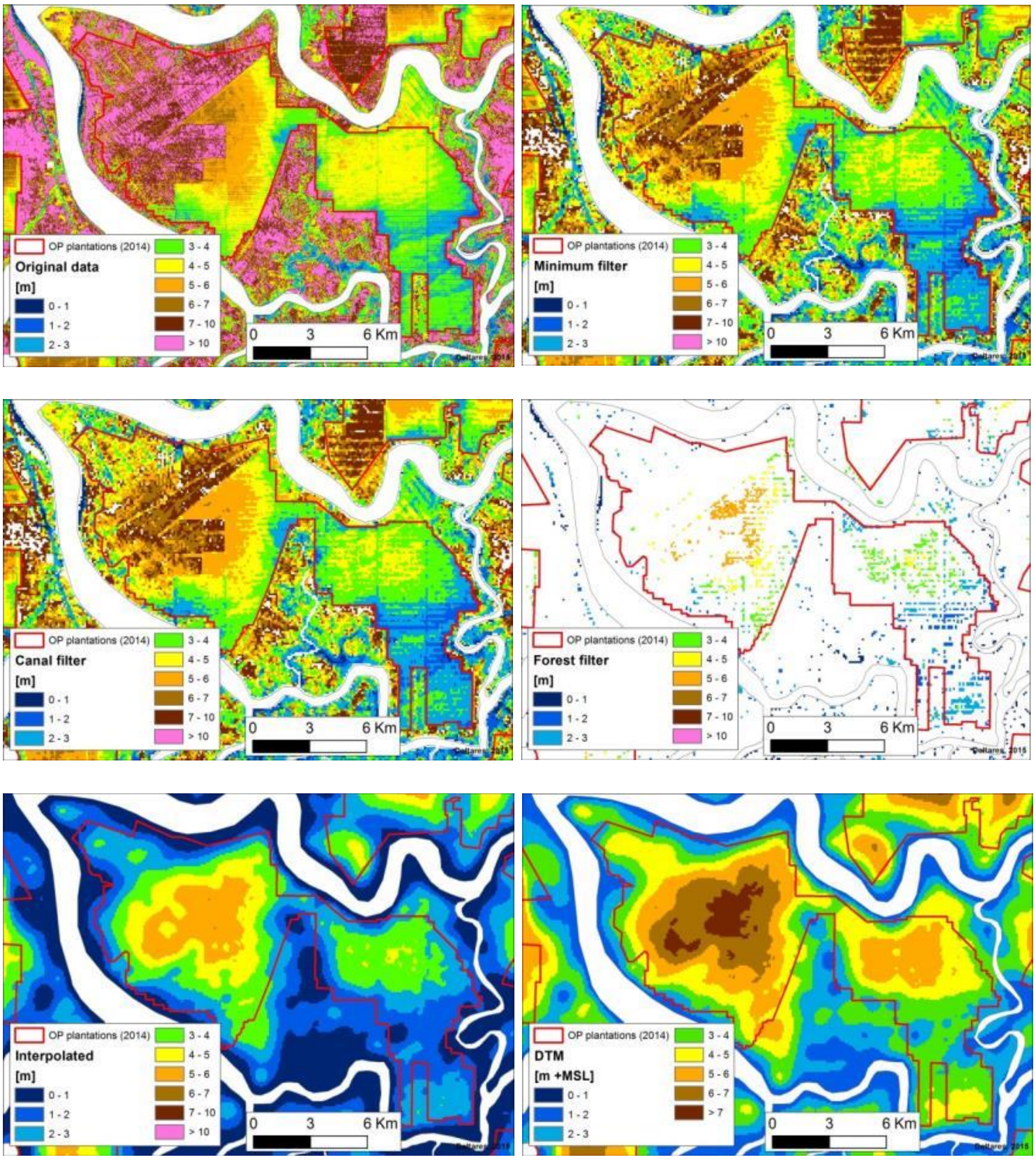

Figure 15 Individual filtering steps to remove the vegetation effects, canal levels and errors from the IFSAR data for a selected part of the study area (an island in the western part of the Rajang Delta, and surroundings; see Figure 13). **Top left:** original data. **Top right:** after minimum filter and removing values above forest threshold (10 m). **Middle left:** after applying the 'canal filter'. **Middle right:** after applying the 'slope filter', which removes most remaining data points. **Bottom left:** after spline interpolation of values between remaining cells. **Bottom right:** final DTM, after correction with +1.6 m following the comparison with filtered SRTM-30 (see text).

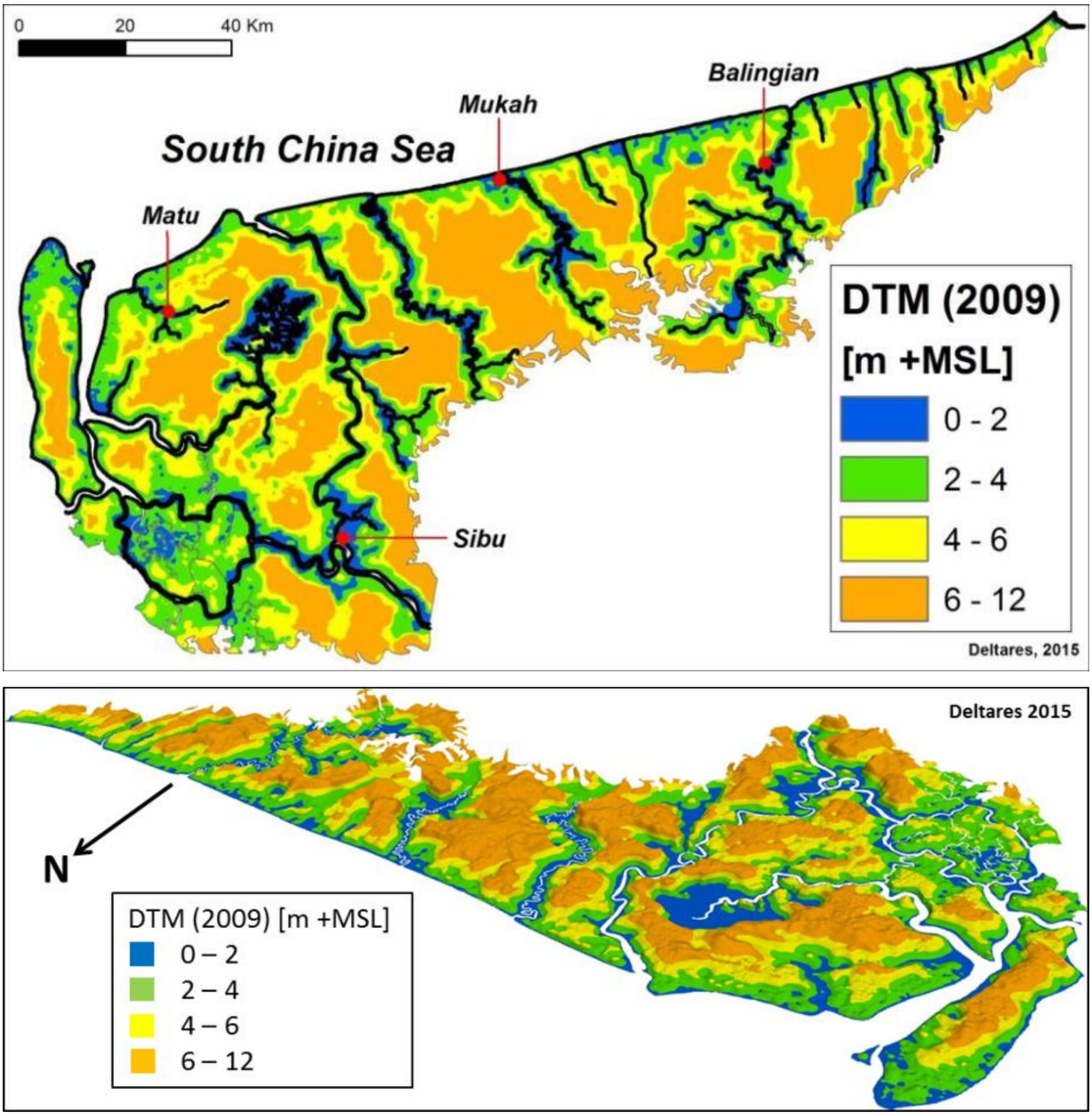

Figure 16 Final Digital Terrain Model for the study area as used in subsidence and flooding assessments. **Top:** Standard view. **Bottom:** Three-dimensional DTM of the study area, looking in a south-east direction from the South China Sea (i.e. the east side of the area is at the left-hand side of the figure).

3.7 Comparing the IFSAR DTM with elevation survey measurements

3.7.1 Elevation distribution

Figure 17 presents the elevation distribution in the study area determined from the final IFSAR DTM shown in Figure 16, for the Rajang Delta and for the entire study area including the Coastal Plain (see Figure 4). The elevation distribution in the delta differs somewhat from that in the wider coastal plain. In the delta, the most common elevations are around 4 and 6 metres whereas this is around 2 and 5 metres when the entire coastal plain is considered. On the other hand, the highest elevations in the delta are at 10 m while this is 12 m for the wider area. With respect to key values for flooding however, the two data populations are almost identical: 24 % of the peat surface is below 3 m, and 53 % is below 5 m.

We conclude that the Rajang Delta DTM in key respects is sufficiently representative for the study area as a whole, and therefore suitable for DTM validation.

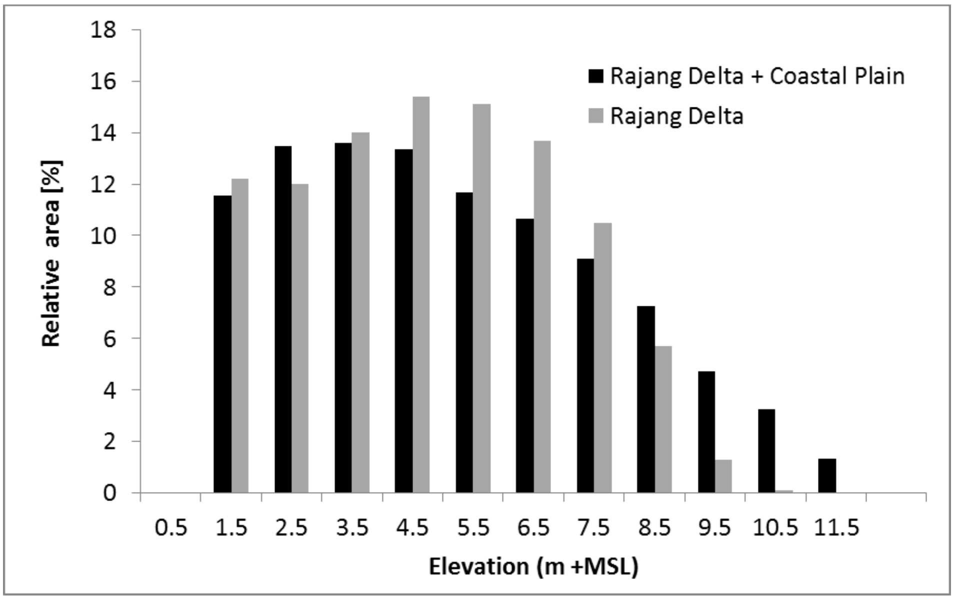

Figure 17 Relative distribution of surface elevation in the IFSAR-derived DTM, for peat in the Rajang Delta and for peat in the study area as a whole.

3.7.2 Validation of the DTM

The morphology of peatlands in Sarawak, and especially in the Rajang Delta, has been studied relatively intensively compared to others in SE Asia. A total of six surveys of peat surface elevation along transects in the Rajang Delta were identified in the literature (see Annex C), and used to validate the IFSAR based DTM for that area, as shown in Figure 18. The locations of these field measurements are known only approximately, so no transect-by-transect comparison was possible. From all elevation points in the DTM for the Rajang Delta, an average cross section profile was therefore derived for comparison with the average of all field measurements. This was only possible over the first 5 km as few of the field survey transects reached beyond that distance. The locations of field survey transects within the DTM is shown in Figure 19.

From the standard deviation around average DTM values it is clear that the variation in elevations is substantial with as many points at 1 km from a river being at 2 m +MSL as are at 4.5 m +MSL, as is also evident from the individual field survey profiles presented in Annex C. This reflects the variation in development history and also current land use (with associated subsidence) in the area.

From Figure 18 it can be seen that peat surface DTM and field elevation measurements are very close (within 0.5 m) over the first kilometre from the rivers. This confirms that the overall referencing to MSL of the DTM (for which the IFSAR-based DTM was moved up by 1.6 m to better match SRTM values in low open areas, see Section 3.6) is correct. Going further away from the river, this difference gradually increases to almost 2 m at 5 km. The average difference between DTM and field measurements over the first 5 km from rivers is about 1 m with the IFSAR-based DTM presenting a higher elevation than the field survey data. Except for the highest areas furthest away from the river, however, the field measurements are within one standard deviation from the DTM.

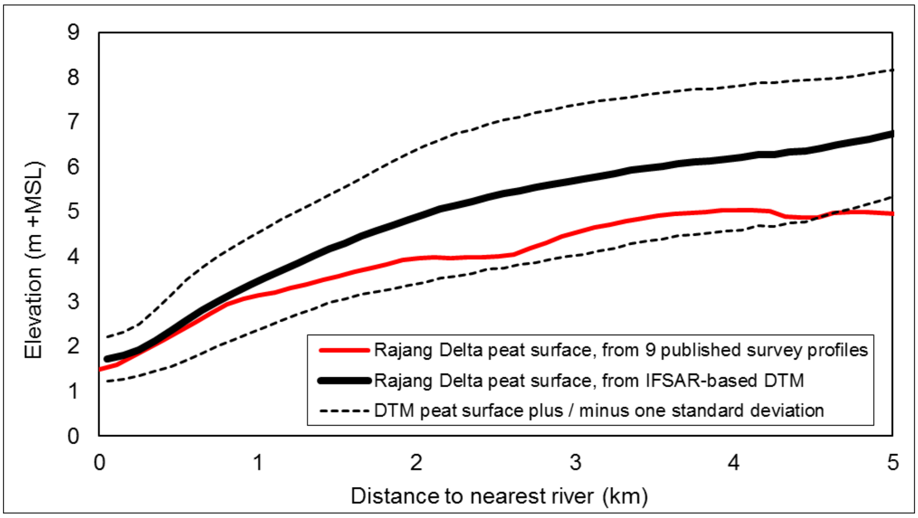

Figure 18 Average peat surface elevation profile as derived from the DTM for the Rajang Delta, with standard deviation, compared with the average profile as derived from field measurements. Non-peat points were excluded from both datasets. For more details on the individual profiles see Annex C. See Figure 20 for application of this profile in a demonstration of drainability limits and flood levels.

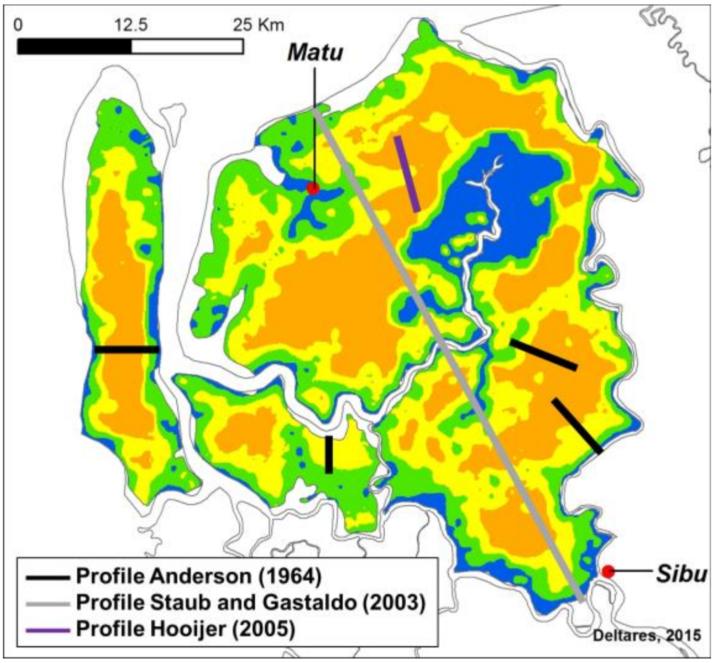

Figure 19 Detailed map of the Rajang Delta DTM (for peat areas only), with transect lines (see Annex C) used for validation. Note that the exact survey locations of Anderson (1964) are unknown, so locations were estimated by relating transect names to local names. Note: this is the same map as presented in Figure 16, however only showing the Rajang Delta (the western part of the study area).

3.7.3 Possible causes of deviations

It should be noted that about half the field elevation measurements (the profiles from Anderson, 1964) pre-date any drainage or clearing activity in the area, and the remaining profiles (Staub and Gastaldo, 2003; Hooijer, 2005) also predate plantations, though most of the forest had been selectively cleared and disturbed at that time. The profiles from literature therefore present the peat surface as it was before major drainage and subsidence started. The IFSAR-derived DTM (Figure 19) on the other hand reflects conditions in 2009 when about half of the Rajang Delta area was already occupied by oil palm plantations and most of the remainder was otherwise drained, so at least one metre of subsidence is expected to have affected DTM elevations (Section 2.4; DID Sarawak, 2001). Therefore, the ~1 m difference between DTM and older field measurements in fact reflects a 2 m difference that would have been found had the field measurements been more recent and post-drainage. In other words, the DTM would have been 1m higher had it been based on pre-drainage data, like the literature profiles.

The substantial subsidence-corrected difference between DTM and field measurements may be caused by several factors. First of all, the field surveys are a random and relatively small sample of a large area with a broad range in morphology conditions – a difference would be expected even when both DTM and field measurements are completely accurate. Secondly, field surveys of surface elevation in dense peat swamp forest are notoriously difficult (because of inaccessibility, poor lines of vision for leveling instruments, and ground instability i.e. instable instruments), and often found to be inaccurate (Hooijer and Vernimmen, 2013); errors of over a metre are expected over longer distances and can be systematic i.e. cumulative in one direction (i.e. with an increasing under- or over- estimation with difference from the starting point, which is the river side). Finally, the DTM itself will have inaccuracies too, related to removal of vegetation signal and also referencing to MSL as discussed in Section 3.6. However, such inaccuracies in the DTM would be expected to be non-systematic i.e. independent of distance to river. The relation between deviation and distance to river that is evident in Figure 18 therefore points at a cause other than DTM inaccuracy.

It should be noted that if the IFSAR-based DTM would overestimate surface elevation, that would contribute to the current study being conservative in its flooding predictions. The final DTM may therefore be used confidently as a conservative representation of the Rajang Delta peatlands for the purposes of projecting future subsidence.

4 Peat subsidence and flooding projections

This chapter presents the results of the peat subsidence and flooding projections for the Rajang Delta as applied to the DTM produced in this study (Chapter 3). It defines the type of flooding that may occur and presents future peat subsidence and flood projections for 25, 50, 75, 100 and 150 years under current drainage conditions and land uses.

4.1 Flood risk types

Two types of flood risk can be defined based on (a) High river and sea Water Levels inundating the land (HWL) and (b) the Free Drainage Limit (FDL), which is the point at which subsidence across the landscape lowers the drainage gradient to rivers to a point that gravity-based drainage becomes problematic. The core principles are demonstrated in Figure 20.

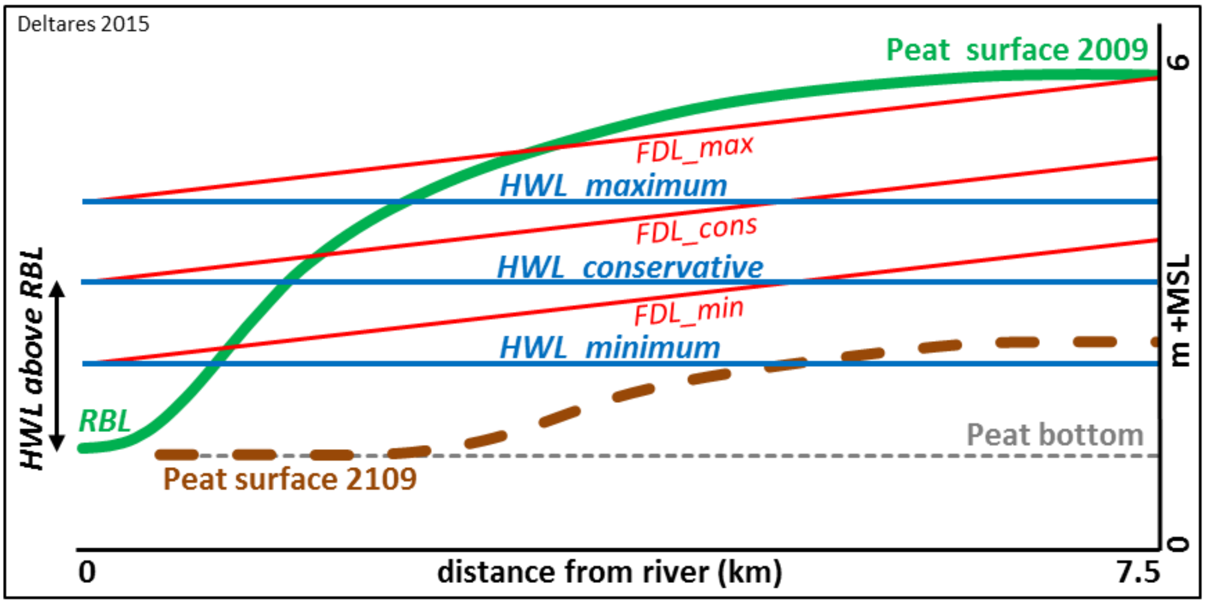

Figure 20 Illustration of the High Water Level (HWL, the level of severe floods that occur at least once every 5 years, but possibly annually) and Free Drainage Limit (FDL, the level below which drainage by gravity becomes impeded and inundation after heavy rainfall is likely) drainage limits in relation to River Bank Level (RBL), which is the elevation of the river side that is known to flood frequently (see Section 3.4). The HWL and FDL are shown relative to the measured peat surface in 2009 (taken from the IFSAR based DTM shown in Figure 18) and 2109 (projected with an annual subsidence rate of 3.5 cm yr^{-1}; Section 2.4). Three potential HWL levels are shown: a conservative HWL flood level may be conservatively defined by an elevation of 2 m above RBL. The minimum likely HWL is assumed to be an elevation of 1 m above RBL and the maximum likely HWL 3 m above RBL. The FDL for each potential HWL is defined by a conveyance gradient of 0.2m km^{-1} from the river, which is generally accepted as the minimum gradient required for gravity drainage. When the peat surface subsides below the FDL, these areas are expected to have impeded drainage and inundation. As subsidence proceeds, the peat surface may fall below the HWL with these areas being affected by more serious flooding. See text for further details.

4.1.1 Defining the coastal and river High Water Levels

The High Water Level (HWL) represents the elevation that can be reached by sea and river levels for prolonged periods (i.e. during the wet season). HWL therefore represents the elevation below which the land surface would be at risk of being flooded regularly, without feasible options to remove flood waters[10]. Where the subsidence process is allowed to continue to bring the peat surface below HWL, agriculture will certainly be impossible.

Coastal High Water Levels

Along the coast, the tidal HWL is determined by tidal regime and storm surges. Tidal flooding usually occurs where the land surface is below the upper limit of the astronomic high tide level of the sea surface. As peak high tides occur only over short periods of less than a day, the risk of flooding can sometimes be managed near the coast, for example by using 'flap gate' sluice systems, or sometimes pumping in small urban areas, but usually only as long as they do not coincide with extreme rainfall events or storm surges. In the long term, i.e. at the decadal time scales analyzed in this study, such a coincidence of conditions is almost inevitable and flooding to at least high tide level is likely. Such events may at first be relatively rare and brief, and may not end agricultural productivity quickly by themselves. However, it will increasingly complicate management, raise cost and reduce yields.

The HWL applied in the calculations for areas directly along the coast (i.e. not rivers or estuaries) is 2 m +MSL, and includes the effect of storm surges. However, there is substantial spatial variation in this parameter, as the normal tidal range (the elevation difference between low and high tide) varies from 2.5 m in the east of the study area to over 5 m in the west (Staub and Gastaldo, 2003; Figure 4). In the Western Delta part of the study area, where marine influence on flood levels is greatest, HWL may occasionally be over 3 m +MSL accounting for rare 'King Tides'. The 2 m +MSL HWL is therefore considered a conservative value.

Table 3 Water levels at monitoring stations in Sibu (from http://infobanjir.water.gov.my/waterlevel_page.cfm?state=SRK&rows_2=1&rowcheck_2=1).

Station ID	*Station Name*	*Normal level*	*Alert Level*	*Warning Level*	*Danger Level*
2218403	Sarawak Maritime	1.80	2.50	2.62	2.90
2218405	Stabau	2.40	3.50	3.74	4.30
2218402	Express Terminal	1.80	2.50	2.62	2.90
2218402	Sg.Bidut	1.80	2.80	2.98	3.40
2318402	Sg.Merah	1.30	1.98	2.14	2.50
2218404	Salim	2.40	3.40	3.70	4.00

River High Water Levels

In rivers further away from the coast, HWL is increasingly determined by river discharge and less by tidal regime. In the study area, the city of Sibu is in the region that is furthest inland and where HWL is likely to be in the higher range. Here river flood levels, often referred to as

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[10] While pumping can solve flooding problems in small urban areas and some larger areas in Europe and the USA, this solution is almost certainly not feasible in rural areas in SE Asia, because i) the protected investments here are too low to justify the very high cost and ii) rainfall intensities are far higher than in other parts of the world, requiring proportionally more pumping capacity.

‘king tide’ locally (even though they are mainly caused by peak discharge in the Rajang river instead of actual tide) are in the range of 3 to 4 metres[11] above Mean Sea Level (+MSL), some 1 to 2 metres above the ‘normal’ river level (Table 3). A list of occurrences of extensive land flooding in Sibu (from DID Sarawak), from 2004 to 2009, suggests that floods of 2 days or more occur over twice a year on average and exceed 0.5 m in flood depth in some locations when river levels exceed about 2.3 m +MSL (at the Sg Merah location), suggesting the lowest land surfaces in the city are below 2 m + MSL. Such levels are reported to occur mostly in the December-January wet period of highest rainfall[12]. Floods of 5 days or longer, during which flood depths exceed 1 m, occur about once a year on average.

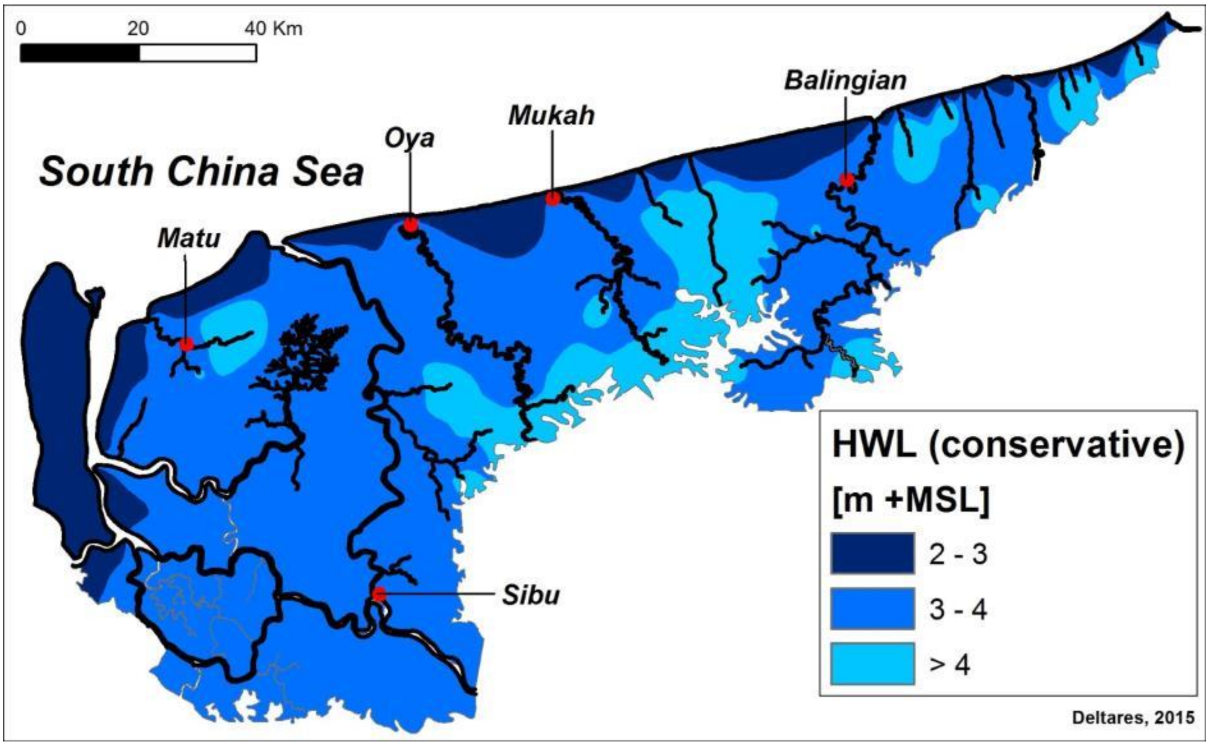

Figure 21 Conservative High Water Level (as defined as RBL +2 m, see text) in the study area.

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[11] See http://infobanjir.water.gov.my/waterlevel_page.cfm?state=SRK&rows_2=1&rowcheck_2=1

[12] See also reports in local newspapers such as http://www.theborneopost.com/2013/12/29/flash-flood-inundating-low-lying-areas-in-sibu/

4.1.2 Defining the HWL for Minimum, Conservative and Maximum Impact Scenarios

As no water level data are available in the public domain for rivers in the area, except at Sibu, we have defined three possible High Water Levels (Figure 20) based on the RBL (River Bank Level) that was also applied in the generation of the DTM (Section 3.4). The RBL is defined as the lowest land elevation that could be identified near or along the river (between 100 and 500 m from the river side, to exclude points at the river side itself), that was not flooded at the time of IFSAR data collection in the dry season (29 June – 16 August 2009) when river levels were low; most RBL points along most rivers are below 2 m +MSL and only just above high tide level. RBL may therefore be assumed to represent a level that is between dry season low water level and 'normal' wet river level (i.e. the level that occurs most of the time). The distribution of river water levels at Sibu in Table 3 suggests that 'danger' flood level is 1 to 2 m above the 'normal' river level. As flood levels can periodically exceed the 'danger' level, and flood levels of 2 m above normal river levels are in fact exceeded in other lowland rivers in the region (Hooijer and Vernimmen 2013; Annex C) we conclude that the conservative HWL flood level that occurs with some frequency may be defined by an elevation of 2 m above RBL. For the minimum HWL, we apply an elevation of 1 m above RBL, and for the maximum 3 m above RBL[13]. These HWL values are matched with the minimum, conservative and maximum subsidence rates for each of the three impact scenarios (Section 2.4).

Along the coast, a fixed HWL of 2 m +MSL is applied in all scenarios, 'Conservative' as well as 'Minimum' and 'Maximum', as this is only influenced by tide levels not river levels.

In the more inland part of the eastern coastal plain section of the study area, e.g. along the Oya and Mukah rivers, the rivers are narrow and meandering. Here, the HWL rises more abruptly at around 25 to 35 km from the coast (Figure 22), as is reflected in HWL levels shown in Figure 21.

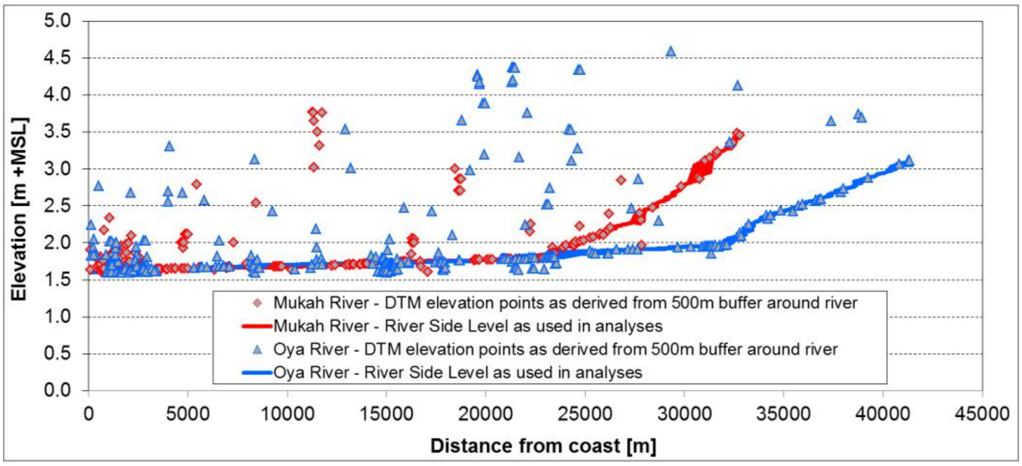

Figure 22 River levee levels along the Oya and Mukah rivers as determined from the IFSAR DTM (after correction to SRTM levels), by selecting all points before interpolation in a zone of 100 to 500 m from rivers. The fitted line through lowest levee elevation points was used to implement the HWL threshold to the eastern 'coastal plain' part of the model.

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[13] It should be noted that, as HWL along rivers is defined as an elevation above RBL, and RBL defines the DTM along rivers, an upward or downward shift in DTM reference level would not affect the area affected by flooding along rivers as RBL would also move up or down. However, since the HWL along the coast is fixed to MSL not to the DTM, a shift in DTM reference level will affect the flood extent.

4.1.3 Establishing the Free Drainage Limit, FDL

Impaired drainability starts when the peat surface approaches the local Free Drainage Limit (FDL), defined by adding a conveyance gradient of 0.2 m km^{-1} (DID Sarawak, 2001) to High Water Level (HWL), calculated as a function of distance from the river. When land subsidence brings the peat surface below FDL, it becomes increasingly difficult to remove heavy rainfall from the land. The frequency of first waterlogging and later flooding increases as the peat surface subsides further below FDL, and sustained crop cultivation will require increased water management efforts. A soil depth of 0.5 m above the water table is added to FDL levels, which is the minimum required to grow most crops including oil palm on peatland (DID Sarawak, 2001).

4.2 Conservative future subsidence and flood risks

The conservative subsidence rate of 3.5 cm yr^{-1} (Section 2.4) is applied to the DTM shown in Figure 16 over a period of 150 years. After each 25 year time step, we test for each cell whether it is above or below the conservative High Water Level (HWL) and Free Drainage Limit (FDL) thresholds. The result is a series of maps showing flooding and drainability conditions after 25, 50, 75, 100 and 150 years. We do not account for the reduction in subsidence rate that is likely to occur as an area gets more frequently flooded, as this relation is unknown and we assume that no substantial reduction in subsidence rate will occur until an area has become flooded for a period of months each year, which is many years after agricultural production is likely to be affected. Plantation managers would also be expected to maintain drainage canals and water table depths in line with crop requirements, which would also maintain subsidence rates until flooding becomes a significant problem.

4.2.1 Flood Risks in 2009 and 2059

Figure 23 compares the flood risks in 2009 based on the existing IFSAR-derived DTM and in 2059 after 50 years of subsidence of 3.5 cm yr^{-1}. In 2009, flood risks are mostly limited to the river floodplains, parts of the coastal area and two low-lying areas: one area in the south-west of the study area located in Sarikei and Sibu administrative divisions between the Muara Payang and Hulu Seredang rivers, and another in the central Batang Lassa river area. The first area has mostly shallow or mixed peat soils and mineral soils with elevation predominantly only 2-4 m above MSL (see Figure 16). Owing to these conditions, oil palm plantation development in this area is confined to small pockets of elevated deep peatland. Similarly the Batang Lassa river area is a very low lying area, mostly covered with mangrove, that has been partly designated as a national park.

The 2009 flood risk map also shows the the 2014 distribution of plantations (Figure 23, top). Three points become apparent. First, already almost half (43.5 %) of the total peat area (plantations and non-plantation areas) lies below the FDL with about one third (29.9 %) also being below HWL, confirming that flooding is already a problem in many areas. Second, the presence of palm oil plantations appears to be associated with a relative current absence of flood risk as predicted by this model, with 29 % being below FDL and 18 % below HWL (Table 5). In fact, most parts of the study area that in 2009 are considered not to have any risk of flooding or impeded drainage were occupied by oil palm plantations. Third, if the distribution of oil palm is compared with the map of deep peat (Figure 4), it is clear that oil palm growers have targeted the elevated deep peat areas, i.e. the higher elevations of peat domes, probably to avoid the problems of low lying land that has existing flood problems.

By 2059 following fifty years of drainage and subsidence, the flood projection suggests that almost three-quarters of the peat area (69 %) will be below FDL and 54 % below HWL (Figure 23, bottom). Within existing (2014) plantations, these percentages are 56 % and 39 % respectively (Table 5).

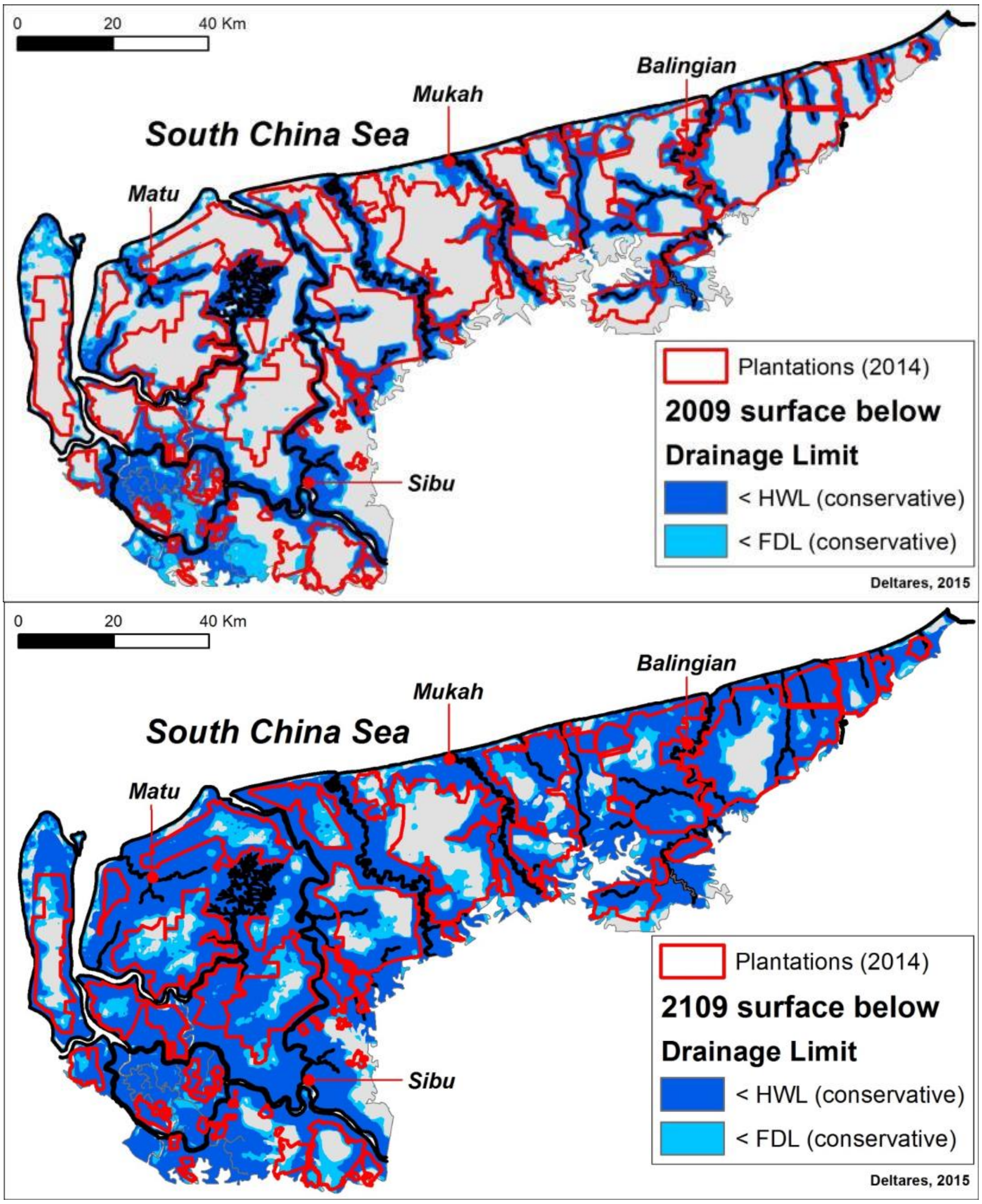

Figure 23 Estimation of flood extent (land surface below HWL) and drainability problems (land surface below FDL) as modeled for 2009 (top) and as projected for 2109 (bottom) under the 'Conservative Impact' scenario, i.e. applying a subsidence rate of 3.5 cm yr^{-1} and conservative flooding thresholds (Figure 20). Note that flooding is still limited at present, occurring mostly in natural floodplains and estuarine mudflats. In these maps, only the condition that is considered to have the greatest impact on land use is shown, with the surface being below HWL being more impacted by flooding than being below FDL. In some areas, peat surface levels are or will be below both thresholds, but only HWL is shown.

4.2.2 Peat subsidence and flood risk 2009-2159

The conservative subsidence rate of 3.5 cm yr^{-1} was applied to the IFSAR-derived DTM to model the likely impacts of subsidence on the peat landscape in the study area over the next 150 years. Figure 24 shows how peat subsidence from existing plantations and drainage will likely impact the landscape at 25, 50, 75, 100 and 150 years into the future.

Within 100 years, subsidence will have proceeded so that most of the landscape is potentially at or below below 2 m above MSL and flooded much or most of the time. Substantial parts of only two areas are projected to remain more than 4 m above MSL – an area to the south of Mukah and an area to the east of Balingian.

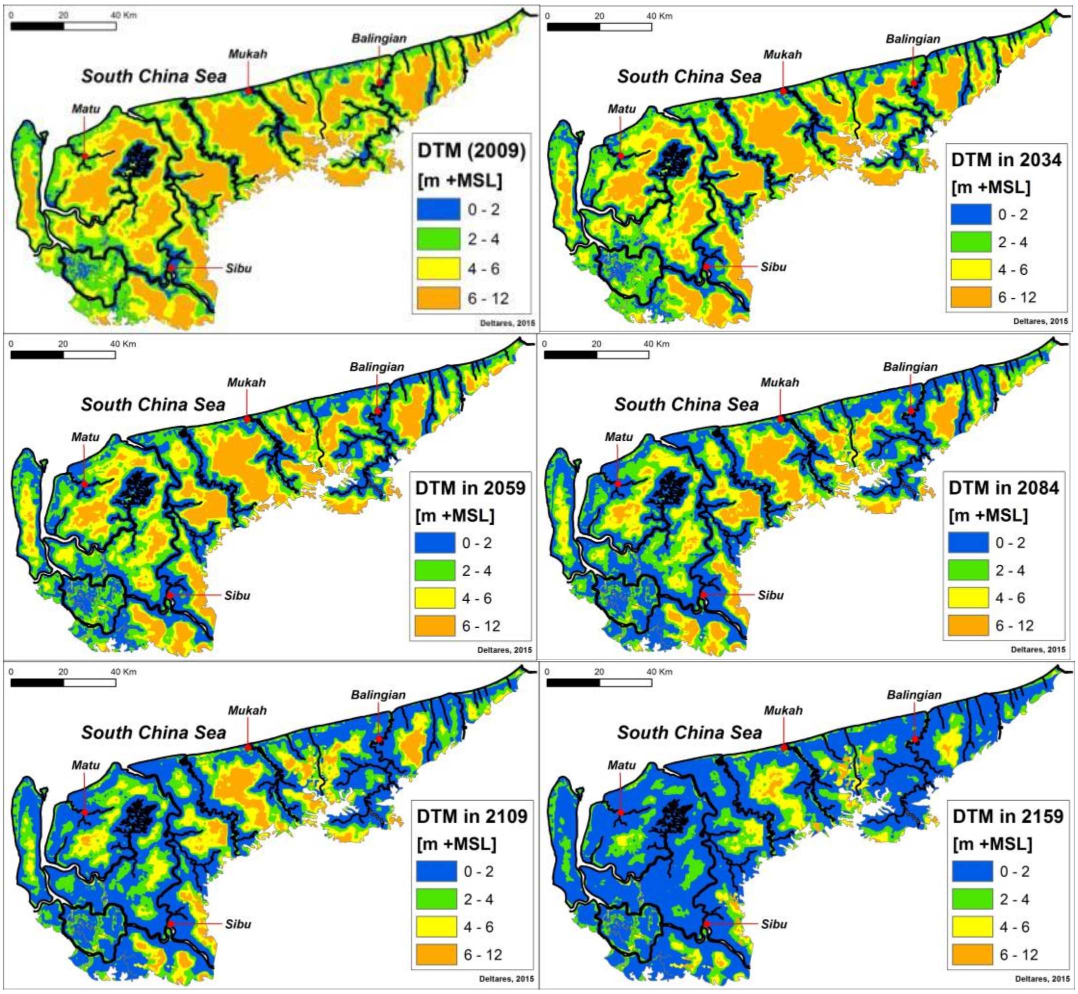

Figure 24 DTM at 0, 25, 50, 75, 100 and 150 years after 2009 applying a subsidence rate of 3.5 cm yr^{-1} in the 'Conservative Impact' scenario (Section 2.4).

Elevation characteristics of the 2009 DTM as well as the elevation model after 25, 50 and 100 years of subsidence are provided in Table 4. In 2009, the average land surface in the study area was 4.9 m +MSL. The average peat surface in plantations (2014 extent) was 6.0 m (Table 4). 43.9 % of the land surface is below 4 m + MSL, 67.0 % below 6 m and 95.8 % below 10 m. For plantations on peat, these figures are 23.5 %, 51.3 % and 93.2 % respectively (Table 4).

The landscape in the study area 50 years after 2009, by 2059, will be several metres lower than it was in 2009. The average land surface will be on average at 3.6 m with 63.5 % being below 4 m and the peat surface in plantations (as identified for 2014) will be at 4.4 m with 47.8 % below 4 m. By 2109, 100 years after 2009, the average land surface will be at 3.0 m with 79.6 % being below 4 m and the peat surface in plantations (as identified for 2014) will be at 3.3 m with 71.5 % below 4 m.

Table 4 Elevation characteristics of IFSAR-derived DTM (2009) and in 2034, 2059 and 2109 from subsidence modeling ('Conservative Impact' scenario, i.e. subsidence rate 3.5 cm yr^{-1}) for the whole study area, for the peat area within the study area and for the 2014 plantation on peat area.

Elevation characteristics	2009	2034	2059	2109
Total area				
Mean [m]	4.9	4.2	3.6	3.0
% <2 m	15.1	25.5	36.0	56.0
% <3 m	30.4	40.9	51.3	69.1
% <4 m	43.9	54.3	63.5	79.6
% <6 m	67.0	75.2	82.5	93.2
% <8 m	84.8	90.5	94.5	99.2
% <10 m	95.8	98.4	99.8	99.9
Peat area				
Mean [m]	5.2	4.3	3.7	3.0
% <2 m	11.6	23.3	35.3	58.0
% <3 m	25.0	37.0	48.7	69.0
% <4 m	38.6	50.3	60.8	79.0
% <6 m	63.6	73.0	81.2	93.4
% <8 m	83.4	89.9	94.5	99.7
% <10 m	95.4	98.3	99.9	100.0
Oil palm on peat area				
Mean [m]	6.0	5.1	4.4	3.3
% <2 m	4.5	11.7	20.7	44.3
% <3 m	12.9	22.1	33.5	58.1
% <4 m	23.5	35.4	47.8	71.5
% <6 m	51.3	63.4	74.4	90.5
% <8 m	77.2	86.1	92.0	99.6
% <10 m	93.2	97.4	99.9	100.0

Based on the 'Conservative Impact' scenario, the potential for flooding based on HWL and FDL criteria is shown as a time series from 2009 to 2159 (Figure 25; the maps for the 'Minimum' and 'Maximum' impact scenarios are provided in Annex B). The full results for the 'Conservative Impact' scenario showing the area below the HWL, FDL and combined

HWL+FDL are shown for the total study area, the peatland area and the plantation area in Table 5 (tables for the ‘Minimum’ and ‘Maximum’ impact scenarios are provided in Annex B).

The assessment clearly shows that much of the area including areas planted with oil palm will therefore experience floods within decades rather than centuries under the ‘Conservative Impact’ scenario. By the end of the century, only a few areas will remain to be suitable for oil palm production. The loss of suitable area is due to the wide prevalance of flooding and poor drainage resulting from subsidence.

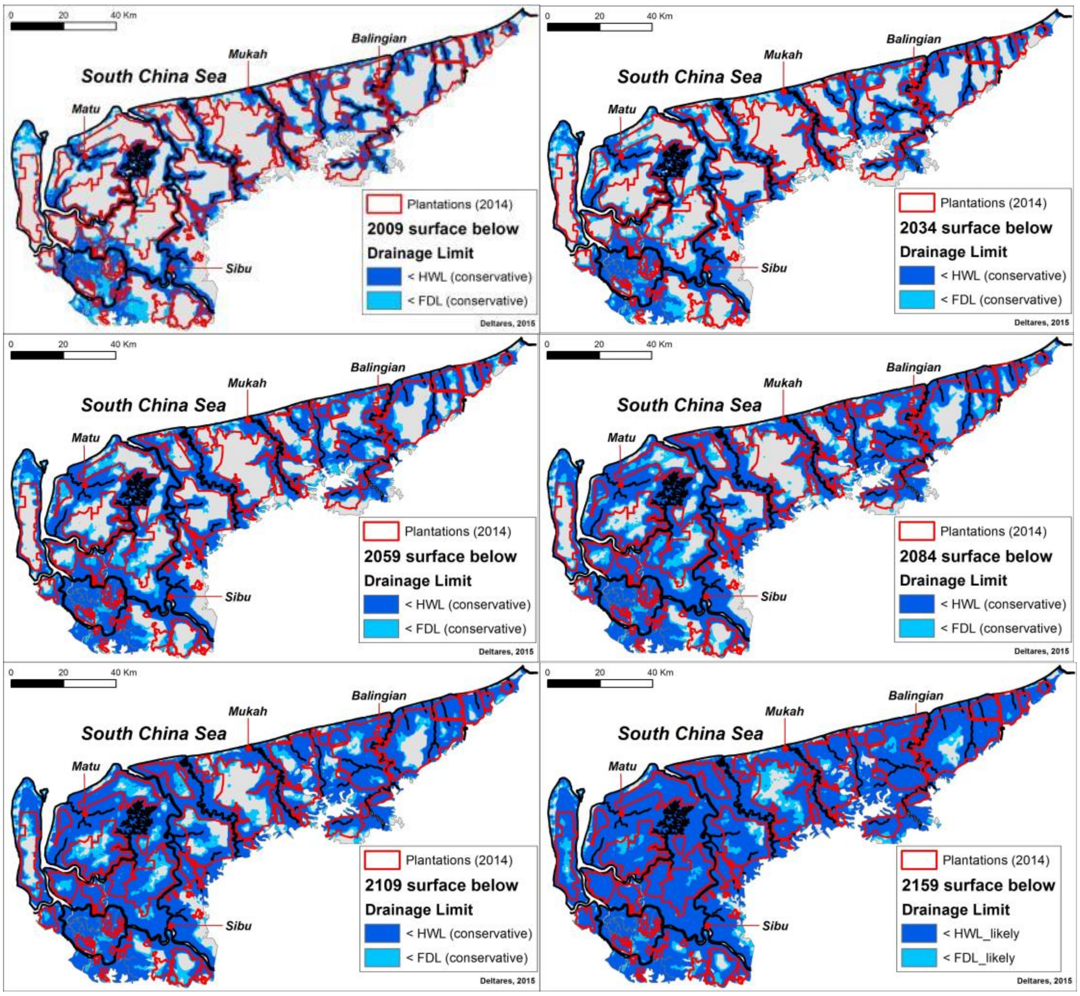

Figure 25 ‘Conservative Impact’ scenario flood extent projection for 0, 25, 50, 75, 100 and 150 years, applying a conservative subsidence rate of 3.5 cm yr^{-1} and conservative flooding thresholds (Figure 20) after 2009 (the date for which the DTM was created using IFSAR data). It can be seen that drainability loss (surface < FDL) create major problems within 50 years, with 42.2 and 56.2 % of the plantations on peat affected by some form of flooding or drainability loss after 25 and 50 years respectively (Table 5). After 100 years, only 13.1 % of the total land area is not affected by drainability loss, with 73.8 % of the land being below HWL (Table 5) i.e. certainly lost for any economic use. Maps for the ‘Minimum’ and ‘Maximum’ impact scenarios are provided in Annex B.

Table 5 Areas that are frequently flooded (below HWL) or have impeded drainability (below FDL), in ha and as % of total area, for the total study area, the total peatland area within the study area and for existing (June 2014) plantation area, in the 'Conservative Impact' scenario, assuming all land would be drained to a degree that causes a subsidence rate of 3.5 cm yr^{-1}. Note that all peat in the area is assumed to subside (88.1 % of the area), but not mineral soils (11.9 % of the area). Note that FDL_conservative presents the area that is ONLY below the FDL level but not below the HWL level. Tables for the 'Minimum' and 'Maximum' impact scenarios are provided in Annex B.

Impact scenario	'conservative' scenario					
Drainage limit	HWL (cons.)		FDL (cons.)		HWL + FDL (cons.)	
Subsidence rate	3.5 cm/yr		3.5 cm/yr		3.5 cm/yr	
year	ha	%	ha	%	ha	%
Total area						
2009	291736	34.4	116416	13.7	408152	48.1
2034 (after 25 yrs)	381095	45.0	127387	15.0	508482	60.0
2059 (after 50 yrs)	471288	55.6	125271	14.8	596559	70.4
2084 (after 75 yrs)	553455	65.3	118200	13.9	671655	79.2
2109 (after 100 yrs)	625464	73.8	111188	13.1	736652	86.9
2159 (after 150 yrs)	739692	87.3	69279	8.2	808971	95.4
Peat area						
2009	223346	29.9	101247	13.6	324593	43.5
2034 (after 25 yrs)	312705	41.9	112218	15.0	424923	56.9
2059 (after 50 yrs)	402898	53.9	110102	14.7	513000	68.7
2084 (after 75 yrs)	485065	65.0	103031	13.8	588096	78.7
2109 (after 100 yrs)	557074	74.6	96019	12.9	653093	87.5
2159 (after 150 yrs)	671302	89.9	54110	7.2	725412	97.1
Plantation on peat area						
2009	72001	18.3	41376	10.5	113377	28.8
2034 (after 25 yrs)	107906	27.4	58125	14.8	166031	42.2
2059 (after 50 yrs)	153627	39.0	67653	17.2	221280	56.2
2084 (after 75 yrs)	203207	51.6	70528	17.9	273735	69.5
2109 (after 100 yrs)	251384	63.8	70098	17.8	321482	81.7
2159 (after 150 yrs)	335711	85.3	41146	10.5	376857	95.7

4.3 Effect of HWL definition and subsidence rates on flood risk projection scenarios

As part of the study, we assessed the effect of alternative specifications for HWL and subsidence rates on projected future flood risks and drainability problems across the study area. The 'Minimum Impact' scenario (HWL of 1 m, subsidence rate of 2 cm yr^{-1}), 'Conservative Impact' scenario (HWL of 2 m, subsidence rate of 3.5 cm yr^{-1}) and 'Maximum Impact' scenario (HWL of 3 m, subsidence rate of 5 cm yr^{-1}) (see Section 2.4 and Section 4.1.2) are applied to the IFSAR-derived DTM over a period of 150 years.

Table 6 presents the flooding and drainability conditions according to the three subsidence scenarios in 25 year time steps (see also Figure 26). The results for the total area and peat area are very similar, reflecting that the majority of the study area is peat. Unsurprisingly, the different HWL levels and subsidence rates applied in the flood risk model can be seen to have an influence on the extent of flood risk at different time period into the future, but they have limited impact on the final outcome: in all scenarios, almost half (46 - 86 %) of the peat area is below FDL within 50 years, and over two-thirds (61 - 99 %) in 100 years.

Table 6 Comparison of peatland that would be frequently flooded (i.e. below HWL+FDL) under the ‘Minimum’, ‘Conservative’ and ‘Maximum’ impact scenario projections, assuming all peatland would be drained as if it were oil palm plantation.

Impact scenario	'minimum' scenario		conservative' scenario		'maximum' scenario	
Drainage limit	HWL+FDL (min.)		HWL+FDL (cons.)		HWL+FDL (max.)	
Subsidence rate	2 cm/yr		3.5 cm/yr		5 cm/yr	
Year	ha	%	ha	%	ha	%
Total area						
2009	307169	36.2	408152	48.1	503252	59.4
2034 (after 25 yrs)	364580	43.0	508482	60.0	629117	74.2
2059 (after 50 yrs)	421757	49.8	596559	70.4	730275	86.2
2084 (after 75 yrs)	478706	56.5	671655	79.2	791827	93.4
2109 (after 100 yrs)	532123	62.8	736652	86.9	826921	97.6
2159 (after 150 yrs)	623105	73.5	808971	95.4	832936	98.3
Peat area						
2009	230358	30.8	324593	43.5	417045	55.8
2034 (after 25 yrs)	287769	38.5	424923	56.9	542910	72.7
2059 (after 50 yrs)	344946	46.2	513000	68.7	644068	86.2
2084 (after 75 yrs)	401895	53.8	588096	78.7	705620	94.5
2109 (after 100 yrs)	455312	61.0	653093	87.5	740714	99.2
2159 (after 150 yrs)	546294	73.2	725412	97.1	746729	100.0
Plantation on peat area						
2009	72564	18.4	113377	28.8	163897	41.6
2034 (after 25 yrs)	95869	24.3	166031	42.2	241877	61.4
2059 (after 50 yrs)	122198	31.0	221280	56.2	313802	79.7
2084 (after 75 yrs)	153035	38.9	273735	69.5	360557	91.6
2109 (after 100 yrs)	184767	46.9	321482	81.7	388844	98.8
2159 (after 150 yrs)	244680	62.1	376857	95.7	393708	100.0

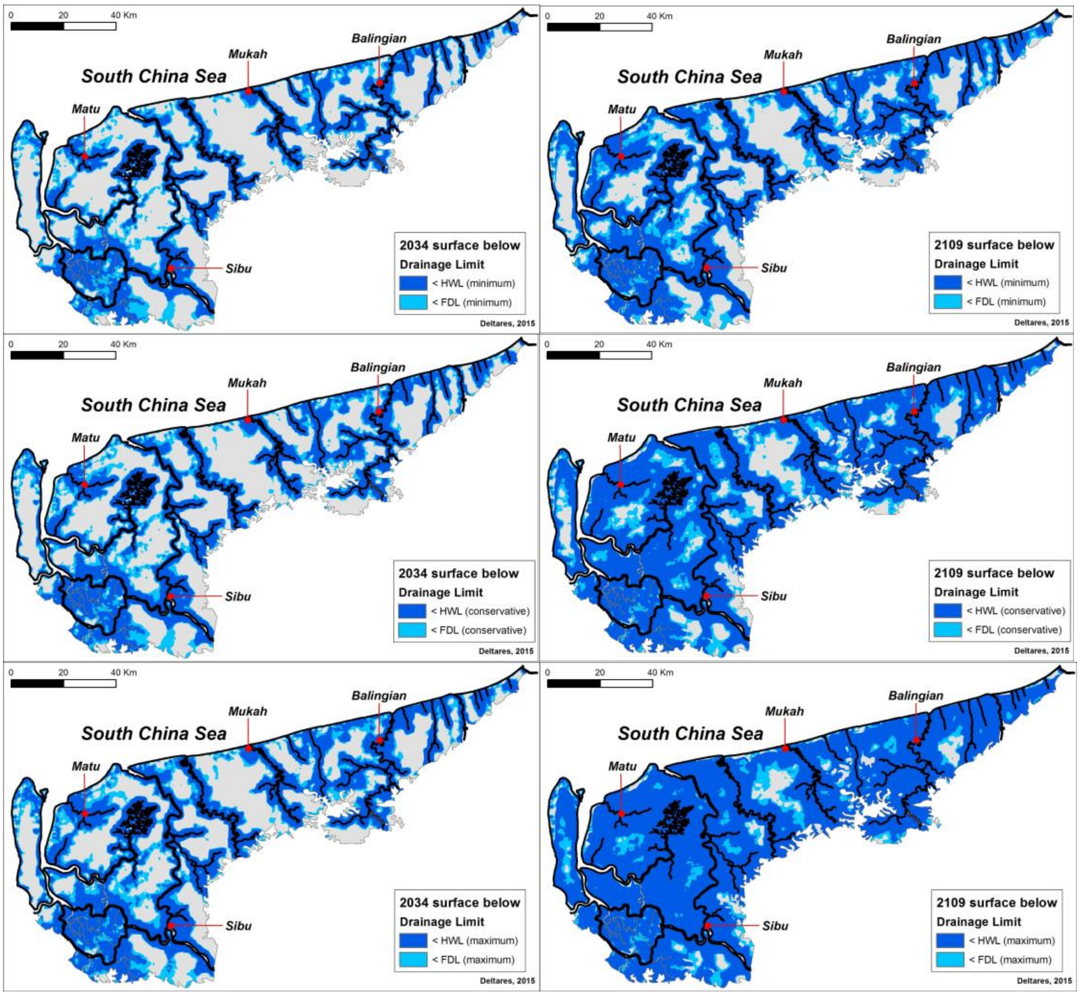

Figure 26 Comparison of flooding and drainability conditions according to the 'Minimum' (top), 'Conservative' (middle) and 'Maximum' (bottom) impact scenarios, after 25 (left) and 100 (right) years. The corresponding flooding and drainability limits are shown in Figure 20.

These results can also be displayed graphically to show how the area affected by flood risk increases over time as subsidence proceeds (Figure 27). In the 'Conservative Impact' scenario, practically all peatland and plantation on peatland in the study area will be affected by drainage problems within a little over one hundred years. This loss of drainability happens even faster in the 'Maximum Impact' scenario, while in the 'Minimum Impact' scenario, which is considered to be unlikely, the loss of drainability is slower. The difference between the overall peatland area and plantation on peat is relatively minor highlighting that the location of the oil palm plantation on top of the peat domes will not provide significant protection from the impacts of subsidence and flood risk.

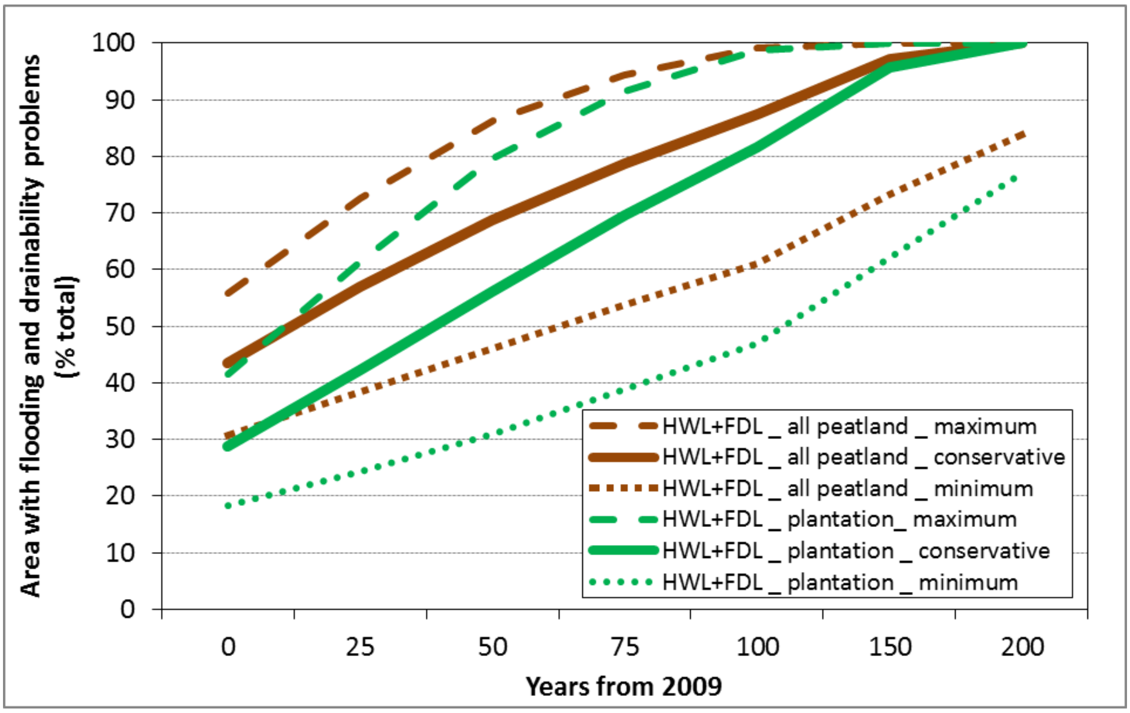

Figure 27 Future projections of the proportion of the peat area (brown lines) and oil palm area (green lines) with combined flooding (HWL) and drainability (FDL) problems. The 'Conservative Impact' scenario is shown by the full lines, 'Maximum Impact' scenario by the hatched lines and the 'Minimum Impact' scenario by the dotted lines.

5 Discussion and potential solutions

It is important to recognize that the qualitative knowledge underlying the flooding projections presented in this report is not new; the inevitability of flooding in most drained coastal lowland peatlands has been well understood for decades. What is new is the confident quantification of these processes because a relatively accurate elevation model was not available in the public domain until now and a consensus on subsidence rates in drained tropical peatlands has only been reached recently (Section 2.4).

5.1 Projections of increased flooding

Our study confirms suggests that flooding is probably already a problem for oil palm production in parts of this landscape and will certainly become much worse within decades if drainage continues. The 'Conservative Impact' scenario predicts that 29.9% of the peatland was already below HWL (i.e. having high flood risk) by 2009, which will increase to 41.9 % by 2034, 53.9 % by 2059 and 74.6 % by 2109 (Table 5). The 'Maximum Impact' scenario, with higher subsidence rate and flood level, finds 41.4 %, 57.9 %, 72.9 % and 93.3 % below the HWL for these years respectively (Table 8 and Table 9 in Annex B).

There are currently no field observations or remote sensing data available to verify whether these modeled areas affected by drainability problems and flooding are correct. Moreover, it should be considered that in the early stages of developing problems, increased flood risk does not have to lead to an actual increase in flood extent as areas may be kept dry by dikes (which are possible on shallow peat, not on deep peat) and gates. While these measures will fail when subsidence continues and flood risk increases, they may initially reduce flood extent to lower values than what we present here.

5.2 Confidence level of the assessment

The assessment presented in this report is conservative, i.e. it is more likely to underestimate the severity of the future flooding problem than to overestimate it. This is due to a number of factors:

- The DTM may overestimate peat surface elevation by 1 to 2 metres (Section 3.7) compared to published field survey results of elevation. Assuming these field surveys were correct, the peat surface will now be closer to Mean Sea Level than we have found, and the flooding is more imminent than we projected regardless of the subsidence rate applied.
- In our assessment we have assumed the peat surface as presented in the 2009 DTM has already undergone the initial subsidence spike that follows drainage, of 1 metre or more in the first year (DID Sarawak, 2001). Where this initial rapid subsidence has yet to take place, wholly or partly, this assumption is conservative as it underestimates actual subsidence rates.
- We have assumed that peat surface subsidence in the area is only caused by biological oxidation, and not fires. As fires do occur in the area (see Figure 11) and are known to cause additional subsidence (Page *et al.*, 2002; Ballhorn *et al.*, 2009; Hoojjer *et al.*, 2014), this is likely to contribute to an underestimation of subsidence in some of the area.

- Finally, we have not accounted for (relative) Sea Level Rise (SLR). The latest middle scenario by IPCC predicts 0.5 m of SLR in the next 100 years but this is now widely considered too conservative. A high scenario predicts over 1 m of SLR. Moreover, coastal river levels in the region are often assumed to rise faster than sea levels due to sediment accumulation resulting from widespread upstream deforestation, although this is poorly documented.

In summary, we conclude that actual developments will probably be somewhere between the 'Conservative' and 'Maximum' impact scenarios, and the 'Minimum Impact' scenario should be considered least likely. Indeed, a rapid field assessment in 2015 of flood occurrence in selected oil palm plantations (Annex E) revealed that the model results substantially underestimate current flood occurrences at these locations, suggesting that we either overestimate surface elevation or underestimate flood levels.

5.3 Flood implications for crop production

The threat of flooding to oil palm plantations on peat domes is illustrated by the fact that nearly all existing oil palm plantations were located away from the lower peatland i.e. above the current (2009) conservative High Water Level as can be seen in Figure 28. This also forms an implicit confirmation of the validity of the elevation model and flood levels used in this analysis.

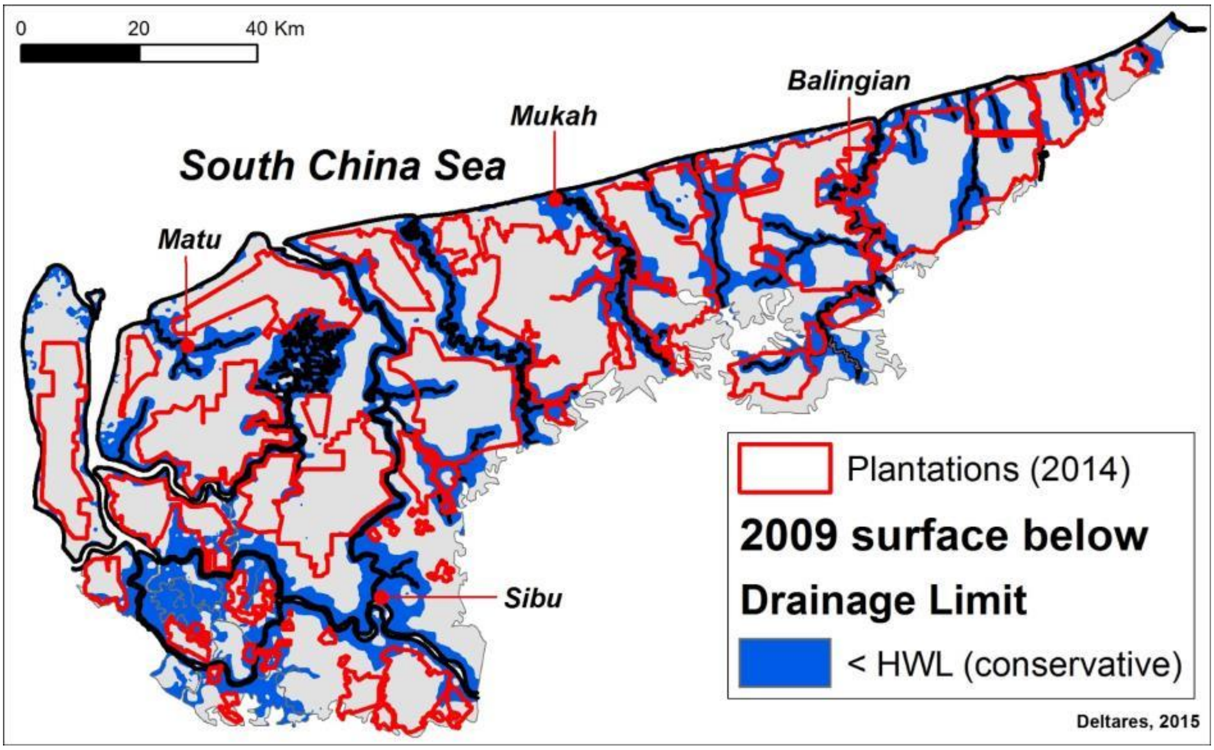

Figure 28 2009 surface below the conservative HWL drainage limit. Shown as well the 2014 plantation extent.

It is known that oil palm has limited tolerance to flooding (DID Sarawak, 2001), and a link between flood frequency and oil palm production loss is often observed[14]. It is therefore expected that crop production will continue to decline as drainage becomes increasingly problematic and the frequency of first waterlogging and then flooding increases. The projection of subsidence and increased flood risk presented in this report does not allow exact determination of the time at which loss of drainability will end production of palm oil and other crops, since this may depend on acceptance by land managers of yield losses and their capacity to invest in water management improvements. Our assessments suggest that some 18 % of oil palm plantations area on peat is already experiencing severe flooding (Table 5). Yet to our knowledge there are currently no published reports of large scale plantation abandonment in the area, suggesting this is a gradual rather than abrupt process. However, it is possible, and indeed often observed during field checks outside of Sarawak, that oil palm producers are reluctant to admit to water management problems or production failures.

Abandonment of plantations may occur at some point between the peat surface being at FDL, when drainage becomes problematic, and at HWL when flooding may be semi-permanent. Although there are no established records at present, it seems safe to assume that plantations will be abandoned long before the peat surface reaches HWL, at the point where prolonged annual floods become the norm.

The fate of plantations after abandonment is unclear, but without rehabilitation efforts their likely future will be as degraded wastelands at high risk of fire during dry years when water tables are low, and of extended flooding during wet periods, preventing the return of natural forest beyond some pioneer species.

Whatever the precise timing and pathways, the end result of continued drainage in this area is evident. It will become increasingly difficult to drain the land, resulting first in frequent waterlogging and occasional flooding, but eventually in flooding that is so frequent and deep that agriculture will be impossible and plantations will need to be abandoned. Even in the ‘Minimum Impact’ scenario, that we consider to be unrealistic, almost half (46.9 %) of the area will suffer from drainage problems within 100 years, compared to 81.7 % in the ‘Conservative Impact’ scenario (Table 6).

Sarawak has an estimated 1 million hectares of land planted for oil palm with plans to expand this area by a further 1 million hectares by 2020[15]. The Rajang Delta peatland study area represents approximately 40 percent of Sarawak’s current planted area, so these findings have important implications both for current oil palm production and plans for future expansion.

5.4 Research and policy recommendations

This study has provided a technical assessment of the potential impacts of peat subsidence on flood risk in the Rajang Delta, Sarawak that has implications for government and the private sector operating in both this landscape as well as other tropical peatland regions. It will be important to find long-term solutions to this issue, which is for each region to define for themselves. The following recommendations are suggested for consideration as to how to respond to the challenges of peat subsidence and flood risk in tropical peatlands.

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[14] See for example http://www.theborneopost.com/2015/01/13/palm-oil-production-drops-most-in-eight-years/

[15] http://www.recoda.com.my/priority-sectors/palm-oil/

5.4.1 Pumping drainage unlikely to be a solution

There have been suggestions that if the peat surface subsides below flood levels and gravity drainage will no longer be possible, there may be an option of moving towards pumped drainage. There is, however, no evidence that this is possible at the large scale and to our knowledge there have been no attempts (beyond a few small scale inconclusive trials) to apply pumping infrastructure in any plantations on peat in SE Asia, even in plantations that are already unproductive and even abandoned because of flooding. This is not surprising considering the major cost of pumping, exacerbated by the very high rainfall intensities in the region that will necessitate a pumping capacity that by far exceeds that in temperate climates on a unit area basis. In most of the world, pumping and dike building at such a large scale is only feasible for urbanized areas where high levels of investment and economic benefits justify the high cost. It should also be considered that building dikes on deep peat has never been successfully attempted at the large scale and may not be possible; dikes made of peat (sourced locally) are too light to resist much pressure and will oxidize (i.e. disappear into the atmosphere), whereas dikes made of mineral material (which needs to be sourced elsewhere, bringing up cost) will sink into the peat. Either way, dikes on peat need constant maintenance and supply of new material, and have an inherent high risk of failure.

It is recommended that a sound engineering study and cost-benefit analysis is conducted into the feasibility of large scale mechanical pumping drainage of plantations in drained tropical peatland to evaluate options for businesses and governments.

5.4.2 All lowland tropical peatlands require subsidence and flood analysis to be urgently undertaken as part of land use and economic planning

While carbon emissions in relation to peatland drainage has received much attention, the flooding consequences of peatland drainage need to receive much more attention as they affect direct economic interests and the lives and livelihood prospects of people living in peatland regions. Given the prevalance of oil palm and drainage-based peatland land uses in SE Asia, it is clear that a major research and development initiative is required to assess potential crops and economic opportunities that can drive a sustainable rural economy in these regions that does not depend on peatland drainage but can be applied in rewetted peatlands. Elevation models appear to have been one of the key data that have been lacking in spatial planning for peatlands throughout SE Asia. Our recommendation, therefore, is to develop such models for all coastal lowland peatlands in SE Asia as a matter of urgency and use them as part of land use planning as described below.

The current study used published data on peat characteristics (thickness, position of the peat bottom), as it was not possible to conduct field investigations. Surveys of peat characteristics, flood occurrence and oil palm condition in the area are recommended.

5.4.3 Peatland land use needs sustainable land use solutions and the end of drainage for long-term economic and environmental sustainability

This report has identified that most drainage-based plantations in the study area are likely to be viable only for a time period measured in decades, not centuries, and with mitigation becoming less feasible as the problem worsens. Recent expansion of oil palm plantations on peat in the study area therefore appear to have been based on a short term vision of economic viability, without accounting for future sustainability in relation to subsidence and flooding issues, and without quantification of future conditions. What is needed to assess truly sustainable solutions for the area, therefore, is a comprehensive long term perspective considering all costs and benefits of all development and conservation options, and application of improved data and sound scientific insights.

For realistic and rational land use decision-making for the Rajang Delta and other peatlands in the region, we propose a distinction of four categories of peatlands (Table 7). In this classification, we distinguish between forested and deforested peatlands on the one hand, and areas with substantial and negligible future flood risk on the other. Future flood risk is determined through assessments as presented in this study.

Table 7 Classification of peatland based on (A) natural forest cover as an indicator of disturbance and (B) potential future flooding problems as an inidicator of long-term sustainability. Four classes of peatland are identified as shown. See text for details.

Criteria for Peatland Land Use Potential	**Significant future flooding problems**	**Limited future flooding problems**
Forested (Natural, semi-natural, degraded)	**(1)** Forested peatlands where drainage would inevitably lead to flooding problems but that are still in a condition that allows conservation and rehabilitation. Both economic and environmental considerations determine that such areas are a priority for conservation and, where necessary, rehabilitation.	**(2)** Forested peatlands where drainage is unlikely to lead to future flooding. In such areas, there is a well-informed policy choice to be made between agricultural development (including carbon emissions, loss of environmental functions and biodiversity) and conservation. Conservation is the most appropriate choice in regions that have already experienced substantial loss of peat swamp forest and/or where remaining forest has High Conservatiuon Value.
Deforested (cleared, burned, plantation)	**(3)** Peatland that is deforested and has become either plantation or fully degraded wasteland, but where continued drainage will lead to flooding sooner or later. Whether to continue production, or conversion to productive use, on such land is a political and economic choice, that should however be based on sound science and data and should take into account long term impacts and alternative land-use options. The sustainable option for these areas is to invest in zero drainage production systems or, where conservation values in the surrounding landscape are high, to rehabilitate back to natural forest.	**(4)** Peatland used for productive agriculture that will not be lost to flooding because the mineral substrate that will be left after all peat has oxidized is above the drainage limit. This is the least problematic category, with economic rationale probably determining that such lands should probably remain in productive use despite carbon emissions and environmental concerns, as investments in a more sustainable future for peatlands are better directed elsewhere. Exceptions may exist where the mineral sub-soil consists of problematic soils, such as e.g. white sand areas or acid sulphate soils

According to our assessment, most peatland in the Rajang Delta study area is in Category 3, i.e. already deforested and certain to flood in future if drainage continues. For such lands, companies and policy makers would be expected to develop contingency plans specifying for how many decades these plantations are expected to remain productive under different scenarios. This includes a Business As Usual (BAU) scenario i.e. continuation of plantations regardless of these issues, possibly with improved best practice water management, which will, however, have limited impact and are unlikely to reduce subsidence rates (and carbon emissions) by much more than 20 percent (Hooijer *et al.*, 2012).

5.4.4 The long-term future of the oil palm and plantation sector on peatland in SE Asia depends on a managed transition from peatland to suitable mineral soils

Peat subsidence and the loss of drainability also presents significant challenges to long-term oil palm production from tropical peatlands both in the study area and more broadly in the region. To secure the long-term future of oil palm production, a transition in planting that moves the plantation area from peat to mineral soils is required. Such a transition could be planned and managed at the end of the current or subsequent planting cycle depending on plantation age and overall condition of the peatland. The planning of such a transition should identify potential mineral soils that are already deforested and lack conservation value. In the end, it will be far better for government and industry to plan and manage this transition than have it imposed through the inevitability of the impacts of peat subsidence.

5.5 Conclusions

There remains, therefore, a fundamental choice that will need to be taken at some point by businesses and farmers, supported by government policy makers and politicians, between abandoning plantations or moving towards a more sustainable type of plantation using flood tolerant species with very limited drainage. In practice, this generally means utilising local swamp species with valued timber and/or non-timber products that can be grown without drainage (see Giesen, 2013). However, this choice is best made before the land is prone to such severe flooding, which may preclude the planting and re-establishment of indigenous, productive and valued swamp tree species in the area. This will also mean that the oil palm sector, and other plantation industries dependent on drained peatland for production, will at some point in time need to relocate to suitable mineral soils. Such a transition is best undertaken sooner rather than later and managed over the medium-term.

Another reason to move towards rehabilitation quickly is that the presence of remnants of natural forest will greatly speed up the return of a ‘return to nature’ that may be the eventual outcome in large areas once drainage is no longer possible (as proposed by DID Sarawak, 2001) and yield a better result than when all such remnants are gone and there is no natural stock to be reestablished. In summary, governments and the private sector in tropical peatland regions need to consider how best to manage the transformation of drainage-based peatland land use to a sustainable zero drainage approach sooner rather than later.

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Annex A - Detailed steps in DTM generation

The different steps in DTM generation, as explained in Chapter 3 and shown in detail for a smaller area in Figure 15 are shown in full for the whole study area in Figure 29.

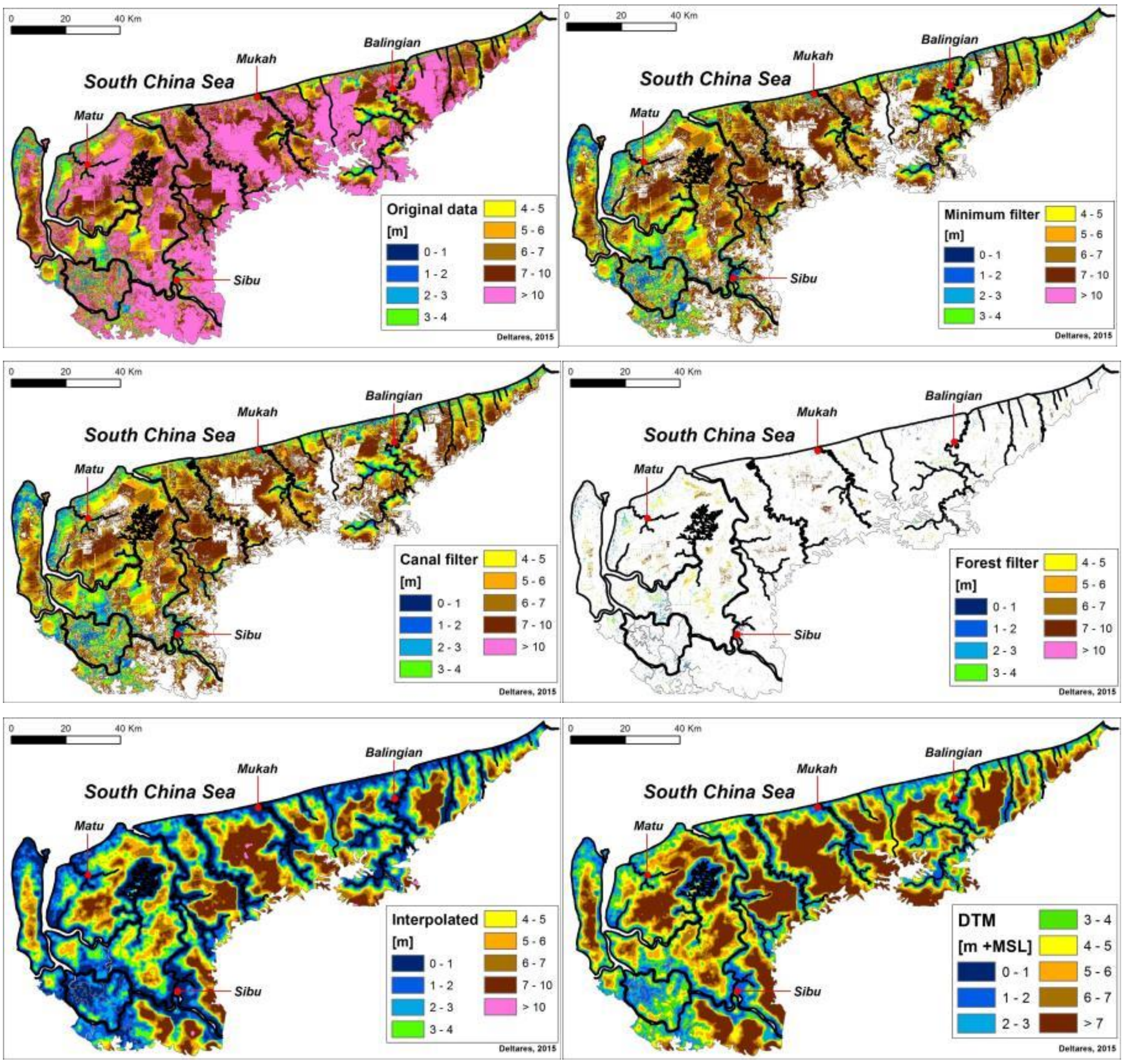


Figure 29 Individual filtering steps to remove the vegetation effects, canal levels and errors from the IFSAR data. **Top left:** original data. **Top right:** after minimum filter and removing values above forest threshold (10 m). **Middle left:** after applying the ‘canal filter’. **Middle right:** after applying the ‘slope filter’, which removes most remaining data points. **Bottom left:** after spline interpolation of values between remaining cells. **Bottom right:** final DTM, after correction with +1.6 m following the comparison with filtered SRTM-30.

Annex B - Full flood projection maps and tables

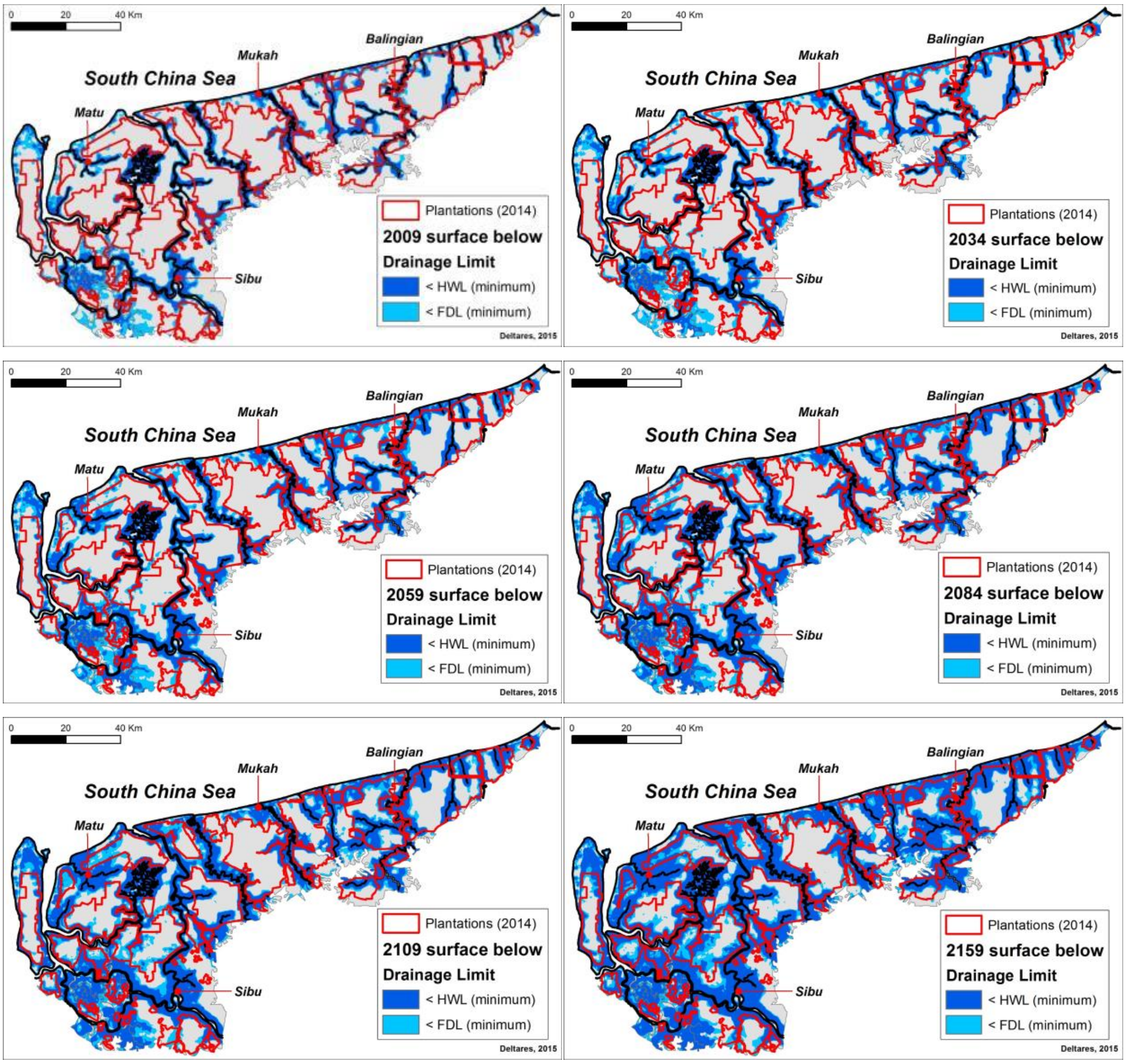


Figure 30 Flood extent projection for 0, 25, 50, 75, 100 and 150 years applying a subsidence rate of 2 cm yr^{-1} and minimum flooding thresholds ('Minimum Impact' scenario) after 2009 (the date for which the DTM was created using IFSAR data).

Table 8 Areas that are frequently flooded (below HWL) or have impeded drainability (below FDL), in ha and as % of total area, for the total study area, the total peatland area within the study area and for existing (June 2014) oil palm plantation area, in the 'Minimum Impact' scenario, assuming all land would be drained as if it were oil palm plantation and that this causes a subsidence rate of 2 cm yr^{-1}. Note that all peat in the area is assumed to subside (88.1 % of the area), but not mineral soils (11.9 % of the area). Note that FDL_minimum presents the area that is ONLY below the FDL level but not below the HWL level.

Impact scenario	'minimum' scenario					
Drainage limit Subsidence rate	HWL (min.) 2 cm/yr		FDL (min.) 2 cm/yr		HWL + FDL (min.) 2 cm/yr	
year	ha	%	ha	%	ha	%
Total area						
2009	196187	23.1	110982	13.1	307169	36.2
2034 (after 25 yrs)	244937	28.9	119643	14.1	364580	43.0
2059 (after 50 yrs)	295767	34.9	125990	14.9	421757	49.8
2084 (after 75 yrs)	348763	41.1	129943	15.3	478706	56.5
2109 (after 100 yrs)	400238	47.2	131885	15.6	532123	62.8
2159 (after 150 yrs)	499285	58.9	123820	14.6	623105	73.5
Peat area						
2009	139825	18.7	90533	12.1	230358	30.8
2034 (after 25 yrs)	188575	25.3	99194	13.3	287769	38.5
2059 (after 50 yrs)	239405	32.1	105541	14.1	344946	46.2
2084 (after 75 yrs)	292401	39.2	109494	14.7	401895	53.8
2109 (after 100 yrs)	343876	46.0	111436	14.9	455312	61.0
2159 (after 150 yrs)	442923	59.3	103371	13.8	546294	73.2
Plantation on peat area						
2009	40340	10.2	32224	8.2	72564	18.4
2034 (after 25 yrs)	56981	14.5	38888	9.9	95869	24.3
2059 (after 50 yrs)	76323	19.4	45875	11.7	122198	31.0
2084 (after 75 yrs)	98006	24.9	55029	14.0	153035	38.9
2109 (after 100 yrs)	121947	31.0	62820	16.0	184767	46.9
2159 (after 150 yrs)	178037	45.2	66643	16.9	244680	62.1

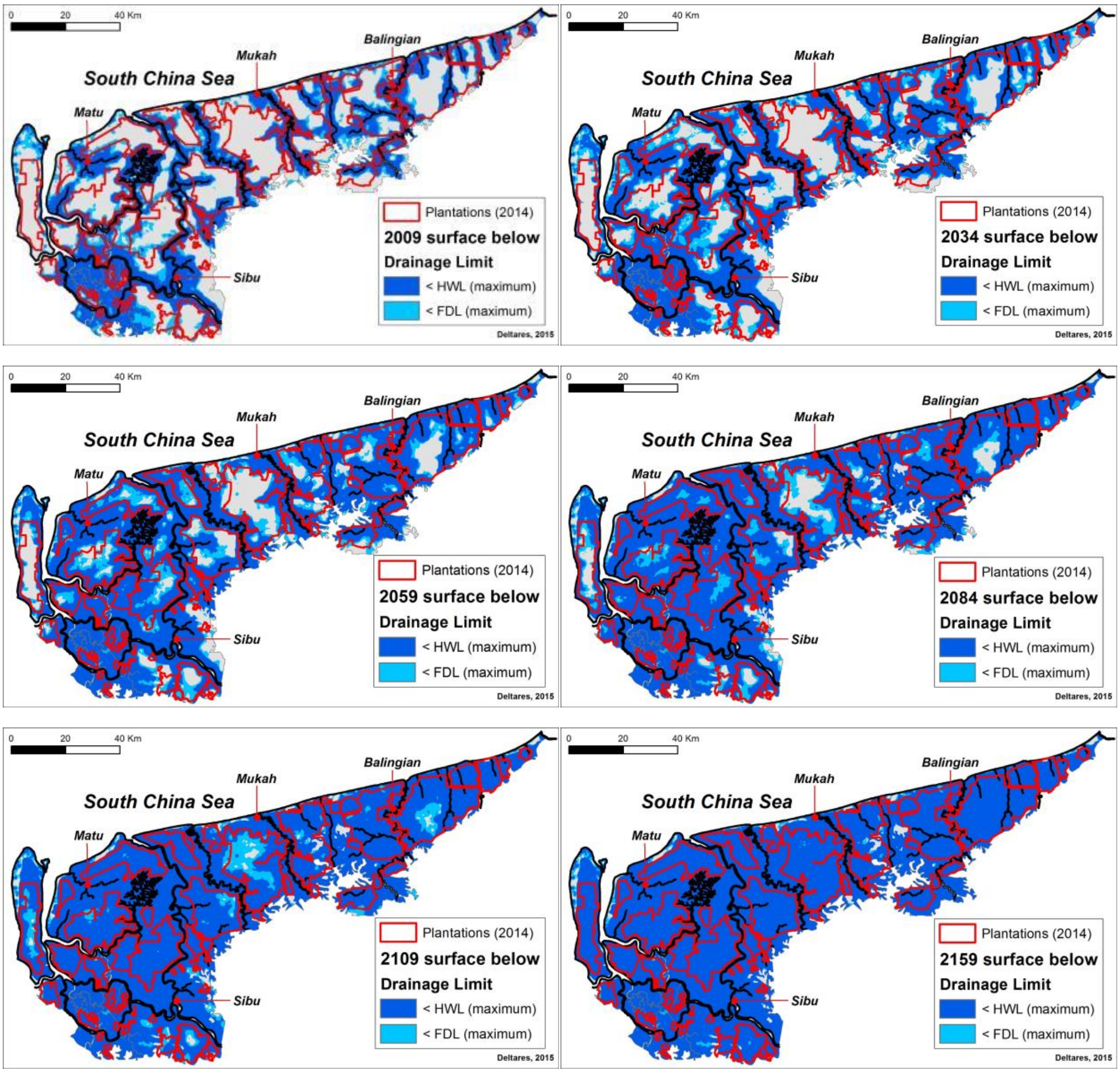


Figure 31 Flood extent projection for 0, 25, 50, 75, 100 and 150 years applying a subsidence rate of 5 cm yr^{-1} and maximum flooding thresholds (‘Maximum Impact’ scenario) after 2009 (the date for which the DTM was created using IFSAR data).

Table 9 Areas that are frequently flooded (below HWL) or have impeded drainability (below FDL), in ha and as % of total area, for the total study area, the total peatland area within the study area and for existing (June 2014) oil palm plantation area, in the 'Maximum Impact' scenario, assuming all land would be drained as if it were oil palm plantation and that this causes a subsidence rate of 5 cm yr^{-1}. Note that all peat in the area is assumed to subside (88.1 % of the area), but not mineral soils (11.9 % of the area). Note that FDL_maximum presents the area that is ONLY below the FDL level but not below the HWL level.

Impact scenario	'maximum' scenario					
Drainage limit	HWL (max.)		FDL (max.)		HWL + FDL (max.)	
Subsidence rate	5 cm/yr		5 cm/yr		5 cm/yr	
year	ha	%	ha	%	ha	%
Total area						
2009	383466	45.2	119786	14.1	503252	59.4
2034 (after 25 yrs)	506826	59.8	122291	14.4	629117	74.2
2059 (after 50 yrs)	619040	73.0	111235	13.1	730275	86.2
2084 (after 75 yrs)	709648	83.7	82179	9.7	791827	93.4
2109 (after 100 yrs)	770694	90.9	56227	6.6	826921	97.6
2159 (after 150 yrs)	820711	96.8	12225	1.4	832936	98.3
Peat area						
2009	309184	41.4	107861	14.4	417045	55.8
2034 (after 25 yrs)	432544	57.9	110366	14.8	542910	72.7
2059 (after 50 yrs)	544758	72.9	99310	13.3	644068	86.2
2084 (after 75 yrs)	635366	85.1	70254	9.4	705620	94.5
2109 (after 100 yrs)	696412	93.3	44302	5.9	740714	99.2
2159 (after 150 yrs)	746429	99.9	300	0.0	746729	100.0
Plantation on peat area						
2009	108784	27.6	55113	14.0	163897	41.6
2034 (after 25 yrs)	171957	43.7	69920	17.8	241877	61.4
2059 (after 50 yrs)	242700	61.6	71102	18.1	313802	79.7
2084 (after 75 yrs)	307116	78.0	53441	13.6	360557	91.6
2109 (after 100 yrs)	353971	89.9	34873	8.9	388844	98.8
2159 (after 150 yrs)	393494	99.9	214	0.1	393708	100.0

Annex C – Survey profiles of peat surface and bottom elevation in Sarawak

Peatlands in Sarawak have historically been studied quite well compared to peatlands elsewhere in SE Asia, by international scientists with an interest in peatland ecology, development and characteristics, who have seen these as representative for peatlands through SE Asia. As a result, a large number of profiles of peat thickness and surface elevation for peat domes in Sarawak have been published in international literature, probably more than for the rest of SE Asia combined.

Published profiles were used in the current study to validate two characteristics of peat domes, namely the position of the peat bottom and of the peat surface relative to River and Sea level, both of which are key in this assessment. For this purpose, available profiles have been separated into two groups: those inside the Rajang Delta and those outside: mostly along the Baram river to the East and near Kuching to the West.

A total of 6 profiles were identified for the Rajang Delta part of the study area, and used to validate the IFSAR based DTM created in this study: in Anderson (1964; 4 profiles), Staub and Gastaldo (2003; 1 profile) and Hooijer (2005; 1 profile) (Figure 18; Figure 19).

A further total of 16 profiles were identified for other peatlands in Sarawak: in Anderson (1964; 4 profiles), Esterle *et al.* (1991; 2 profiles), Tie and Esterle (1991; 5 profiles), Melling and Hatano (2005; 1 profile) and Sayok *et al.* (2008; 1 profile), PS Konsultant (1998; 1 profile), Staub and Gastaldo (2003; 1 profile). The latter two are in fact inside the study area, but are in the coastal plain part not in the Rajang Delta.

The individual profiles for the Rajang Delta are described on the following pages, while other profiles are presented without description. In Figure 32 below, we present a summary graph of profiles in the Rajang Delta. To analyse profiles, they were cut up in segments starting at the river, up to the watershed divide i.e. the highest part of the peat dome. Thus, the 6 profiles for the Rajang Delta yielded 9 segment profiles for analysis.

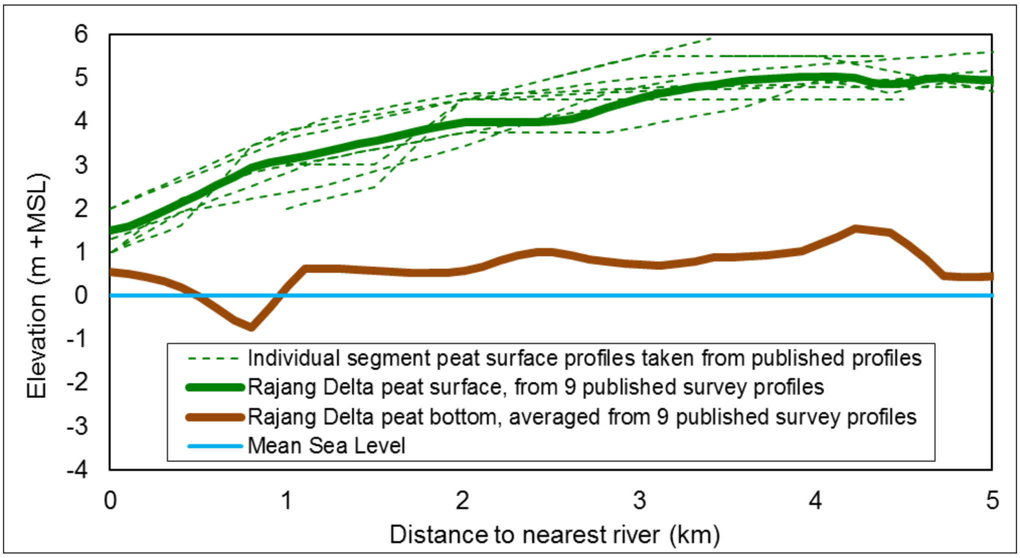


Figure 32 Summary graph of individual and average peat surface elevation profiles for the Rajang Delta part of the study area. The average peat bottom elevation is also shown.

Profiles for the Rajang Delta

Profiles from Anderson (1964)

Measurements in the early 1960s, predating any forest clearing or drainage, include 4 transects in the Rajang Delta (the top 4 in the Figure below) presenting peat thickness and elevation. Elevation measurements are relative to River Level, which is less than a metre above mean Sea Level in this area in the dry season but can be much higher in the wet season (however surveys will probably have been in the dry season as the swamps are even more inaccessible when flooded).

Note that the transects are measured in Feet and Chain; 1 Feet = 0.3048 m; 1 Chain = 20.12 m. Along four transects in the Rajang Delta the surface is at most 5 metres (16 feet) above MSL. The peat bottom is always below River Level along these transects, and more that 1 metre below River Level, i.e. below MSL, along over 90 % of the transects. Peat surface slopes rarely exceed 1 m km^{-1} except for narrow zones near rivers where they can be up to 2 m km^{-1}.

Note that field elevation measurements are almost certainly less accurate than peat thickness measurements, as elevations are notoriously hard to measure in this terrain.

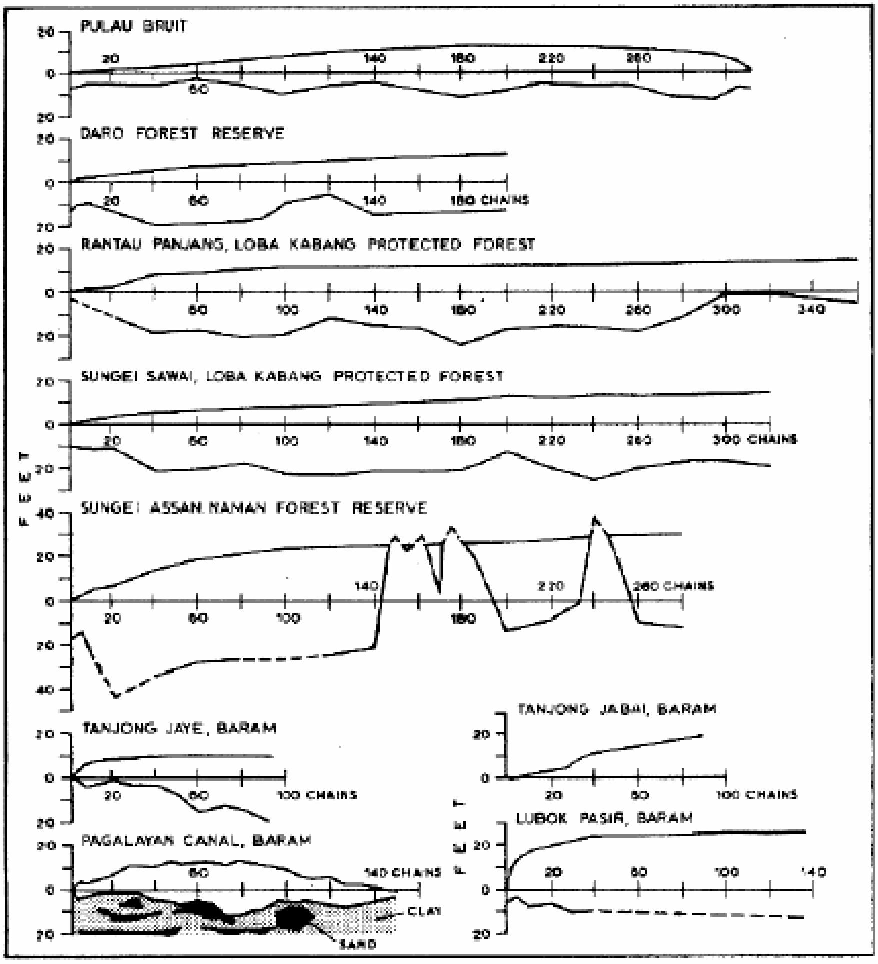


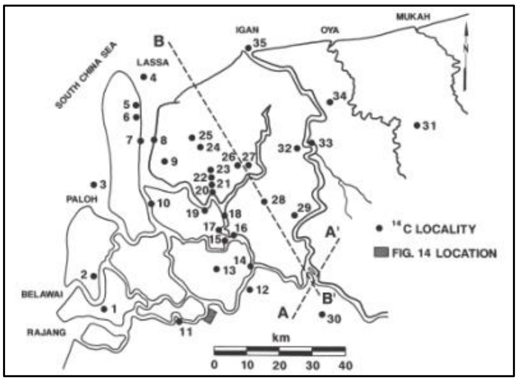
Fig. 2. Peat profiles in the Rajang delta and Baram river.

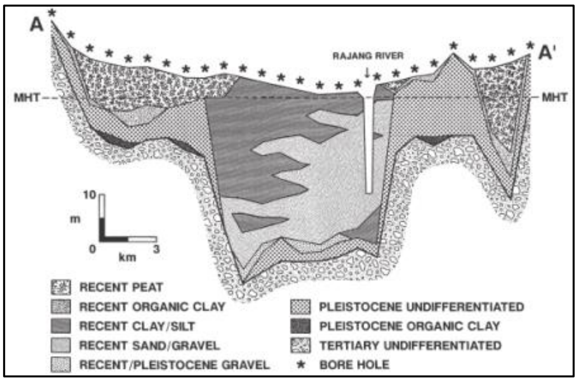
From Anderson J.A.R. (1964) The structure and development of the peat swamps of Sarawak and Brunei. The Journal of Tropical Geography, 18, 7-16.

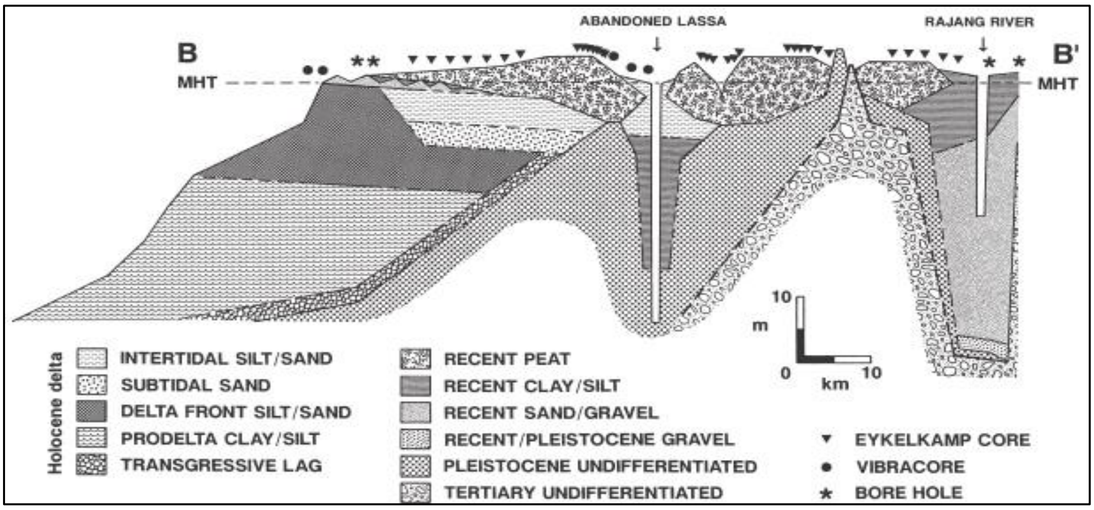
Profiles from Staub and Gastaldo (2003)

"The Rajang River Delta plain covers 6,500 km^2, and peat greater than 3 m thick covers about 50 % of the delta- plain surface. The measurements presented here are from the 1990s and mostly predate large-scale forest clearing and peatland drainage. The surfaces of most peat deposits are domed or raised; the surfaces of these deposits are up to 4–6 m higher than spring high-tide levels, with elevation differences increasing inland from the coast. To the east of the deltaic Igan river the adjacent coastal plain is 4,500 km^2 in area; 80 % of which is peat greater than 3 m thick with surfaces are to 7 m higher than the adjacent river channels during flood events. Peat throughout the area is up to 15 m deep."

Peat surface slopes are mostly below 2 m km^{-1} except over short distances near rivers. Peat thickness along transects through the delta (A-A' and B-B') exceeds 5 metres along 90 % of their length, and peat surface elevation is up to 5 metres above Mean High Tide, with the peat bottom being nearly always more than 2 metres below MHT. Assuming that MHT is around 1.5 or 2 metres above Mean Sea level in this area (tidal range is around 4 m; Staub and Gastaldo, 2003), this implies that the peat bottom is nearly always around or below MSL. Note that while transect A-A' is an actual transect that follows measurements along a line, B-B' is a synthetic transect that includes measurements further away from the line. Also, it is not clear whether all elevations were actually measured in the field.





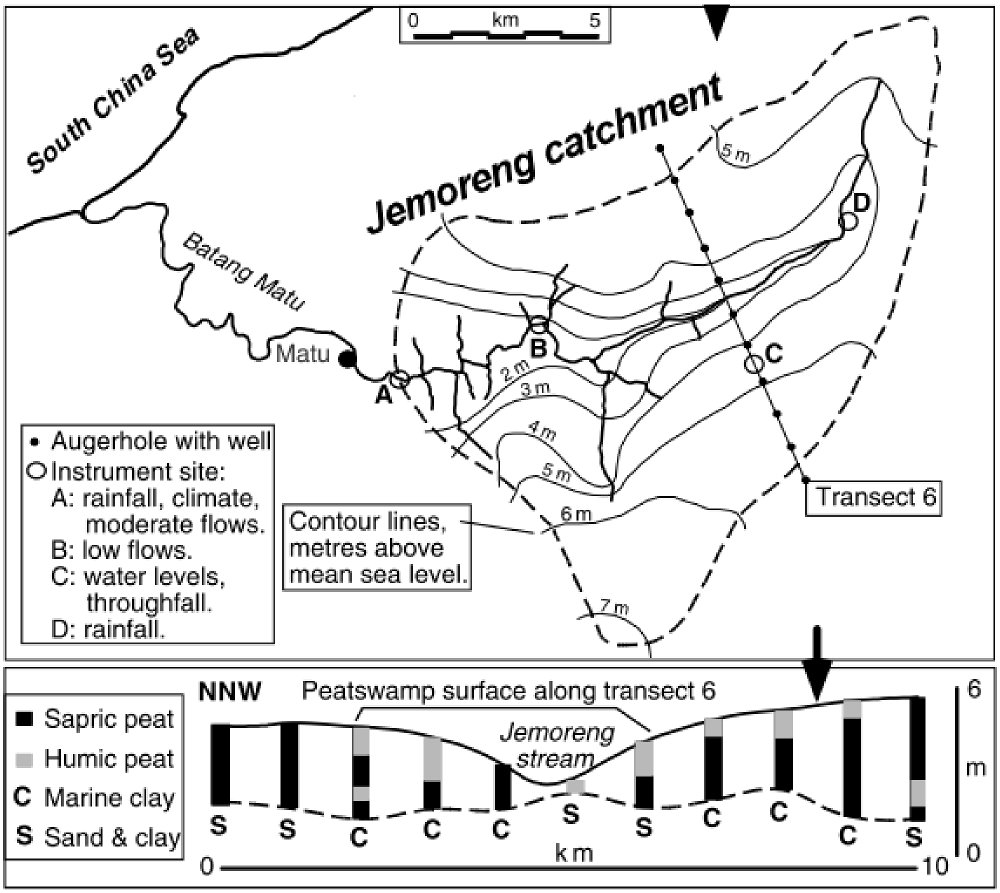


From Staub, J.R, and Gastaldo, R.A. (2003) Late Quaternary sedimentation and peat development in the Rajang River Delta, Sarawak, East Malaysia. In: tropical deltas of southeast asia, sedimentology, stratigraphy, and petroleum geology. Edited by: Sidi, F.H., et al. SEPM (Society for Sedimentary Geology) Special Publication Number 76, 71-87.

Profile from Hooijer (2005)

A profile published in Hooijer (2005) is representative for a large number of unpublished profiles in the area as collected in the Sarawak Water Resources Study Project for Sarawak Government (WRSP, 1997), from which a partial terrain model was produced as shown in the Figure below. This shows that peat surface elevations vary from 1 to 7 m +MSL in this area, with surface slopes rarely exceeding 1 m km^{-1}. The elevation of the peat bottom was found to be between 1 and 2 m +MSL.

It should be noted however that even in the large-scale professional WRSP study, referencing elevation data to Mean Sea Level was found to be very challenging and the referencing is therefore not considered very accurate – actual elevation could be up to a metre higher or more likely lower. On this basis, we assume that other studies that used older technology with fewer resources, must have similar or probably greater referencing inaccuracies.



From Hooijer A. (2005) Hydrology of tropical wetland forests: recent research results from Sarawak peat swamps, in: Forests-Water-People in the Humid Tropics, edited by: Bonell, M. and Bruijnzeel, L. A., Cambridge University Press, 447–461.

Profiles for peat domes in the rest of Sarawak, outside the Rajang Delta

NB this category also includes the A-A' profile in Staub and Gastaldo (2003), and 4 profiles in Anderson (1964), that are shown amidst Rajang Delta profiles.

Profile PS Konsultant (1998)

Another profile derived from the Sarawak Water Resources Study Projects (1997) was published by PS Konsultant (1998). This profile crosses the coastal plain to the East of the Rajang Delta, from the coastline to the Balingian river.

Peat surface elevation in this area did not exceed 4.5 m + MSL at the time of the survey, while the peat bottom is mostly between 0 and 1 m +MSL. Slopes are mostly below 2 m km^{-1}.

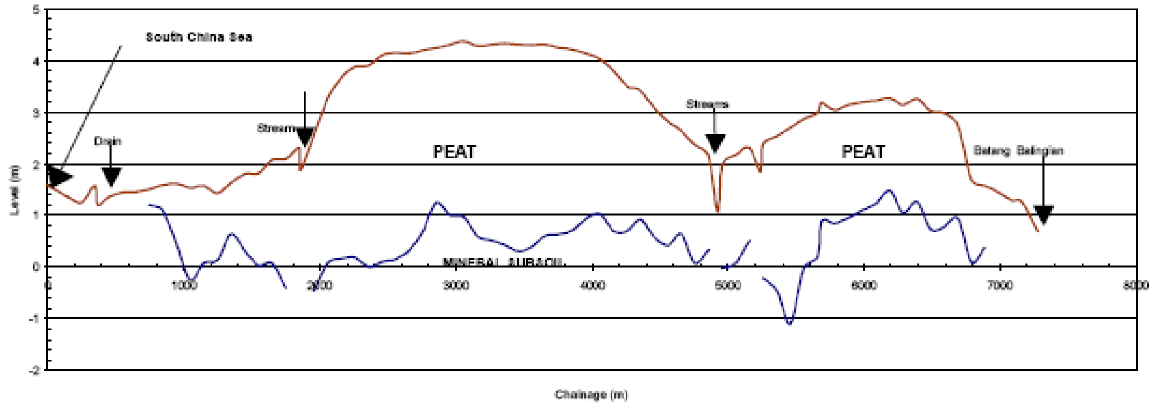


Figure 4. Cross-section through a peat dome (PS Konsultant 1998)

PS Konsultant (1998) Detailed Design and Construction Supervision of Flood Protection and Drainage Facilities for Balingian RGC Agricultural Development Project, Sibu Division, Sarawak (Inception Report), Department of Irrigation and Drainage, Kuching. pp.24.

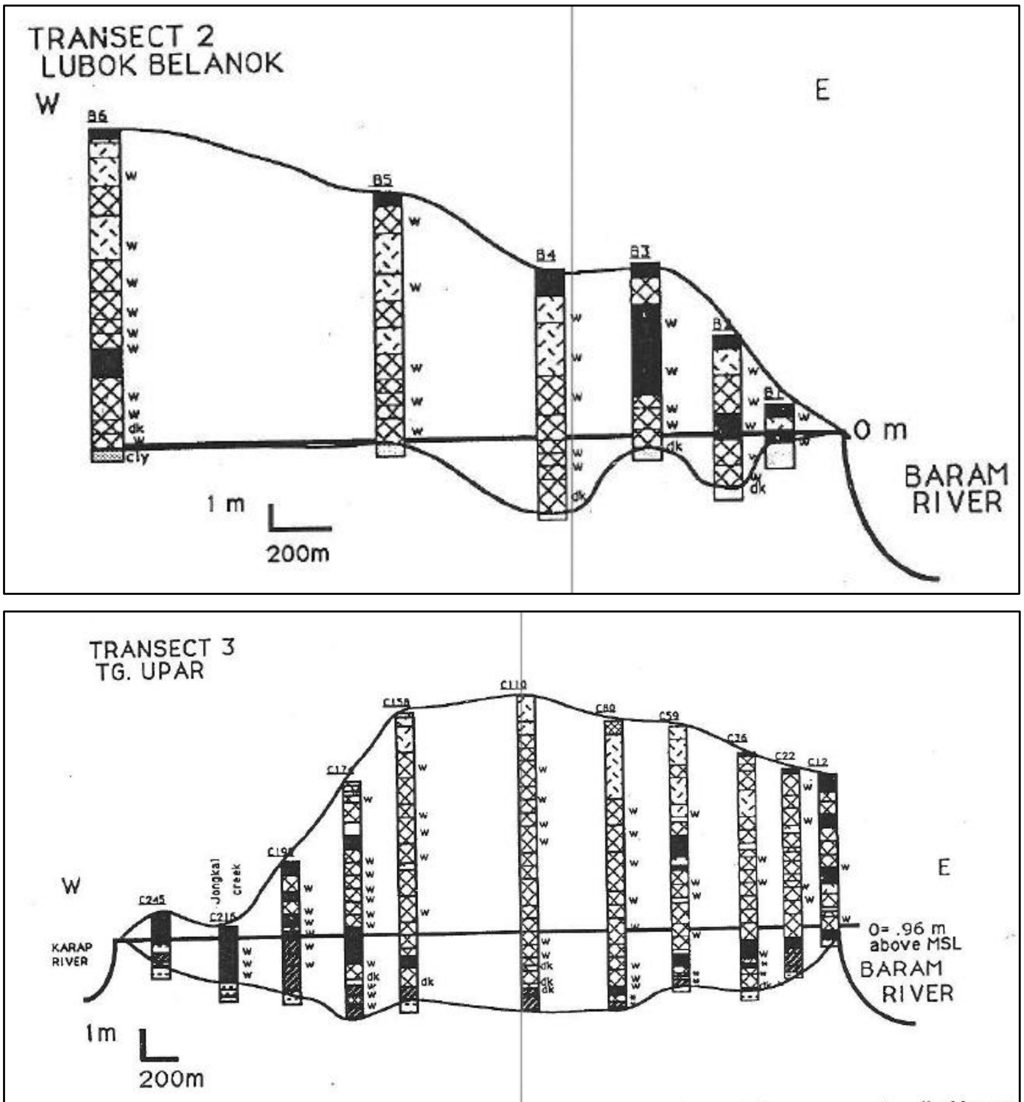
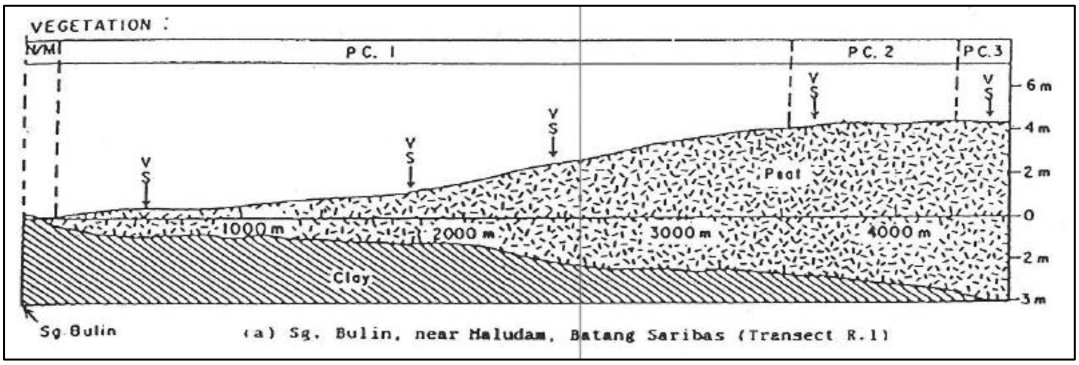
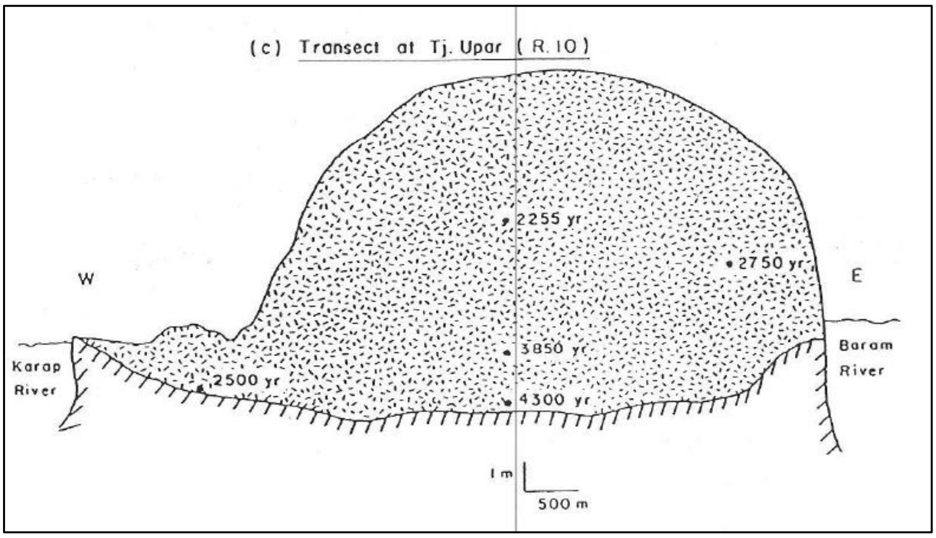


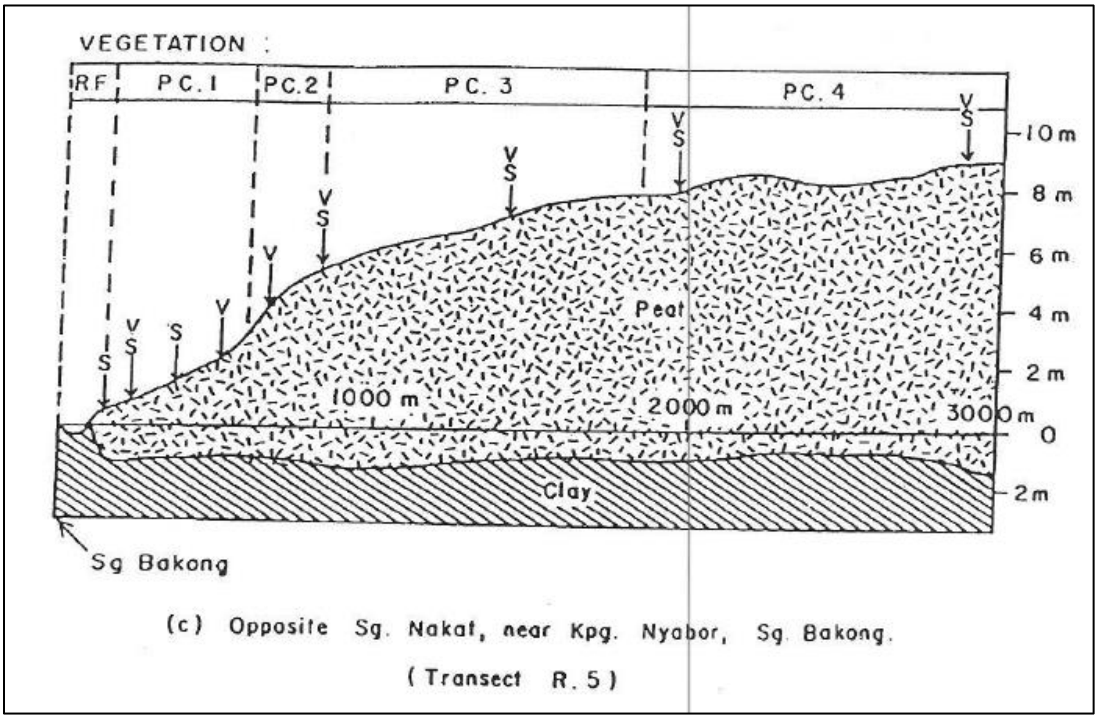
Figure 4. Cross sections of peat transect I, II and III in the Baram River area Sarawak. Peat types are described in text. Note that all three are not to scale

From Esterle J.S., Calvert G., Durig D., Tie Y.L. & Supardi. (1991) Characterization and classification of tropical woody peats from Baram River, Sarawak and Jambi, Sumatra. Proceedings of the International Symposium on tropical peat, 6-10 May 1991, Kuching, Sarawak, 33-48.



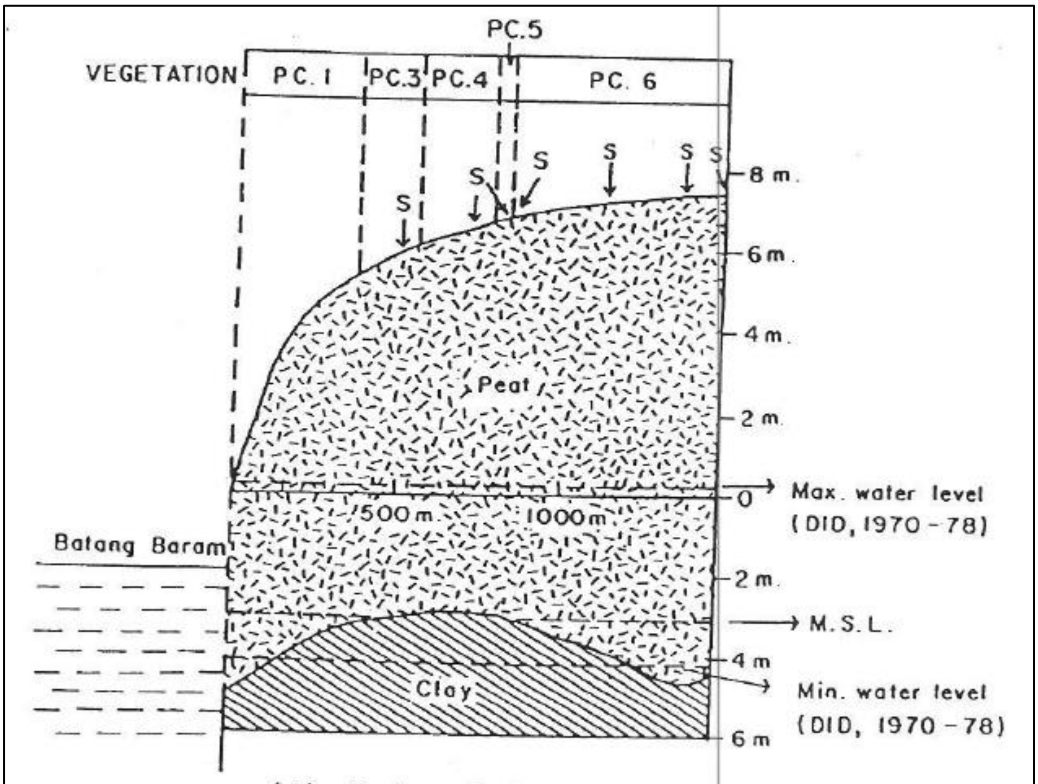
(a) Sg. Bulin, near Maludam, Batang Saribas (Transect R.1)


(c) Transect at Tj. Upar (R.10)

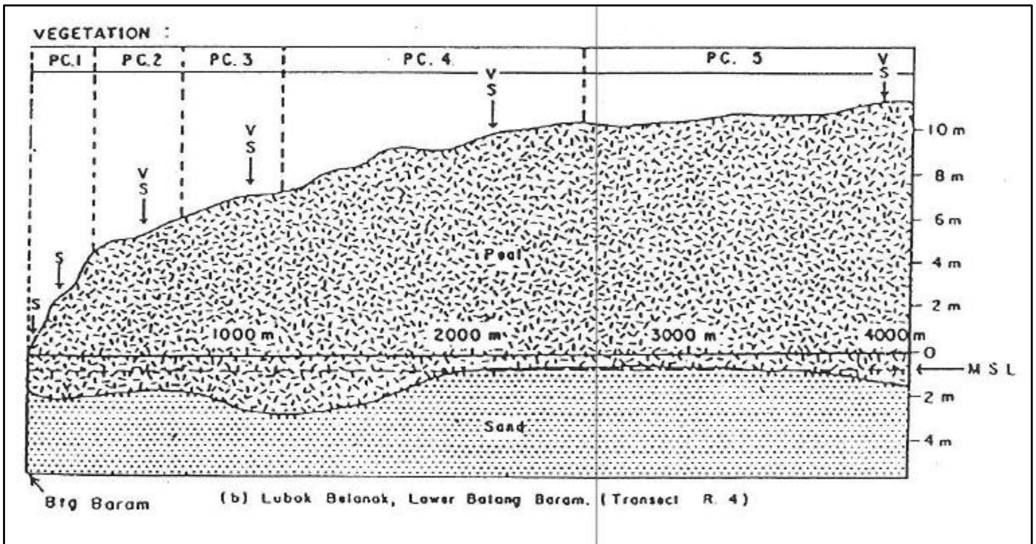


(c) Opposite Sg. Nakat, near Kpg. Nyabor, Sg. Bakong.

(Transect R. 5)



(d) Tanjung Pasir, Marudi.
(Transect R. 7)



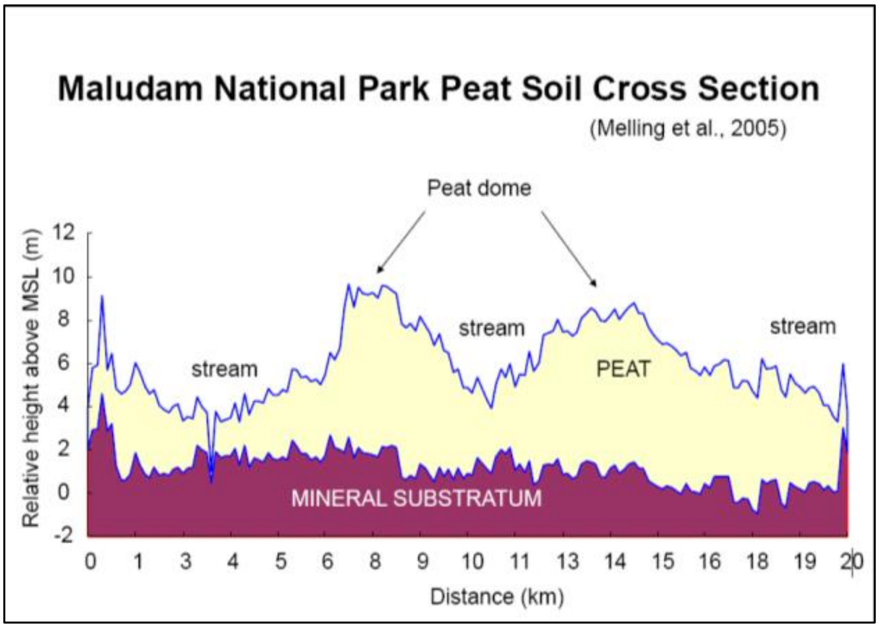
(b) Lubok Belonok, Lower Batang Baram. (Transect R. 4)

NOTES / SYMBOLS : (1) Vertical axis – Elevation in metres above the starting point (arbitrary).

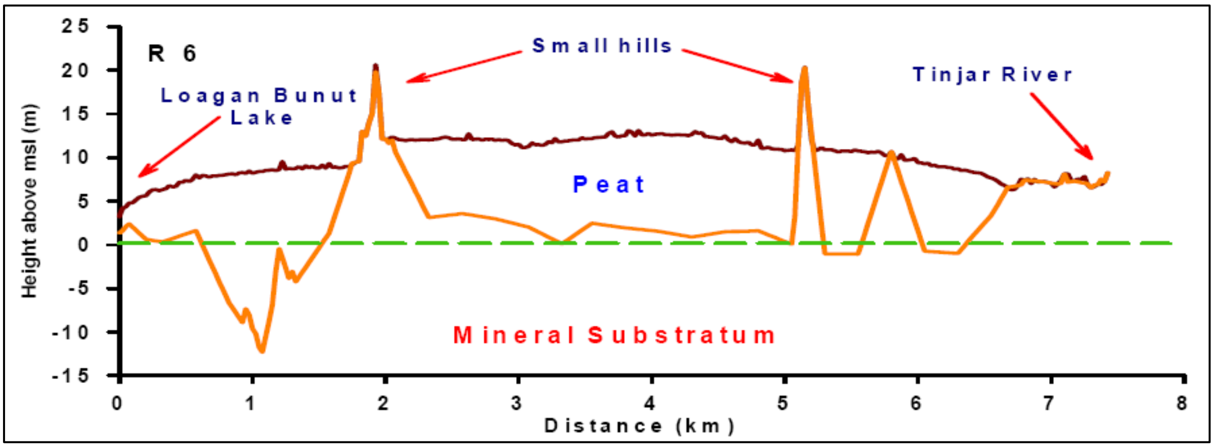
(2) Horizontal axis – Distance in metres from the starting point.

(3) N/M = Nipah / Mangrove ; RF = Riverine Forest ; P.C. = Phasic community of Peat Swamp Forest. (1 = Mixed Swamp Forest ; 2 = Alan Forest ; 3 = Alan Bunga ; 4 = Padang Alan ; 5 = Tristania / Parastemon / Palaquium Association; 6 = Padang Paya or Padang Keruntum).

From (this and previous page) Tie, Y.L. and Esterle, J.S. (1991) Formation of lowland peat domes in Sarawak, Malaysia. In: Proceedings of the International Symposium on tropical peat, 6-10 May 1991, Kuching, Sarawak 81-89.



From Melling, L. and Hatano, R. (2005) Peat soils study of the peat swamp in the Maludam National Park, Betong Division, Sarawak. Alterra Green World Research, The Netherlands, Forest Department Sarawak, Malaysia, Sarawak Forestry Corporation, Malaysia. JWG/MNP/2004/01, 37 pp.



From Sayok, A.K. *et al.* (2008) Some characteristics of peat in Loagan Bunut National Park, Sarawak, Malaysia. Carbopeat Conference proceedings, Yogyakarta, 7pp.

Annex D – DTM for cleared oil palm concessions in the Baram Delta

For the second largest peat dome complex in Sarawak, the Baram Delta near the Brunei border IFSAR data were purchased in the same format as for the Rajang Delta (Figure 13). As can be seen from the map, in 2009 much of the area (outside the oil palm plantations) was still densely forested as is also clear from the Landsat composite image of 2009 (Figure 34). It was therefore not possible to create an accurate elevation model for areas outside of the 2009 oil palm plantation extent, and no subsidence and flooding projection was possible as was produced for the Rajang Delta. However, a crude DTM (Figure 35) could be constructed following the same filtering steps as for the Rajang Delta as explained in Chapter 3.

Figure 35 shows that, despite the limitations of the DTM, it is clear that much of the Baram Delta peatland is very low-lying. According to this DTM, 72 % of the area is below 4 m +MSL and 89 % below 6 m +MSL. In terms of elevation distribution, the inland and coastal parts of this peatland are not very different. This suggests that a subsidence and flooding projection for the area, that will be possible once a more accurate DTM has been achieved, would yield similar figures as for the Rajang Delta.

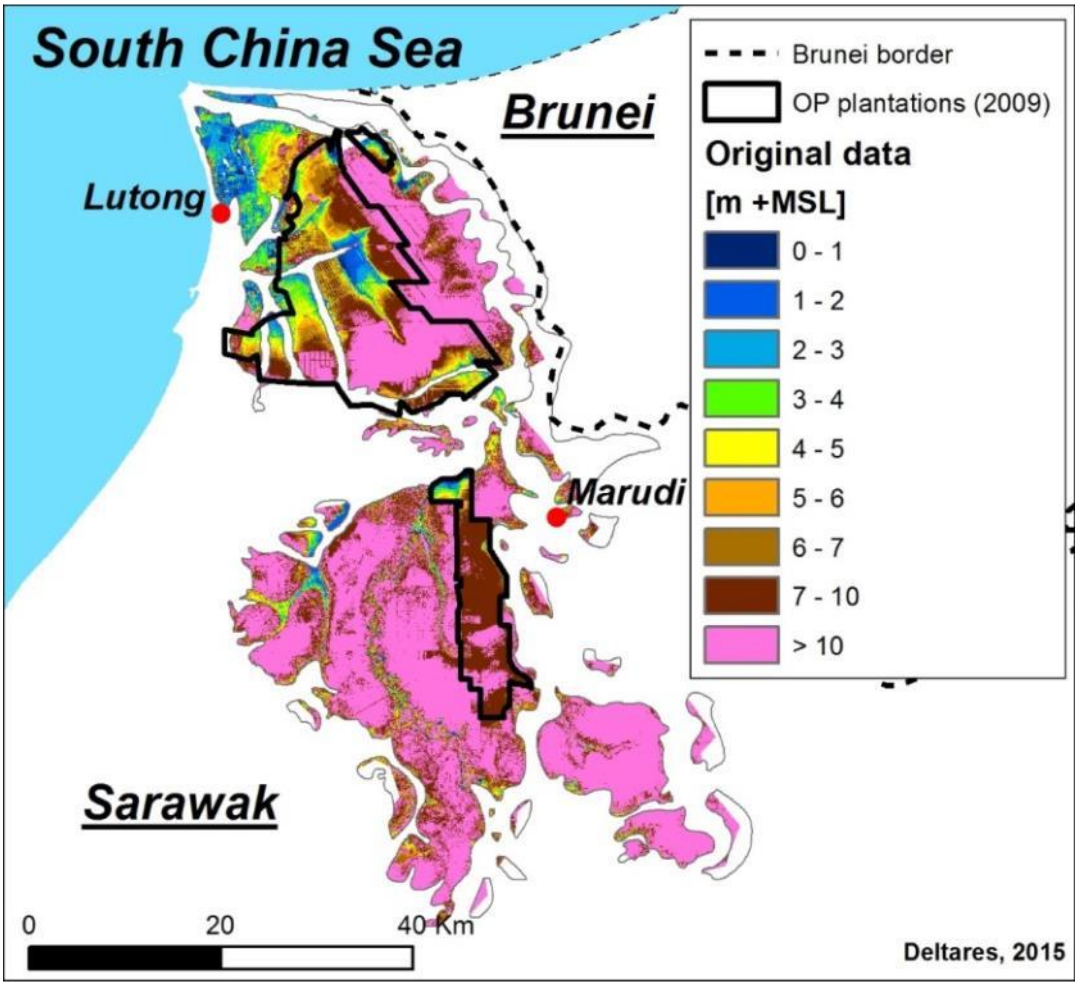


Figure 33 Original (unfiltered) IFSAR data for the peat domes in the Baram Delta. Extent (2009) of oil palm plantations is shown as well. Data >10 m mostly indicate forested land.

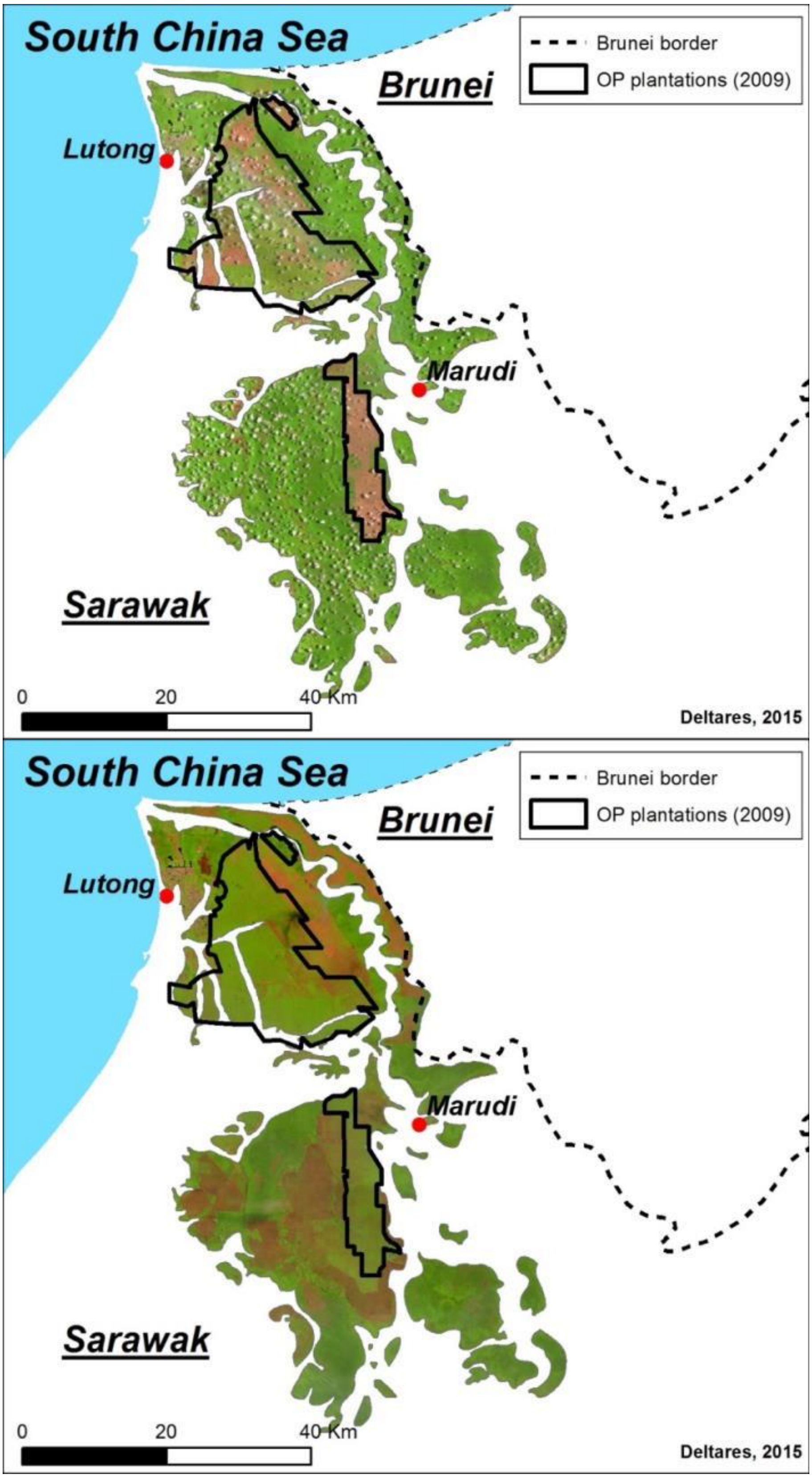


Figure 34 Top: Landsat composite image of 2009 (year IFSAR data were acquired) for the peat domes in the Sarawak (Malaysian) part of the Baram Delta. Extent (2009) of oil palm plantations is shown as well. **Bottom:** Landsat composite image of 2014, showing that remaining forest in 2009 area been mostly cleared by 2014.

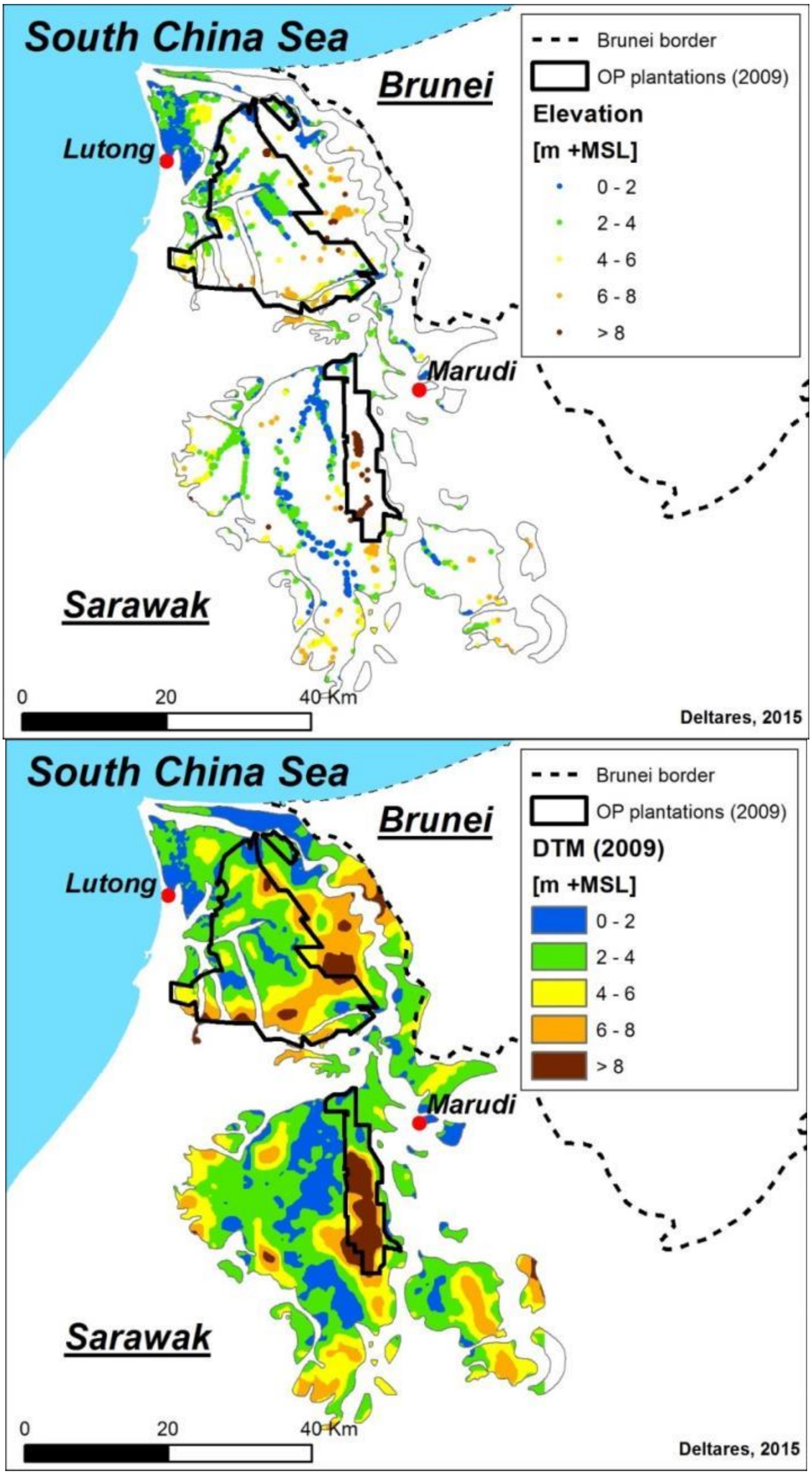


Figure 35 Top: Remaining IFSAR data points after filtering (elevation values include correction +1.6 m for reference level, as explained in Section 3.6) and **Bottom:** interpolated DTM (including correction +1.6 m for reference level).

Annex E – Rapid field flood assessment in oil palm plantations

Parallel to the model studies, a rapid field assessment was conducted in April 2015 of growth and flood conditions in oil palm plantations in the study area, by an UNIMAS research team that was lead by Dr Sayok. The results of that study will be reported separately. Here, summary results pertaining to flooding are presented in Table 10.

Flooding regime was determined from discussions with local plantation staff (for flood levels and duration) and observation of flood marks. Observation locations were selected the basis of accessibility (**Error! Reference source not found.**). This has meant that most locations were relatively close to rivers and low-lying. The average elevation of locations as determined from the IFSAR based DTM is 4.5 m, which is 1.5 m below the average elevation of plantations overall (Table 4).

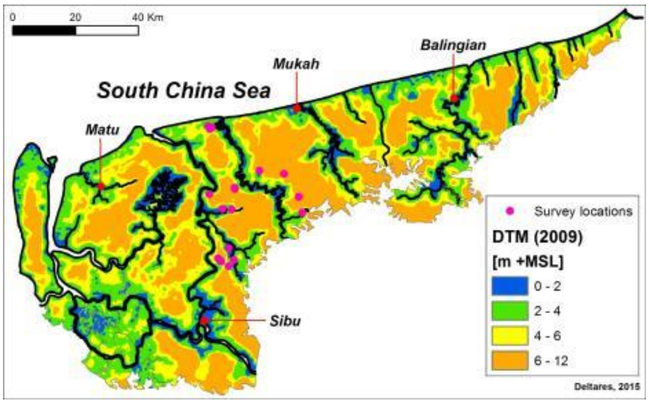


Figure 36 Locations and codes of rapid assessment locations (Table 10) in the study area.

It was found that flooding regularly occurred at all locations that were visited, ranging in depth from 0.3 to 0.6 m on average but with maximum depths ranging from 0.6 to 1.5 m. The frequency of floods could not be accurately established but was estimated at once a year on average. The average flood duration was 3 days, but rare peak floods last 10 days on average over all locations with a maximum of 45 days in one location. Of the 25 locations, flooding by river water was seen as the main or partial cause in 19 cases. Flooding by rainfall alone was seen as the cause in 6 cases.

This finding suggests that of the locations visited, 76 % could already be below High Water Level in reality. This is more than is predicted by the Conservative flooding model, which suggests that only 40 % (10 of the 25 locations) are flooded by river water in 2009. Most remarkable in this respect are locations V, W, X and Y, that are elevated as high as 7.2 to 9.1 m + MSL according to the DTM, and are well above flood levels even in the Maximum scenario, but are already severely flooded in reality. We conclude that the flood risk calculations in this study are indeed conservative, either by underestimating flood levels or (for these locations more likely) by overestimating surface elevations.

Ground water table depths at the locations during the survey varied widely, from 0 – -0.3m at 6 locations (24 %) to -0.7 – -1.3 m at 7 locations (28 %), with an average of -0.5 m. This demonstrates how difficult it is, especially in areas that are at risk of flooding, to maintain water levels in plantations on peatland within a range that both ensures good oil palm productivity and reduces peat loss and subsidence.

Although this was not quantified, indications of falling oil palm productivity and poor palm condition were reported at several locations. All locations had over 1 m of peat thickness remaining, with an average of 3 m. Therefore, subsidence at all locations is still ongoing and flood conditions continue to get worse. This is a rapid assessment, in a selected area, and therefore not representative for the study area as a whole. These results confirm, however, that the risk of flooding in oil palm plantations on peatland in Sarawak is already real.

Table 10 Summary results of a rapid assessment of flooding conditions in oil palm plantations in part of the study area.

Survey location	GPS reading	Age of oil palms (year)	Elevation m +MSL (IFSAR based DTM)	Peat thickness (m)	Water Table (m)	Does the location experience flooding	Cause of flooding (river or local rain)	Average flood depth (m)	Maximum flood depth (m)	Average duration of flood events (day)	Maximum duration (day)
A	2° 26' 53.01" N 111° 53' 50.72" E	17	3.5	3	0.0	Yes	Rain	0.3	0.6	2	7
B	2° 27' 58.09" N 111° 54' 46.10" E	16	1.7	0.9	-0.4	Yes	River	0.3	0.9	1	3
C	2° 27' 57.62" N 111° 54' 46.50" E	16	1.7	1.45	-1.2	Yes	River	0.3	0.9	1	3
D	2° 29' 59.37" N 111° 53' 52.07" E	15	1.6	<1	0.0	Yes	River	0.3	0.9	1	3
E	2° 27' 42.99" N 111° 52' 34.55" E	16	4.8	>2	-0.3	Yes	Rain	0.3	0.6	1	2
F	2° 27' 58.11" N 111° 52' 19.93" E	16	4.4	>3	0.0	Yes	Rain	0.3	0.6	2	2
G	2° 28' 17.05" N 111° 52' 1.934" E	16	4.7	>3	-0.5	Yes	Rain	0.3	0.6	2	2
H	2° 36' 39.61" N 111° 54' 21.89" E	10	3.0	2.83	-0.3	Yes	River	0.6	1	3	45
J	2° 36' 39.59" N 111° 54' 21.18" E	10	3.0	3	-0.7	Yes	River	0.6	1	3	30
K	2° 36' 44.76" N 111° 52' 47.83" E	9	1.7	>3.17	-0.8	Yes	Both	0.6	1	5	30
L	2° 39' 16.98" N 111° 50' 31.12" E	9	4.2	4.28	-1.1	Yes	River	0.6	1	3	10
M	2° 40' 12.06" N 111° 54' 56.05" E	9	5.2	>4.12	-0.5	Yes	River	0.6	1	3	10
N	2° 40' 22.53" N 111° 54' 51.55" E	9	5.4	>4.72	-0.1	Yes	River	0.6	1	3	10
O	2° 50' 48.03" N 111° 50' 55.65" E	17	3.5	>1.6	-0.5	Yes	Both	0.3	1.2	2	7
P	2° 50' 52.69" N 111° 50' 25.75" E	17	4.4	>1.5	-0.7	Yes	River	0.45	0.9	3	7
Q	2° 51' 0.097" N 111° 50' 21.01" E	2	4.3	>2	-0.4	Yes	Both	0.3	1.2	2	7
R	2° 50' 58.83" N 111° 50' 21.17" E	17	4.5	>2.5	-0.4	Yes	Rain	0.3	0.9	2	7
S	2° 50' 29.94" N 111° 50' 38.59" E	2	4.5	1.4	-0.4	Yes	Both	0.3	1.2	2	7
T	2° 50' 30.41" N 111° 50' 38.04" E	17	4.5	>1.96	-0.4	Yes	Rain	0.3	0.9	2	7
U	2° 36' 3.988" N 112° 6' 28.87" E	1	4.0	>2	-0.5	Yes	Both	0.3	1.5	4	10
V	2° 38' 47.38" N 112° 5' 54.57" E	1	7.2	>5	-0.6	Yes	Both	0.3	1.5	4	10
W	2° 38' 47.33" N 112° 5' 52.06" E	1	7.2	>4	-0.3	Yes	Both	0.3	1.5	4	10
X	2° 42' 44.03" N 112° 3' 20.62" E	2	8.8	>2	-0.5	Yes	Both	0.3	1.5	4	10
Y	2° 42' 44.97" N 112° 3' 20.15" E	2	9.1	>2	-0.9	Yes	Both	0.3	1.5	4	10
Z	2° 43' 18.00" N 111° 59' 7.324" E	1	6.5	>5	-1.3	Yes	Both	0.3	1.5	4	10
	Average	**9.9**	**4.5**	**~3**	**-0.5**	**—**	**—**	**0.4**	**1.1**	**2.7**	**10.4**
	Min	**1.0**	**1.6**	**0.9**	**-1.3**	**—**	**—**	**0.3**	**0.6**	**1.0**	**2.0**
	Max	**17.0**	**9.1**	**>5**	**0.0**	**—**	**—**	**0.6**	**1.5**	**5.0**	**45.0**

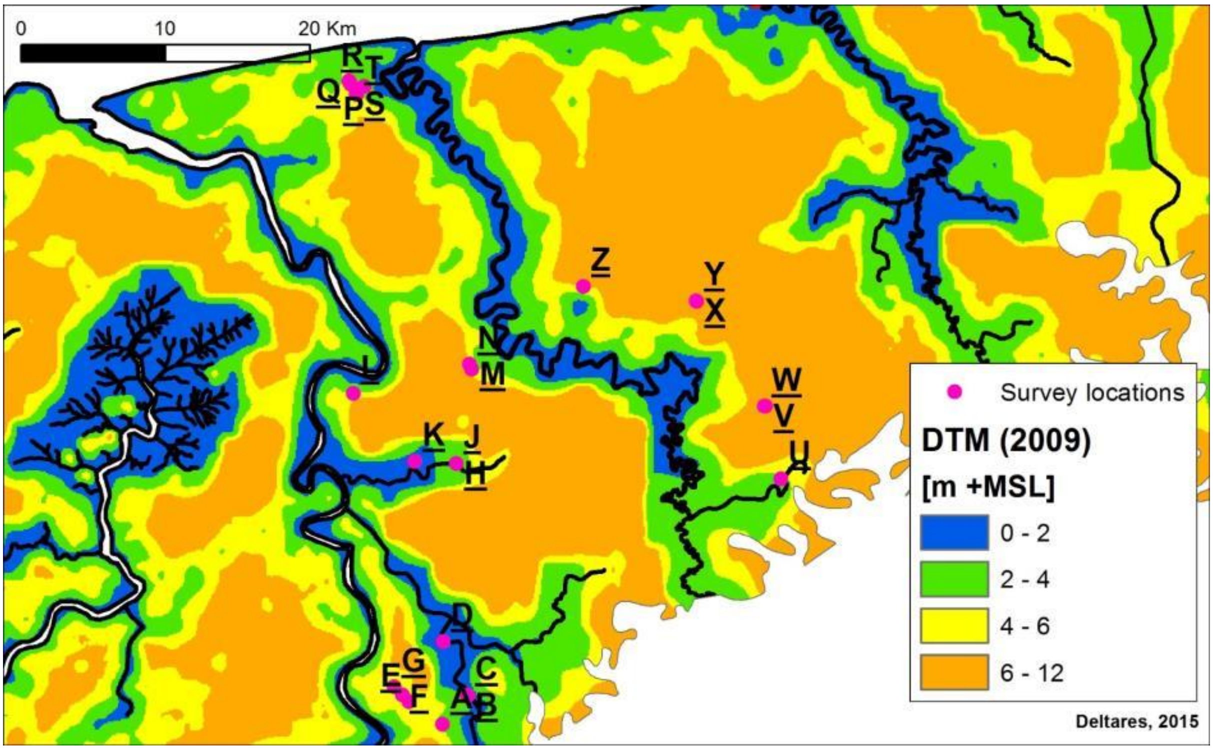


Figure 37 Locations and codes of rapid assessment locations (Table 10) in a selected part of the study area, with DTM in the background.

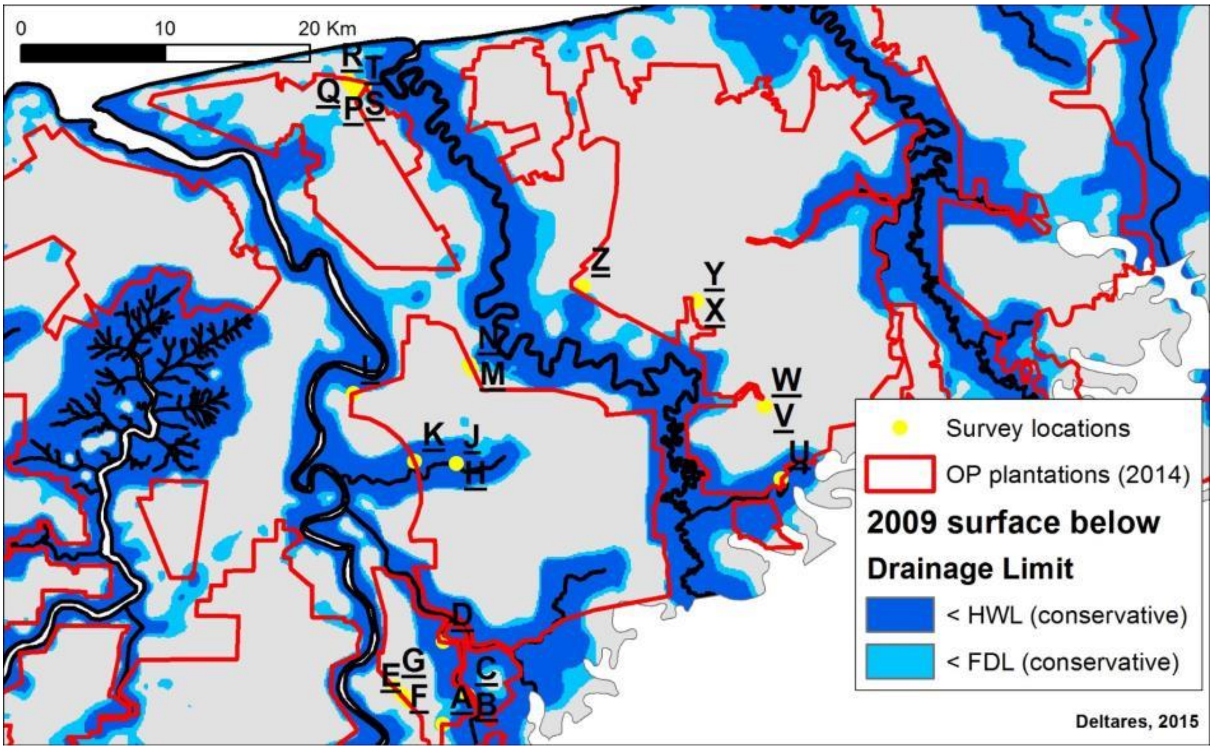


Figure 38 Locations and codes of rapid assessment locations (Table 10), with modeled 2009 flood risk map (Conservative scenario) and plantation boundaries in the background.