Government of Central Kalimantan **Government of Indonesia** **Government of the Netherlands**

Master Plan for the Rehabilitation and Revitalisation of the Ex-Mega Rice Project Area in Central Kalimantan

PEATLAND SUBSIDENCE SCENARIOS FOR THE EMRP AREA

Technical Report No. 3

OCTOBER 2008

Euroconsult Mott MacDonald and Deltares | Delft Hydraulics
in association with
DHV, Wageningen UR, Witteveen+Bos, PT MLD and PT INDEC

Master Plan for the Rehabilitation and Rehabilitation of the Ex-Mega Rice Project Area in Central Kalimantan

Technical Report Number 3

Peatland Subsidence Scenarios for the EMRP Area

Al Hooijer
Marjolijn Haasnoot
Marnix van der Vat
Ronald Vernimmen

Deltares | Delft Hydraulics

With a contribution from
Henk Wösten

Wageningen UR

Government of Indonesia

Royal Netherlands Embassy, Jakarta

Euroconsult Mott MacDonald / Deltares | Delft Hydraulics

in association with

DHV
Wageningen University & Research
Witteveen+Bos Indonesia
PT. MLD
PT. Indec

October 2008

Table of Contents

1 Summary

This document presents the results of the EMRP Master Plan project Cluster 3 (‘Hydrology and Water Management’) on peatland subsidence modelling and scenario assessment, as well as activities and methods used. The document supports the actual EMRP Master Plan report, which presents some results of the subsidence scenario work, but in far less detail.

Rehabilitation projects in the EMRP area peatlands, be it for agricultural development, forest conservation or carbon conservation, will need to take into account the impacts of drainage and carbon stocks and on drainability of the land, and the effectiveness of rehabilitation measures in reducing these impacts. Objective and accurate methods to assess effectiveness of measures are required. At present no methods exist that will allow such assessment at the scale and level of detail that is relevant for project design and implementation. It is therefore crucial for the success of rehabilitation projects that such methods are developed, and the EMRP Master Plan project aims to provide a basis for this.

We have developed and applied a method that provides a powerful demonstration of the impacts of different management strategies for EMRP peatlands. The method to quantify subsidence and CO_2 emission with the Peatland Subsidence Scenario Assessment Tool (PSSAT) is based on decision rules describing relations between drainage regime, groundwater depth, subsidence and CO_2 emission. These relations have been based on existing data and knowledge for the EMRP area and other peatlands in South East Asia.

PSSAT has been used to assess the impact of three different management scenarios:

1. ‘Existing drainage’ (reference) scenario;
2. ‘Maximum drainage’ scenario in which all plantation concessions on deep peat are implemented; and
3. ‘Modified Inpres’ scenario with maximum conservation area and minimum drainage

For each scenario the tool has provided an assessment after 25 and 50 years of parameters such as groundwater depth and level, subsidence rate, surface elevation, remaining peat depth, drainability, extent of flooding and CO_2 emission.

Scenario results provide a clear indication of potential impacts and are a strong tool for communication and comparison between management scenarios. The effect of drainage on subsidence through shrinkage and decomposition in EMRP peatlands is found to be significant, but because of the apparent low hydraulic conductivity of the peat, it appears mostly confined to a zone of a few kilometres from drainage canals with the worst effects confined to the first kilometre or so. Calculated present annual subsidence rates are estimated to be 66 mm/y at 50m from a canal, 23 mm/y at 500m, 18 mm/y at 1000m, 12 mm/y at 2000m and 6 mm/y at 5000m. The result is that the extent of the long-term subsidence impact of isolated canals is also relatively limited compared to some other peatland areas, whereas in densely drained areas like plantations the surface subsides faster and more uniformly over large areas.

Further drainage in the EMRP peatlands for plantations will result in increasing soil subsidence and consequently also CO_2 emission. Not only does this influence global climate and biodiversity of peatlands negatively, the use of the area for agricultural purposes will also be limited in time. Our current projections for the ‘existing drainage’ and ‘maximum drainage’ scenarios foresee a rapid increase of water management problems related to reduced surface gradients and elevation above sea level. Drainability of agricultural areas will be poor, and increased flooding by River water should be expected.

Sustainable development of the EMRP area as investigated under the ‘modified Inpres’ scenario seems the best of the examined scenarios if results are evaluated on flood risk, CO_2 emission and peat conservation. The latter implies the best possible results for peat related biodiversity as well.

These preliminary PSSAT results allow comparison and demonstration of the effects of different scenarios. For quantification of the possible market value of reduced/avoided emissions, or design studies for optimum water management, more refined calculations are required. The presented results are highly tentative, with uncertainties in model results are easily as high as 50%, because the underlying science is very much in development. Improvement of model descriptions of subsidence and CO_2 emissions require first of all monitoring to overcome current data limitations.

The current approach aimed to define knowledge rules that are consistent with the scarce subsidence data available. These knowledge rules are entirely empirical. For more accurate subsidence modelling, what is needed is a process-based model that takes into account the actual processes that determine peat shrinkage and carbon loss. This will also allow more accurate modelling of carbon emissions.

2 Introduction

2.1 This report

This document presents the results of the EMRP Master Plan project Cluster 3 (‘Hydrology and Water Management’) on peatland subsidence modelling and scenario assessment, as well as activities and methods used. The document supports the actual EMRP Master Plan report, which presents some results of the subsidence scenario work, but in far less detail.

The subsidence modelling work was a small task in Cluster 3, which mainly dealt with hydrological issues. However, since the subject of peatland subsidence and CO_2 emissions has received so much interest lately, we decided to present this work in more detail and in a separate report.

2.2 The importance of understanding and projecting subsidence and CO_2 emissions in the EMRP area

The reason the EMRP Master Plan project was developed is that the area is subject to some extraordinary conditions that can not be dealt with without thorough assessment based on improved knowledge of key processes. In the peatlands that cover most of the EMRP area, the three main issues are:

1. fires (which causes haze and health problems and reduces agricultural productivity),
2. increased flooding and loss of drainability due subsidence i.e. ‘sinking’ land surface (which reduces agricultural productivity), and
3. CO_2 emissions from peat decomposition and fires which contribute to a global rise in atmospheric CO_2 concentration (that is widely seen as responsible for climate change).

These three key issues are closely related and are largely the result of peatland drainage.

Rehabilitation projects in the EMRP area peatlands, be it for agricultural development, forest conservation or carbon conservation, will need to take into account the impacts of drainage, and the effectiveness of rehabilitation measures in reducing these impacts, on forest and carbon stocks and on drainability of the land. Objective and accurate methods to assess effectiveness of measures are required. At present no methods exist that will allow such assessment at the scale and detail level that is relevant for project design and development. It is therefore crucial for the success of rehabilitation projects that such methods are developed, and the EMRP Master Plan project aims to provide a basis for such further development.

The activities described in this report aim to A) demonstrate the principles involved in subsidence caused by drainage, B) demonstrate the speed and scale of subsidence impacts under different management scenarios, C) explore the uncertainties and the further data collection and research required to reduce those. The results of these activities have a high associated degree of uncertainty, as this has been a rapid assessment with limited data. During the project (and in ongoing peatland research projects elsewhere), it was found that knowledge gaps were greater than expected.

2.3 Analysis and projection approach

In the EMRP MP project, methods were refined and applied to quantify the effect of drainage in terms of peatland subsidence, flooding risk and CO_2 emissions. Methods and results are presented in this report.

The two main activities described in this report are A) assessments of the impact of drainage resulting in development of ‘decision rules’ and B) application of these decision rules in the model application PSSAT (Peatland Subsidence Scenario Assessment Tool). The current PSSAT application results serve three purposes:

1. Demonstrate impacts to non-expert decision makers, so they can be taken into account in the decision process.
2. Quantify impacts, with a very significant range of uncertainty.
3. Identify knowledge gaps, so subsequent research can be more effective in filling them.

2.4 Uncertainties and knowledge gaps

There are several reasons why the current PSSAT results should be considered only a first step towards accurate quantification of drainage impacts in peatlands. There are fundamental gaps in published knowledge on the fundamental relations that control peat decomposition and subsidence. During the project, gaps in data available for the EMRP area (water depth, peat type, subsidence rate) were found to be greater than anticipated. Finally, in the last months of this short and intensive project relevant research results were identified in ‘grey literature’ that would have benefited the PSSAT application if there had been time to use them. **For these reasons, current results should be considered to be highly tentative. Further work will be needed to fill knowledge gaps and produce more definitive results.**

3 Data and considerations on subsidence rates in the EMRP area

Peat subsidence is the result of four irreversible processes:

1. Consolidation: the compression of saturated peat due to increased 'overburden' i.e. pressure on deeper peat when water is lost from the top peat due to drainage. Most consolidation occurs rapidly after drainage, in the first 1 or 2 years after drainage. No peat matter is lost in this process, i.e. bulk density increases.
2. Shrinkage: gradual volume reduction of peat in the unsaturated zone due to loss of water from pores. No peat matter is lost in this process, i.e. bulk density increases.
3. Oxidation: gradual volume reduction of peat in the unsaturated zone due to decomposition of organic matter. Peat matter is lost in this process, partly to the atmosphere as CO_2, and to a lesser degree to discharge water.
4. Fires: fast but periodic or rare complete loss of organic matter from the unsaturated zone. Peat matter is lost to the atmosphere in this process, as CO_2 and to a lesser degree CO.

These processes (except possibly fire in some cases) occur in all periodically aerated peat, but they are greatly enhanced by drainage. In undrained peat, the rate of production of new organic material by vegetation is somewhat greater than or similar to the subsidence processes, resulting in a slightly rising or stable peat surface and carbon store. In drained peat this balance is lost; the subsidence processes are orders of magnitude greater and peat surface and carbon store decline rapidly.

The subsidence rate in the EMRP area is expected to vary significantly in space, as a result of differences in a number of variables that are know to varying extent:

- surface water depth in drainage canals,
- drainage canal density,
- upslope peatland catchment area,
- canopy cover over the peat,
- hydraulic conductivity of the peat,
- degree of peat humification,
- fire history at the site and near the site,
- and other land management aspects.

Shrinkage and oxidation cause major changes in the characteristics of the peat material. Coarse vegetation remains are broken down into smaller fragments, and large pores are reduced to small pores. In the process, the ease and speed with which remaining organic material in the unsaturated zone is further decomposed, is reduced. Moreover, when subsidence proceeds the depth of the peat layer and the overall gradient of the peat landscape are reduced, and the hydraulic conductivity in the unsaturated zone greatly diminished, resulting (except in densely drained landscapes) in reduced groundwater flow and hence in ultimately higher water tables. Hence, subsidence rate will decrease with time. In order to accurately predict peat subsidence rate, and its change in time, it is necessary to know the current humification stage of the peat (on which we have limited data) and to understand its impact on shrinkage and oxidation (on which limited knowledge exists for tropical peat).

In undrained conditions the least decomposed (i.e. most fibric) peat often occurs in the middle part of peat domes, where slopes are lowest and distance to drainage greatest. At the sides of peat domes the peat is naturally drained and consequently more decomposed (sapric peat). In the vertical direction a similar sequence can be found: the deepest peat is oldest and tends to be more decomposed. In theory, therefore, one would expect a ‘nested’ peat type model where peat in the central and upper parts would be least decomposed and have highest subsidence rates and hydraulic conductivities. In practice, however, no such zoning could be identified for the EMRP area. It is possible this is partly because of data shortage. But it does appear that, if there is a spatial pattern in peat characteristics, it is more complex than a large-scale ‘nested’ model.

The key to predicting future subsidence rates, flood patterns and CO_2 emissions following drainage lies in understanding the relation between water depth and peat decomposition (and fire frequency). At present, only few studies have been published on which to base such a relation, and it is found that these studies allow only generalized empirical relations rather than process-based relations taking into account peat characteristics in different areas. The relations applied in the Master Plan project subsidence modelling were developed after evaluating the following sources:

1. The limited data on peat type distribution available to the project.
2. Analysis of 26 elevation and groundwater depth transects, surveyed in the CKPP Mapping Project in 2007, perpendicular to drainage canals and 1km long, allowing a rough assessment of cumulative minimum subsidence in a large number of locations in EMRP peatlands, as a function of the distance to a canal.

3. Hydrological assessments and model results in the current project, allowing us to better understand the relation between distance-to-canal, groundwater depth and subsidence.
4. An inventory report by Henk Wösten (WUR), evaluating the applicability of the ‘subsidence is 10% of average water depth’ rule-of-thumb, based on work in Malaysia, to the EMRP area.
5. Subsidence data collected by CIMTROP/UnPar in Block C of the EMRP area.
6. Work in the ongoing Kampar Science Based Management Project, presenting a first step towards a non-linear and time dependent relation between water depth and subsidence.

3.1 Data on peat characteristics distribution in the EMRP area

The following sources of information on peat characteristics are available to the project:

1. Peat type descriptions in the field during the CKPP mapping Project surveys (Figure 3.1), in terms of ‘fibric’ (least humified, coarse material), ‘hemic’ and ‘sapric’ peat (most humified, ‘soapy’ material).
2. Peat sample analyses during the CKPP Mapping Project surveys (Figure 3.2): water content and carbon content.
3. Bulk density sampling in Blocks B and C in 2001-2002, (Jaya 2005).
4. Bulk density sampling in the MP Project, only in the NW part of Block A and not overlapping with the other data (Figure 3.1).

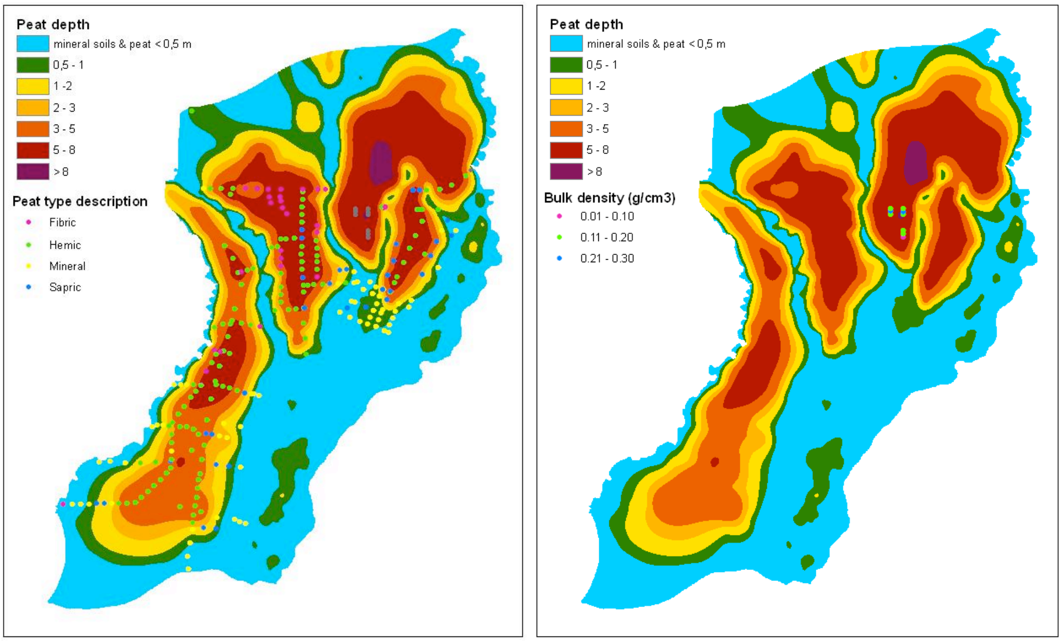


Figure 3.1 Distribution of field peat description points in the CKPP project (left), and bulk density sampling points in the Master Plan project (right).

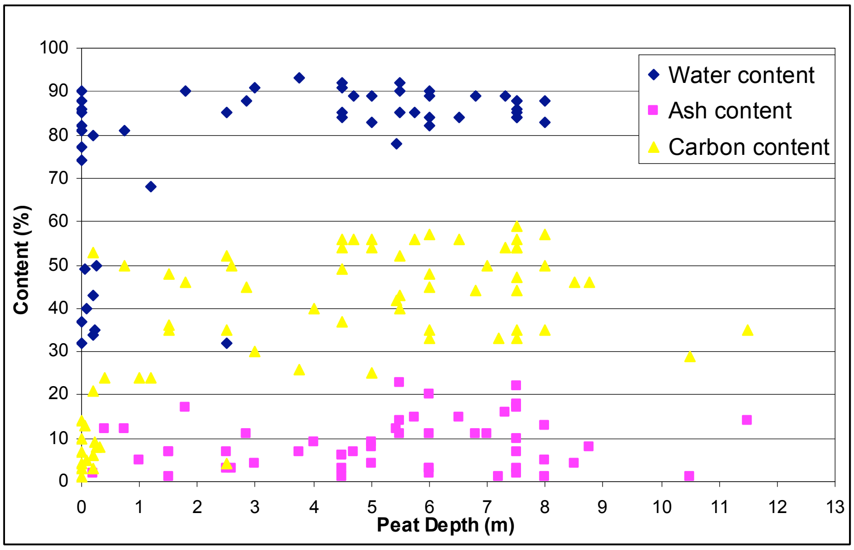


Figure 3.2 Water content, ash content and carbon content in relation to peat depth, in the EMRP area.

A possible further source of information, recent peat sample analyses for the North of Block C (CIMTROP area) carried out by the University of Yogyakarta, was not available to us at the time of writing.

In 2001-2002, Bulk Density of a large number (301) peat samples taken from Block B and Block C (at different depths) was analyzed (Jaya, 2005). On the basis of field tests (Von Post), all peat samples in Block B and Block C were described as either hemic or sapric. Average BD of the 301 samples analyzed is reported to be 0.22±0.14g/cm^3; however this number is too high for the actual peat samples as it includes a number of samples with BDs up to 0.7 g/cm^3 which indicates the peat is mixed with mineral material. More indicative of actual peat conditions is the fact that BD in 66% of the samples is between 0.08 and 0.24 g/cm^3, and most of the remainder is above 0.24 g/cm^3. It appears that samples were taken over the entire peat depth in peat cores, but this is not clear. No co-ordinates of the sample locations are given; if co-ordinates would be available in the future, this would be helpful to determine distribution of peat types in the EMRP landscape, which is not possible at present.

The following is observed from the CKPP and Master Plan project data collected in 2007 and 2008 (all samples are assumed to be taken at 1 and 2 m depth):

- Most peat in all areas (>60% of points) is described as 'hemic'. Where this is not the case, it is difficult to see a landscape-related pattern in the peat type distribution (Figure 3.1), even though there appears to be some relation between peat type and peat depth when all data for different areas are combined (Figure 3.3). As far as a spatial pattern is evident, it appears to be related to different surveyors describing the peat. It should

be noted that peat type descriptions are subjective; Bulk Density data are needed for accurate analysis.
- The three peat characteristics measured in the laboratory for a large number of points, water content, carbon content and ash content, seem randomly distributed in space. No relation with peat depth is evident (Figure 3.2).
- Bulk density varies quite significantly, from 0.09 to 0.23 g/cm3, within a small area in the NW of Block A with a limited peat depth range from 6.5 to 8.5m. The average in that area is 0.17 g/cm3, which indicates hemic peat going towards sapric.

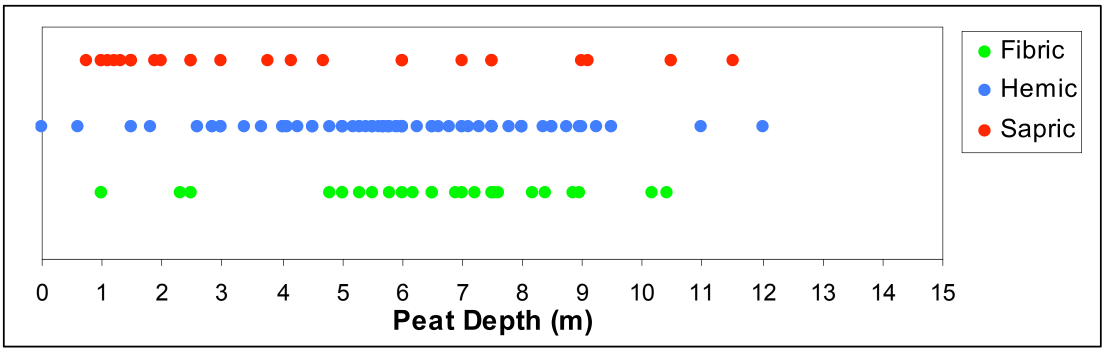


Figure 3.3 Distribution of peat types as described in the field with peat depth.

Although there are no scientific rules for relating bulk density to peat type in tropical peat, peat between 0.1 and 0.2 g/cm^3 is often considered to be 'hemic'. Higher bulk density indicates 'sapric' peat, and lower bulk density indicates 'fibric' peat. Almost all bulk density measurements therefore confirm that the peat in Blocks A, B and C should indeed be classified hemic or sapric, as field descriptions indicate.

The main outcomes of this rapid assessment are:

1. All peat descriptions and bulk density measurements available suggest that all or most peat in Blocks A, B and C in the EMRP area is moderately to highly humified (hemic to sapric). This implies that this peat will generally have low hydraulic conductivity, which is an important parameter in assessing the impacts of drainage on peatland hydrology and subsidence after drainage.
2. No peat type distribution patterns are evident, from the data available, that relate to either peat depth or position within the peat landscape (distance from rivers). We can therefore only assume that all peat in Blocks A, B and C in the EMRP area will respond in uniform ways to drainage, in terms of subsidence and CO_2 emission.
3. It is still possible however, even likely, that fibric peat may be found in Block E, where no samples were taken and which contains peatland of greater extent (between rivers) and good

> forest cover. A peat core described in the centre of Sebangau NP near the EMRP area shows that fibric peat indeed occurs there (Figure 3.4). Such peat will have higher hydraulic conductivity (and therefore allow more groundwater flow in drained conditions) than most peat in the EMRP area.

We realize that this finding is hampered by the limited distribution, and possibly accuracy, of peat characteristics data. A priority recommendation is to collect more information on distribution of peat characteristics, both laterally and in the vertical, especially bulk density. Maybe it will help to re-analyze existing datasets, e.g. taking into account peat depth, to get a better picture of peat type distribution.

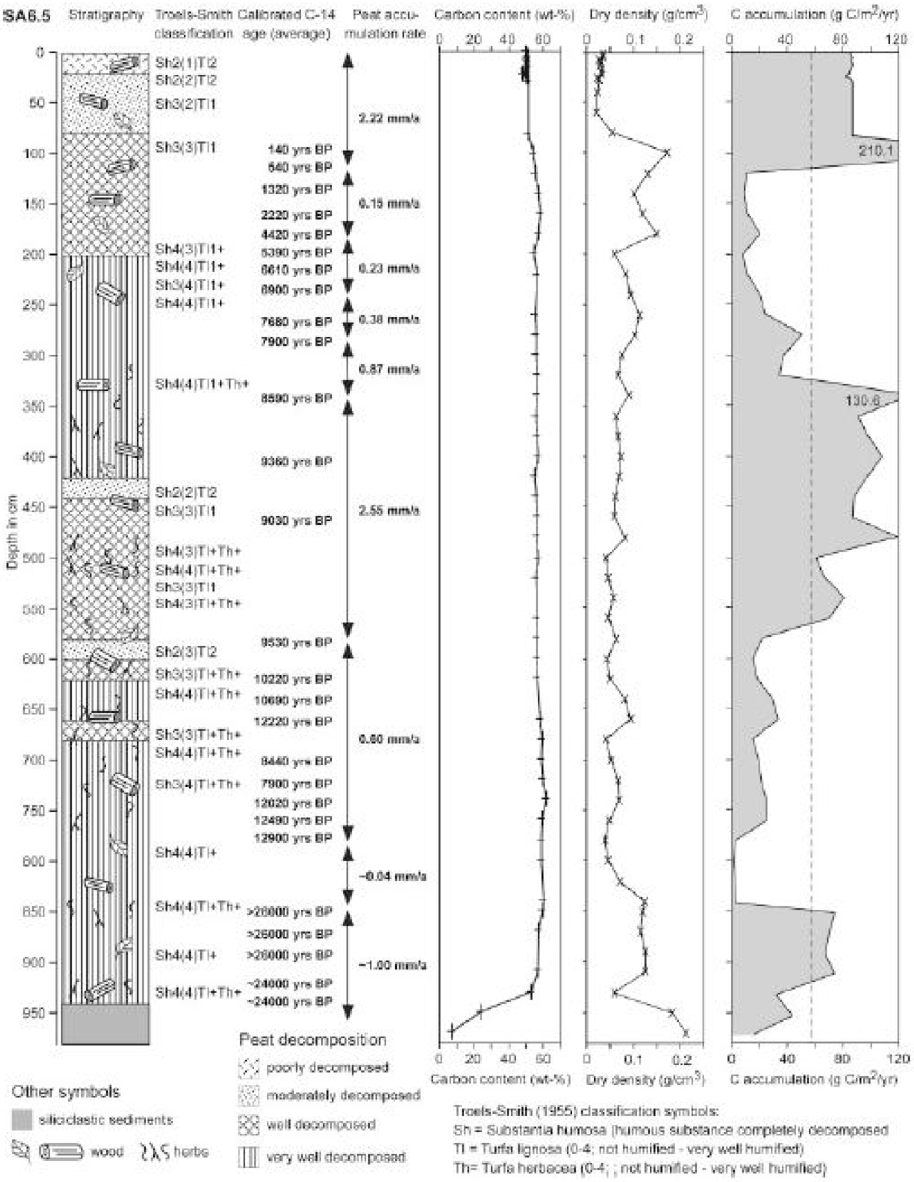


Figure 3.4 Stratigraphic description of peat core SA6.5 in Sebangau NP. Note that bulk density in most of the core is below or around 0.1 g/cm3, indicating fibric or slightly hemic peat (Source: Page et al. 2004).

3.2 Findings on EMRP peatland hydrology relevant to understanding subsidence

Hydrological assessments in the EMRP area, including groundwater modelling (see EMRP Master Plan project Hydrology report), have shown that groundwater tables over most of the area at two study sites (in Block A and Block C) are near the soil surface throughout the wet season (Figure 3.5). The impact zone along canals over which significant groundwater flow to canals occurs is limited to a few hundred metres, due to the low hydraulic conductivity of the peat at these sites and the fact that peat morphology has already adapted to the presence of canals over the last 10 years. In dry periods, water tables in most of the peatland area are now controlled mostly by the meteorological water budget (rainfall minus evapotranspiration), and water tables drop uniformly; they are frequently below 0.5m and sometimes below 1m. In the usually longer wet periods, however, water tables are at the peat surface and excess rainfall is discharged to canals as surface runoff.

This finding of relatively high groundwater tables in drained peatlands in the wet season should not be understood to mean that drainage has limited impact on hydrology in the EMRP area and on subsidence rates. This impact is major and irreversible. In the first period after drainage the hummock-hollow top-layer of the peat, which is crucial in intact peatlands as it keeps the surface wet by slowing down surface runoff, is dried out and removed. Runoff from the now smoother drained peat surface is faster, hence the peat top soil is dry for longer periods. The removal of the forest canopy which blocked solar radiation and maintained moist air near the forest floor also has a role in drying the peat top soil. The more frequently dried top soil will decompose and subside and also presents a fire risk. However, where water tables are often high the subsidence rate will be less than where water tables are lower, nearer to canals.

The fact that water tables in the wet season are low near canals but high further away from canals has created a gradient in subsidence rates away from canals. This explains the surface slopes towards canals that are found in all EMRP peatlands (section XX), and the ‘mini dome’ morphology that has now formed in densely drained peatlands such as the NW part of Block A.

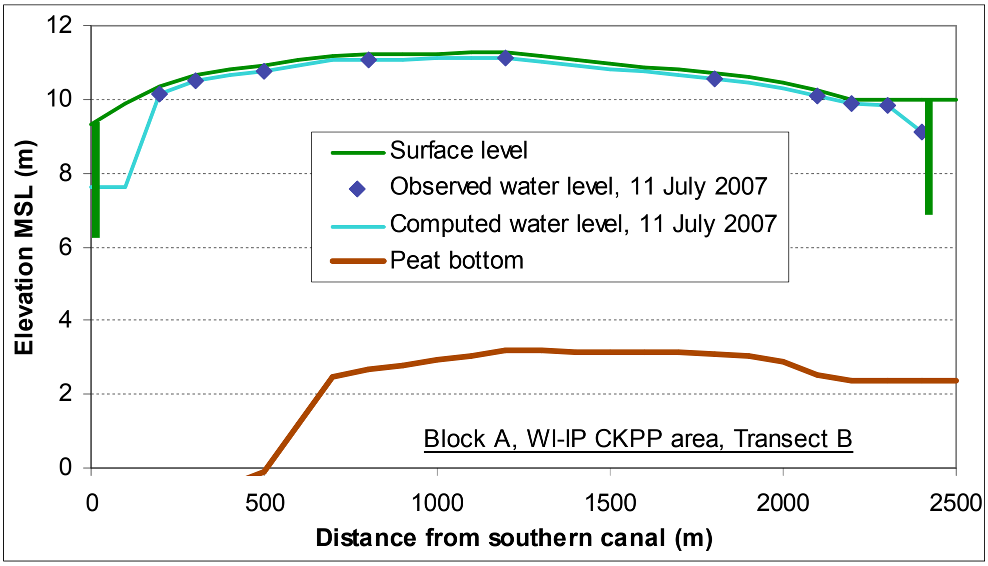


Figure 3.5 Measured and simulated Transect B ground water levels for July 11, 2007 (see EMRP Master Plan project Hydrology report).

3.3 Analysis of elevation and groundwater depth transects perpendicular to canals

In the CKPP Mapping Project in 2007, and in the EMRP Master Plan project, a number of elevation (and groundwater depth) transects of 1km length were measured perpendicular to drainage canals in peatlands, with the aim of improving understanding of subsidence patterns and rates (see Figure 3.6 for locations). From this dataset, only those transects that are drained only on one side are used in the following analyses, excluding the transects in the NW part of Block A where canals are close together at 2.5 km (the area where WI-IP has built dams in the CKPP project). Also excluded are transects in peat of less than 3m depth, and a few where there were questions about the data. The number of transects remaining for this analysis is 26 (see Table 3.1 for the data). At 20 of the 26 transects groundwater depth has also been measured.

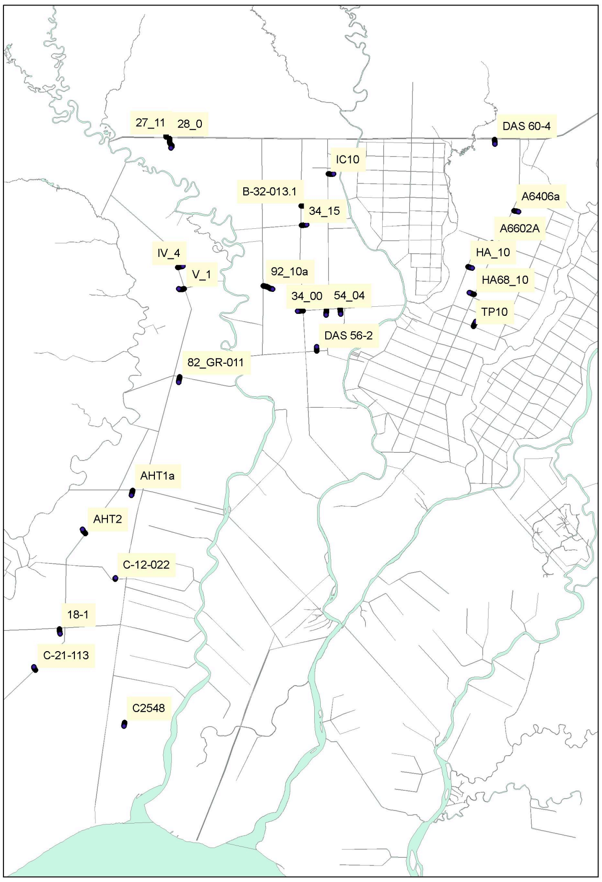


Figure 3.6 Locations of 1km CKPP Mapping Project cross sections perpendicular to canals in peatland (2007). Note that similar cross sections in Block A NW (the CKPP WI-IP area) are not included because these are drained on both sides.

Nearly all drainage canals were developed in 1995-1997, with a few being older, so the peat along the 1km transects has mostly been subject to drainage for 10 to 12 years.

Table 3.1 Attributes of 1km CKPP Mapping Project cross sections.

Code	Slope m/km	Groundwater depth at 50 m	Freeboard (canal water below peat surf.)	Peat Depth (m)	Peat Type	Land cover along transect	Up/down slope in original peat	Location (EMRP Block)
A6602A	-0,51	0,71	1,52	6	?	other	downhill	A
A6406A	-0,37	0,56	2,47	7	?	other	downhill	A
DAS 60-4	-0,28	?	1,73	6	?	forest	downhill	A
B-55-014.1	-0,26	1,18	1,85	3	hemist	other	downhill	B
DAS56-2	0,10	?	1,83	3	?	other	uphill	B
IC10	0,36	0,73	1,41	3	febrist	burnt	downhill	B
AHT1a	0,37	0,37	2,09	7	febrist	other	uphill	C South
54-04+LM91	0,41	1,30	1,88	5	hemist	other	downhill	B
B-32-013.1	0,46	0,70	1,38	7	saprist	other	downhill	B
34-15	0,50	0,36	0,82	7	saprist	other	downhill	B
DAS 60-U	0,55	?	1,71	4	?	forest	uphill	A
34-00	0,57	0,39	1,31	7	hemist	forest	uphill	B
AHT2a	0,58	0,55	2,09	4	hemist	other	downhill	C South
C-12-022	0,58	0,72	0,24	4	hemist	other	flat	C South
18-1	0,70	0,60	2,20	4	saprist	other	flat	C
V_1	0,84	?	2,33	6	hemist	burnt	uphill	C North
28_0	0,84	?	0,98	8	hemist	forest	downhill	B
C2548	0,93	?	0,12	3	hemist	other	flat	C South
IV_4	0,98	?	2,26	5	hemist	burnt	downhill	C North
92-10a	1,06	?	0,43	4	hemist	burnt	uphill	B
HA_10	1,10	1,35	1,78	5	hemist	forest	flat	A
HA68_10	1,10	1,02	1,67	6	hemist	other	flat	A
C-21-113	1,14	0,43	0,13	5	hemist	other	downhill	C South
TP10	1,30	0,48	1,55	4	hemist	other	uphill	A
27_11	1,40	?	2,08	9	hemist	forest	uphill	B
82_GR-011	1,53	0,40	2,73	5	hemist	forest	uphill	C North

In the analyses, we have used elevation and groundwater depth as measured at an average of 50-100m, 500 and 900-1000m away from canals, relative to the surface water level in the canal. Measurements within 50m from canals were discarded because they may be affected by dredging activities, creating berms with higher elevations. As these measurements were part of an intensive field survey in the dry season of 2007, all water depths were measured in the second half of July and August of 2007. This was a rather wet dry season, therefore water depths were not very low, but they were of course lower than in the wet season. For lack of a better measure of 'average' water depth along the transects, we have assumed these measured water depths in further analyses to be representative for the average.

The peat is likely to have burnt, at least close to canals, along many transects. However, the exact burning history of the area (except Block C) is unknown. Some of the transects in (degraded) forest areas might not have burnt, but even in those cases there may have been fires close to canals (NB the request to survey teams to note fire indications in top soil, i.e. 'black soil / ash' as part of the soil survey did not yield clear indications of fire history). Burning is therefore likely to have added significantly to overall subsidence. However we can not tell from the data whether this has affected the peat surface in a uniform way or in a variable way with a greater impact closer to the canal, and we therefore had to assume all subsidence to have been caused by peat decomposition alone. We realize this assumption may not be correct and will introduce further uncertainty to the analysis; we suggest this should be further investigated in a follow-up to the project.

The locations, slopes and other attributes of the transects are presented in the figures and table in this section. Figure 3.7 presents the average peat surface slope and water table slope (July/August 2007) for the 20 transects. Summary observations are given below.

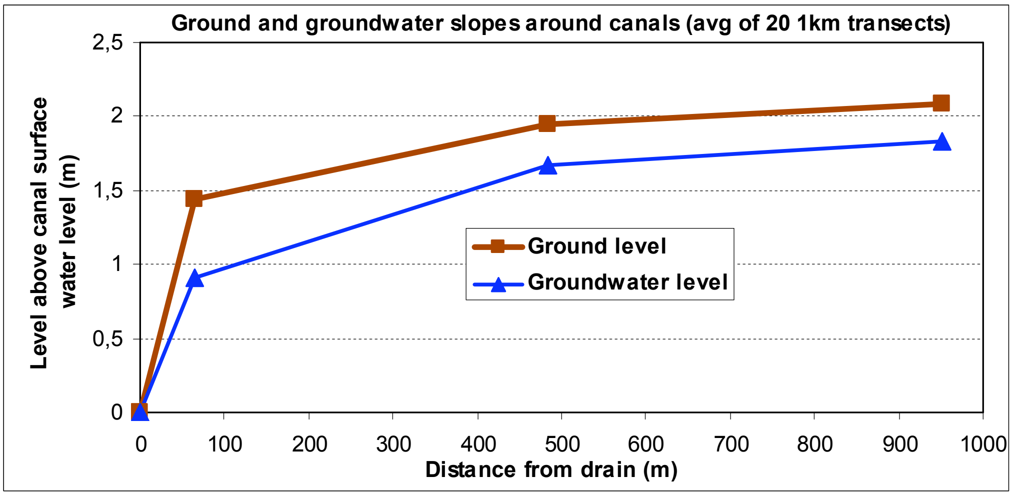


Figure 3.7 Average of 1km elevation and groundwater (July/August 2007) cross sections perpendicular to canals. This data was used to derive subsidence rates in the EMRP area as applied in PSAT subsidence projections.

Transect surface slopes

Average slope along the 20 1km transects is 0.71 m/km. 60% of transects has slopes greater than 0.5m/km, and 25% has slopes between 1.0 and 1.5m/km. These slopes appear significantly steeper than in the central parts of most undrained peatlands (where these transects are located). This will have enhanced surface water flows and (to a lesser extent) groundwater flows, and hence perpetuates subsidence due to the drying of the peat.

Transects slopes in relation to original peatland morphology

As these 1km transects were randomly distributed, and the original pre-drainage peatland landscape consisted of gentle domes, there would have been more or less as many ‘upslope’ transects as there would have been ‘downslope’ transects in the original landscape. In the current landscape however, most slopes are towards canals; the only 4 transects sloping away from canals (all at gradients below 0.5m/km) are in locations where the original morphology would have been ‘downslope’ already. This suggests that the change in slope due to subsidence over the first km from the canal is greater than the original peatland slopes in most cases.

Transect slopes in relation with land cover, peat depth, freeboard and location

No clear relations were found between slopes and land cover (forest, recently burnt, other), between slopes and peat depth (Figure 3.8) and between slopes and freeboard (difference between canal water level and surface level 50m from canal). However, a relation is evident between slope and transect location (Table 3.1): most of both the negative slopes and the steepest slopes are found in Block A, while most of the gradual slopes (0 to 0.5m/km) are in Block B and most of the moderate slopes (0.5-1 m/km) are in Block C. Theoretically, there may be a relation with hydraulic conductivity of the peat here: the greater this is, the lower the water table gradient towards the canal and the more uniform the subsidence is expected to be. However, the limited soil data available do not suggest a clear spatial pattern in bulk densities and therefore in hydraulic conductivity. Another theoretical explanation would be that the different areas have had different fire histories: most of Block C has been burnt (much of it several times), and only little of Block B. However it is not quite clear how this would fit in with the gradients found (Block C having moderate slopes and highest fire frequency).

Changes in transect slopes and subsidence away from canals

Average peat surface slopes are significantly higher over the first 500 m from canals (1.11 m/km) than over the last 500m (0.31 m/km). This confirms that subsidence rates are higher closer to canals (this is assuming fire impacts have been uniform, see above), but it also indicates that subsidence extends beyond 500m. From these data, there is no way of telling at what distance from drains subsidence would stop. In fact, we assume that subsidence occurs in all or almost all of the EMRP peatland area because A) drainage impact on surface water will extends over great distances thereby prolonging the period with water tables below the peat surface (see EMRP Master Plan Hydrology report), B) removal of forest canopy has a ‘drying’ effect on the topsoil which enhances decomposition, and C) fires are likely to destabilize the peat system in ways that cause subsidence after fires are extinguished.

Estimating subsidence from transect slopes

The problem with estimating subsidence rates from transect slopes is that we do not know the original slopes, so assumptions need to be made. If we would assume that no subsidence takes place at 1km from canals, the average slope of all transects suggests that the average subsidence rate at 50m from canals would be 7 cm/y (assuming a drainage period of 10 years). However, we know that subsidence does take place beyond 1km from canals, albeit (in the

EMRP area) at lower rates in the order of 1 to 5 cm/y (see analysis of CIMTROP subsidence data, section 3.4, and of expected subsidence rates following the 'S-curve' method, section 3.7). If we assume a subsidence rate of 3 cm/y at 1km from canals (in addition to the 0.5 to 1m subsidence in the first 1 or 2 years, which is caused by peat consolidation and loss of the hummock-hollow layer, and assumed to be fairly uniform in space, average subsidence rate near canals would be 10cm/y over the first 10 years on record. This fits in well with the finding that subsidence near canals in the North of Block C was 4.5 to 8.3 cm/y at 10 years after drainage (section 3.3), in the knowledge that subsidence decreases in time as peat decomposition proceeds.

Relation between transect subsidence and water depth

Average groundwater depth at 50m from canals, in July-August 2007, was 0.53 m. Average freeboard (difference between canal surface water level and surface level at 50m was 1.44m, indicating that freeboard is a poor indicator of groundwater depth in the EMRP peatlands due to their mostly low hydraulic conductivity: groundwater tables rise steeply away from canals. This was in the dry season, albeit one of the wetter dry seasons on record. Considering the longer-term monitored and modelled groundwater table fluctuations in the area (see Hydrology report), we estimate that average longer-term water depth at 50 metres from canals will be 0.4 - 0.5m below the peat surface, not much different from the situation in July-August 2007. This suggests that the average subsidence rate of 0.1m/y over 10 years of drainage could be up to 20% of average groundwater depth in 2007, (more than the 10%/y earlier proposed on the basis of measurements in Malaysia; see section 3.6).

Of course, groundwater depth near canals shortly after drainage implementation, when subsidence was less advanced and peat surface slopes towards the canals less steep, must have been greater than at present. However average water depth has probably always been significantly less than 1m on average due to the low hydraulic conductivity of most of these peatlands (apart from the surface layer, which is lost shortly after development/fires). Moreover, monitoring and modelling results suggest that average water depth is relatively uniform over most of the peatland way from canals, due to the fact that water tables are close to the peat surface for most of the year, even quite close to canals. There is more spatial variation in minimum water tables, during the dry season, when canals have a much stronger impact on groundwater depths over a zone of several hundreds of metres. As we know that peat decomposition is a function of oxygen availability, and air will be able to enter the soil and enhance decomposition in dry periods of a few months, it is suggested that a measure of water depth in the dry season (e.g. average annual minimum water depth) may be a better descriptor of peat subsidence rate than average water depth appears to be.

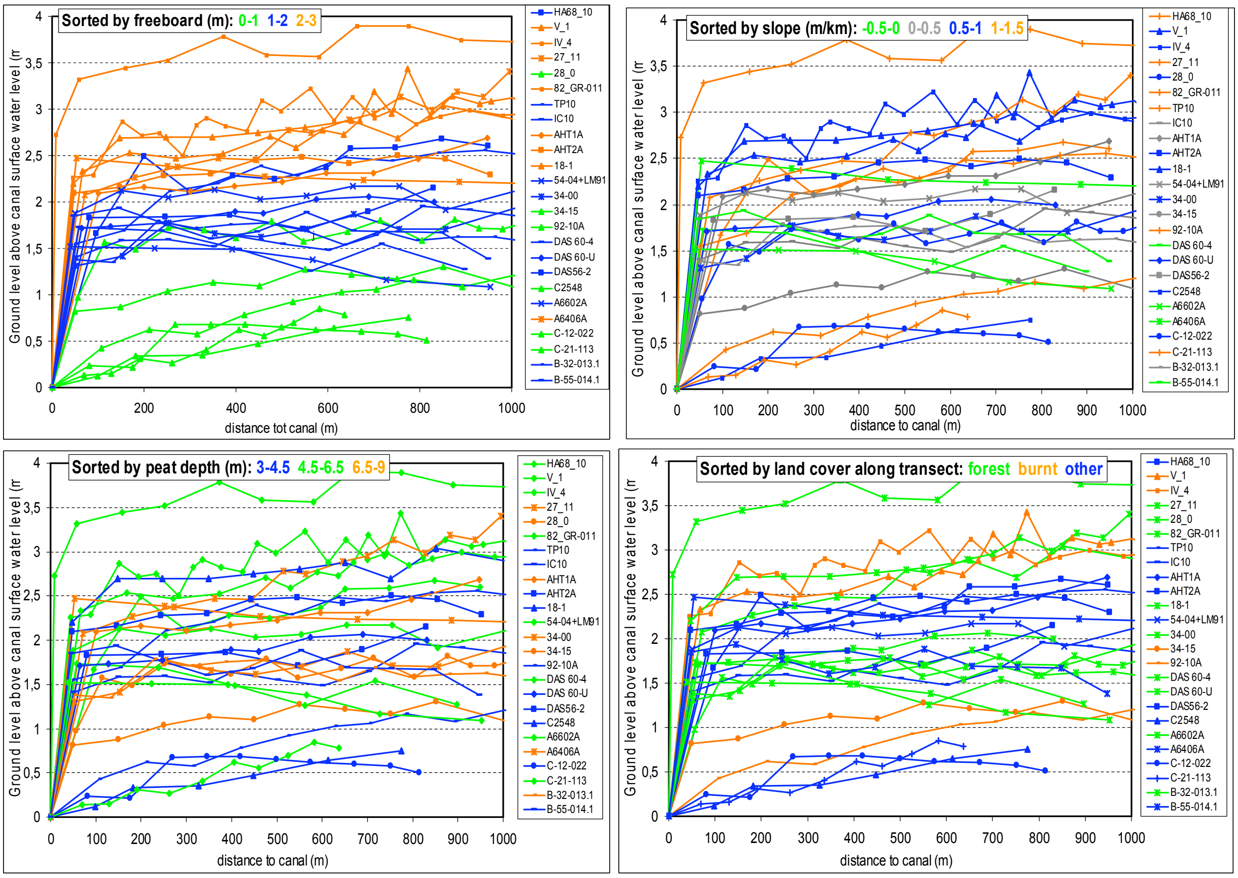


Figure 3.8 Peat surface elevation cross sections perpendicular to canals sorted by different criteria.

3.4 Subsidence monitoring results in the EMRP area

Although subsidence is a key and frequently discussed topic in the EMRP area, there is limited data on actual subsidence rates. As far as we know there has been no long-term subsidence monitoring, or long-term large-scale collection of peat soil data (especially bulk density and carbon content), that would help reconstruction of subsidence history and extrapolation of point data to large area.

2001-2002 subsidence data for Block C (Jaya, 2005)

In the Northern part of Block C, subsidence data were collected over an 18-month period in 2001-2002 (Jaya, 2005). Elevation was measured at 5 transects of 110m length, perpendicular to canals, at the start and end of the period. Average subsidence over the period was found to be 12.5 ± 5.9 cm over the period, or 0.083 m/y.

The area is reported to have been cultivated for agricultural land in 1993, but it is suggested it may already have been in use as transmigration areas since the early 1980s. A precise starting date of the drainage, and therefore the subsidence, is not provided, but we may assume that it was ongoing for some 10 years by 2001/2002. The data could therefore be indicative of subsidence rates 10 years after subsidence started.

These data may be useful in estimating overall subsidence rates in the EMRP area. However they should be interpreted carefully for a number of reasons:

- Measuring subsidence from topographic surveys has been found tricky in other projects, and less accurate than monitoring subsidence from fixed subsidence poles. Indeed, this is indicated by the following:
    - Subsidence measured along the only two fixed poles placed along the transects is significantly lower at 0.0045 m/y (7 and 6.2 cm over the period respectively).
    - Steep water table gradients along canals are found in the area, due to low hydraulic conductivity. This would be expected to be accompanied by steep gradients in subsidence over the first few hundreds of metres away from canals. Such gradients are not evident from the 5 profiles presented, which appear to show fairly uniform subsidence rates.
- For the same reason of steep groundwater gradients away from canals, subsidence over the first 110m is not representative for subsidence further away from canals i.e. in most of the EMRP area.
- No groundwater data are available for the same period as subsidence monitoring. As water depth is the main controlling variable on subsidence rate, this data would be necessary to allow tentative extrapolation of these subsidence data to other areas. From what we know of the area, water depths along the transects may have fluctuated between 0.5 and 2 m, in space and time. Ideally, we would be able to identify a relation between average water depth (or minimum water depth) and subsidence. However if we estimate that average water depth along the 110m transects may have been anywhere between 0.7 and 1.3 metres, and we if we recognize that subsidence rates of will have been somewhere between 0.045 and 0.083 m/y reported (see above), this relation would be somewhere between 0.034 and 0.11 m/y subsidence per metre water depth, which is too wide a range for accurate assessments.
- No peat description or bulk density data is provided for the subsidence transects, which would also have helped to extrapolate these data.

It is concluded that these data are useful in indicating that subsidence in drained peatland in the EMRP area is very significant. However they do not provide a basis for accurate assessment of subsidence rates in the wide range of drainage conditions and peat types found in the wider EMRP area.

2006-2008 subsidence data for Block C (CIMTROP)

In the northern part of Block C, CIMTROP has been monitoring subsidence (and water depth) for two years (2006 to 2008) along a 10 km transect between the Kahayan and Sebangau Rivers (Figure 3.9). The data collected has been analyzed in a rapid assessment by the EMRP Master Plan project team.

The transect runs mostly through burnt peatland covered with shrubs and ferns, but a third of it runs through remaining degraded forest. Peat depth along the transect is limited, between 3 and 4 metres, and the peat is reported to be highly decomposed (sapric).

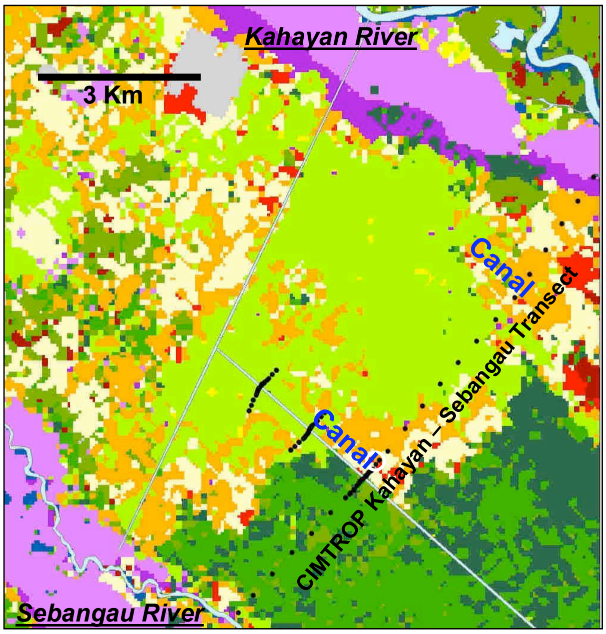


Figure 3.9 Location of the CIMTROP subsidence transect in Block C.

There are two canals draining the area, one of them along the highest point of the peat dome, so drainage has an impact on the entire area by removing surface water much faster from the area than would naturally be the case. This will have prolonged the period during which the water table is below the peat surface, thereby causing dryer topsoils and lower minimum water tables, which has contributed to fire risk in the area. The most profound impact, however, is now found in zones along canals where groundwater tables are affected by drainage even when water tables are below the peat surface. As groundwater flow rates are limited here due to the low hydraulic conductivity and depth of the peat (which is underlain by impermeable clay), these zones are limited to less than 500 metres (section 3.3).

The canals are understood to have been constructed in 1995-1997, although it is possible that the Northern canal (closest to the Kahayan river) was constructed a few years earlier. We assume subsidence has continued for about 10 years on average over the 2006-2008 subsidence record.

Table 3.2 presents the subsidence rates along the transect along with environmental parameters that play a role in controlling peat decomposition processes: water depth and land cover. Figure 3.10 presents profiles of water level and peat depth along the transect. The relation between water depth and subsidence is further elaborated in Figure 3.11.

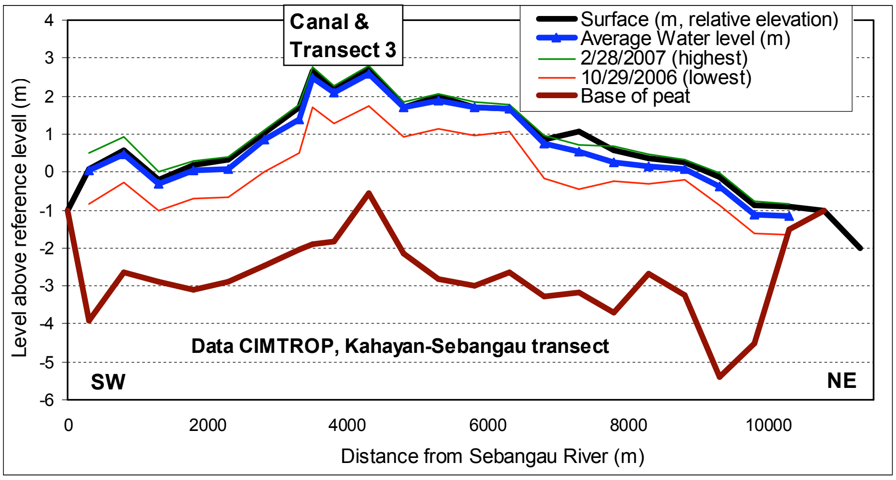


Figure 3.10 Water and peat depth along the Sebangau to Kahayan transect of dip wells (at 500m intervals), where subsidence was monitored over 2006-2008.

Table 3.2 Subsidence as measured over two years along the Kahayan-Sebangau transect in Block C, in relation to environmental variables (data provided by the CIMTROP project).

Distance (km)	Land cover	Peat depth (m)	Water depth 06-07 (m) mean	25%	min	Depth below mark (cm) 26-feb-06	09-mrt-08	Difference (cm)	Subsidence (cm/y)
Kahayan River									
0	degr.	4,0	-0,06	-0,12	-0,91	80	83	3	1,5
500	degr.	3,2	-0,13	-0,21	-0,88	274	276	2	1
1000	degr.	2,7	-0,11	-0,15	-0,82	213	215	2	1
1500	degr.	3,3	-0,14	-0,26	-0,89	224	226	2	1
2000	degr.	3,2	-0,22	-0,25	-1,32	170	174	4	2
2500	degr.	3,5	-0,18	-0,29	-1,01	137	140	3	1,5
3000	degr.	3,8	-0,31	-0,45	-1,20	190	195	5	2,5
Canal (Taruna) ?									
3500	degr.	4,0	-0,07	-0,07	-0,88	216	218	2	1
4000	degr.	3,3	-0,13	-0,11	-0,97	108	110	2	1
4500	degr.	3,9	-0,01	-0,02	-0,78	144	147	3	1,5
5000	degr.	4,8	-0,08	-0,05	-0,84	159	161	2	1
5500	degr.	4,7	-0,01	0,01	-0,76	148	150	2	1
6000	degr.	4,3	-0,01	-0,01	-0,62	249	251	2	1
6500	degr.	4,2	-0,13	-0,16	-1,04	111	114	3	1,5
Canal (Sebangau)									
7000	forest	4,2	-0,52	-0,74	-1,51	104	104	0	0
8000	forest	3,0	-0,22	-0,35	-0,66	138	139	1	0,5
8500	forest	3,5	-0,17	-0,26	-0,47	219	220	1	0,5
9000	forest	5,3	-0,25	-0,33	-0,72	85	84	-1	-0,5 ?
9500	forest	3,7	-0,26	-0,37	-0,77	219	214	-5	-2,5 ?
10000	degr.	0,6	-0,23	-0,39	-0,75	141	142	1	0,5
Sebangau River									

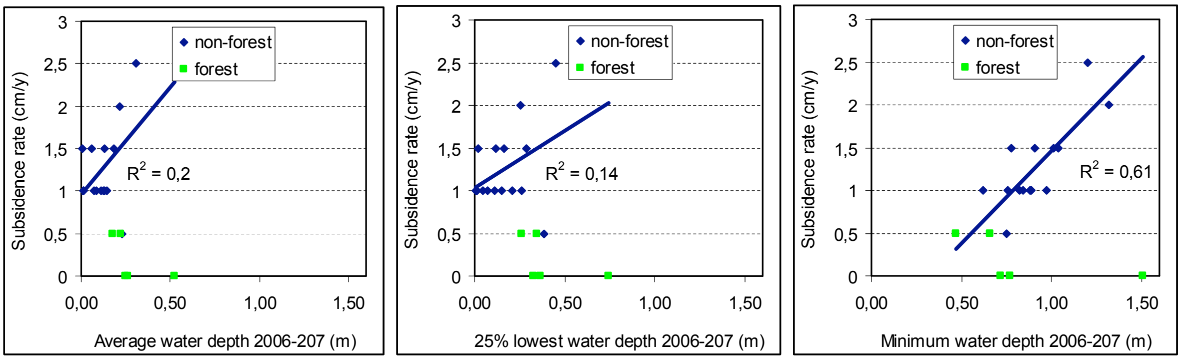


Figure 3.11 Exploratory relations between water depth and subsidence as presented in Table 3.2.

The following observations are made:

- Subsidence rates are between 0 and 2.5 cm/y. This may be lower than expected as subsidence rates in the order of 5 to 10 cm/y are reported elsewhere, in a range of different peat types and hydrological conditions, including a nearby area in Block C (see above; Jaya 2005). This low rate may be explained by the high water tables in the area (due to low drainage intensity and limited groundwater flow) and the reportedly high degree of humification of the peat. Such ‘mature’ peat has already undergone much decomposition in the past and is now less prone to further decomposition than is less humified peat. This may be especially true for peat that has been exposed to fires. However the lack of peat characteristics data does not allow quantification of such relations (see below).
- Subsidence rates are lowest in forest, between 0 and 1 cm/y. In degraded areas, they are between 1 and 2.5 cm/y. As this does not correspond to differences in water depths (which are more or less similar in the two environments, see Hydrology Technical Report), this may be explained by the difference in history (burnt vs. non-burnt) and/or canopy cover.
- Subsidence rates are generally higher near canals, as water tables are lower there, however differences are not great nor consistent. Note that most subsidence poles are well away from the canals.
- A relation is apparent between subsidence and minimum water depth (Figure 3.11). No relation is found between subsidence rate and average water depth. This suggests that average water depth is probably a poor descriptor of the soil moisture regime that controls peat decomposition and subsidence, an insight that is also suggested by recent findings in other peatland studies.
- Accuracy of these subsidence measurements is limited, as subsidence appears negative at two locations, i.e. the peat surface appears to rise. This is attributed by CIMTROP staff to litter fall, indicating that apparently no fixed ‘ground’ plate is used as a reference level in these readings. This raises the

question to what extent litter fall affects the other readings. We conclude that these subsidence readings are more likely to underestimate than to overestimate subsidence rates.

To better understand these findings, we need to know more about the peat characteristics in the CIMTROP study area. It is understood that bulk density and other data for Block C exist at the University of Yogyakarta, but we have not been able to obtain those. However, for the purpose of extrapolating these findings to the greater EMRP area in the current project, the data may tentatively be interpreted as follows:

- Subsidence rate in highly-decomposed (sapric) peat in burnt and degraded peatland well away from canals, with high water tables, is at least 1 cm/y 10 years after drainage started. Where peat is less decomposed, unburnt, or has lower water tables, subsidence rate will be higher. However, as much of the EMRP area appears to be similar to the Block C area, we expect that current subsidence rate well away from canals is generally not more than a few cm/y (it must have been higher shorter after drainage).
- Subsidence rates under forest cover are less than half of what they are in degraded land, even when the difference in water table depth is not great. This suggests that direct solar radiation on the peat surface, causing high top-soil temperatures and low top soil moisture content, may be as important a control on peat decomposition as is water table depth (or rather soil moisture as controlled by water table depth).

3.5 Long-term subsidence record for Johor

A set of monitoring records over 28 years, for a drained peatland in Johor (Peninsular Malaysia), was published by Wösten et al (1997). This is probably the longest subsidence record for SE Asian peatland available in the public domain, and it provides valuable information on the development of subsidence rates in time. Averaged over the 17 records for separate subsidence markers, subsidence over 14 to 28 years after drainage implementation is found to be 4.6 cm/y, and subsidence over 28 to 36 years about 2 cm/y. The reduction in subsidence is extrapolated to the future, suggesting that at present (over 50 years after drainage was implemented) subsidence rates are expected to be below 2 cm /y.

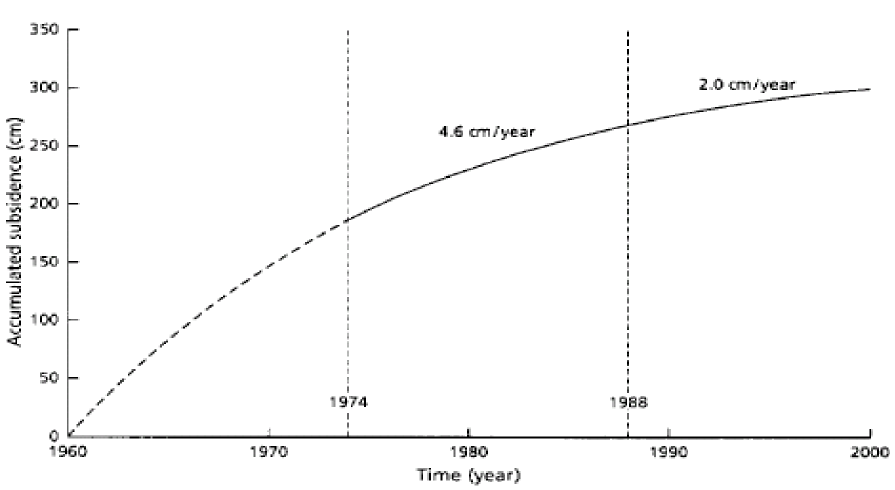
A curve of average subsidence over time in the Johor peatland area is presented in Figure 3.12.. While this curve provides valuable information, there are several uncertainties associated with this record:

- The 17 subsidence poles were placed in the early 1970s, hence the first 14 years of the subsidence record are estimated. It is possible that subsidence in the Johor area could have been higher than suggested by the graph, more similar to the subsidence rates now seen in Kampar Peninsula plantations.

- As other published peatland subsidence records in SE Asia monitoring cover only the first 10 years after drainage, and the Johor record covers the 14-36 years period, there is no overlap and it is difficult to relate this record to other records.
- The far higher subsidence known to occur in the first year after drainage, about 0.5 to 1m as caused by consolidation, may not have been fully accounted for judging from the shape of the curve. It would appear that the entire curve could be 'shifted up' by about 0.5m to accommodate for this, which would of course result in higher cumulative subsidence.
- A major variation in cumulative subsidence is reported for different subsidence poles, fairly even distributed between 0.23 m and 1.37 m over the 22 years (264 months) on record (Figure 3.13). This translates in average subsidence rates between 1 and 6 cm/y. This variation is presumably caused by variations in peat type and especially water depth.
- Subsidence rates from 1996 to 2000 have been extrapolated. The only subsidence pole in the area that actually continued to be monitored annually up to 2007 (Pt. Yassin, 1°44'35.07N, 103°18'06W, in palm oil plantation) appears to have had 1.06m subsidence since 1988, or 5.3 cm/y (data provided by MARDI through Dr Susan Page, September 2007). Only 4 other poles could be relocated in 2007, with a last measurement in 1990: they show values between 0.3m and 0.89m, which is well above 2 cm/y on average. It is therefore suggested that assuming a subsidence rate of 2 cm/y after 40 years of drainage may be conservative for this area.

Overall, it appears that the conclusions published on the Johor study may have been somewhat conservative, in other words there is a greater change that long-term subsidence rates in the Johor study area were somewhat higher than reported than that they would be lower.

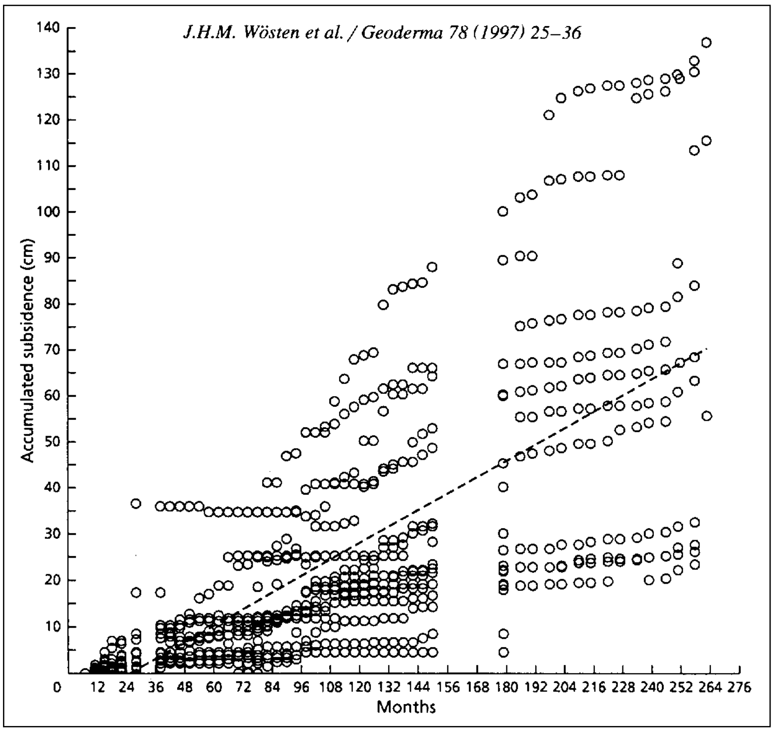
It is concluded that, while the shape of the subsidence reduction curve between 14 and 36 years can serve as a useful reference for other studies, caution is needed when extrapolating the absolute subsidence rates to other peatland areas.



J.H.M. Wösten et al. / Geoderma 78 (1997) 25–36

Fig. 3. Average subsidence versus time relationship for the project area as a whole.

Figure 3.12 Long-term subsidence record for drained peatland in Johor (Malaysia). This is an average over 17 records (Wösten et al, 1997).



J.H.M. Wösten et al. / Geoderma 78 (1997) 25–36

Figure 3.13 Subsidence over time for 17 subsidence markers in a Johor peatland (Wösten et al, 1997).

3.6 The 'subsidence is 10% of average water depth' rule

The Johor subsidence record was interpreted, in terms of a relationship between subsidence and water depth, as following (Wösten et al, 1997):

- Over the second 14 year period after drainage implementation, subsidence equals 9% of groundwater depth.
- Over the third 14 year period after drainage implementation, subsidence equals 4% of groundwater depth.

These numbers were later re-interpreted as a rule-of-thumb for the long term (Wösten and Ritzema, 2002), taking into account that subsidence over the first 14 years (which was not recorded) must have been higher than over the second 14 years:

- On average, subsidence equals 10% of groundwater depth.

This rule has been applied in several subsidence assessments (e.g. Hooijer et al 2006). While it is still may be the best approach for rapid assessments in areas where no local subsidence data are available, it should be noted that some significant uncertainties are involved:

- No consistent record was kept of groundwater depths in the Johor area; it is understood that groundwater depth observations appear to be absent in the first decades on record and limited in the latter years. The very significant variation in subsidence rates reported for different locations in the Johor peatland area (see above) suggest there may have been a significant variation in water depths over the period. It is understood that an average long-term groundwater depth of 0.6m may be assumed. However, this is an estimate and the data basis for deriving relations between water depth and subsidence is limited.
- Other parameters that are not accounted for by this relation also affect subsidence, including peat type, vegetation cover, fertilizer regime, mechanical compaction and soil management.

In an underlying technical report produced early on in the current EMRP Master Plan project, it was suggested that the ‘10% rule’ developed on the basis of subsidence data for a peatland in Malaysia may also apply to the EMRP area, on the basis of subsidence data collected in 2001-2002 in Block C of the EMRP area (section 3.4), but uncertainties are acknowledged (Wösten, 2008). In view of the findings reported in earlier sections of this report (notably sections 3.3 and 3.4), it has since been found that uncertainties in both water depth and measured subsidence rates are too great to apply the 10% rule in the EMRP area.

3.7 Tentative non-linear and time dependent relation between water depth and subsidence, as derived from the Kampar Science Based Management Support Project

The Kampar Science Based Management Support project (Hooijer, 2008), now ongoing in Riau, studies (amongst other things) the relation between water depth and peat decomposition (i.e. subsidence and CO_2 emission) in and around acacia plantations on the Kampar Peninsula peatlands. The project has the benefit of a dense monitoring network of dip wells, for groundwater depth and subsidence, parallel to a monitoring system for CO_2 emission. Part of the subsidence monitoring system has been functioning since 2003, providing a 5 years record of subsidence data and water depth, starting one or two years after drainage canals were constructed.

Although the Kampar SBMSP has only recently started, and results to date are highly tentative, and although the peatland under study there is very different from most EMRP peatlands (the peat being much deeper and less decomposed and the extent of the main peat dome being greater) some considerations for the Kampar Peninsula peatlands are valid for the EMRP peatlands as well.

On the Kampar Peninsula, subsidence rates over the first 5 years after drainage (excluding the first 1-2 years after drainage implementation) are in the order of 10cm/y. For most of this period, ground water depths at most locations have been below 1m; averages between 0.8 and 1.8 m have been estimated for different locations. These high subsidence rates, and the accompanying significant CO_2 emissions, have convinced the plantation managers that water depths need to be reduced. To optimize water depths, taking into account crop requirements and peat conservation requirements, insight in the subsidence rate and CO_2 emission resulting from water depths within 1m is required. It is found, however, that very little data exists for such water depths. In earlier assessments (Wösten and Ritzema 2002, Hooijer et al 2006), a linear relation was assumed to exist between water depth, subsidence and CO_2 emission. We know that, in reality, a non-linear relation must apply.

A first highly tentative assessment of such a non-linear relation was produced in the Kampar SBMS Project (Figure 3.14), for refinement when more data become available. Though crude, this relation is already an improvement over linear relations as it is a three-stage curve (or ‘S-curve’) reflecting some important aspects:

- When the depth of the groundwater table as measured in a dip well is only a few decimetres (0.1 to 0.4 metre, depending on peat type), the peat will in fact be saturated to the surface (through capillary action) and decomposition/subsidence rate will be very limited.
- When the groundwater table is deep enough to create an unsaturated zone, decomposition/subsidence rate will increase.
- When the groundwater depth exceeds a threshold, now though to be somewhere around 1 metre, further water depth increase appears to result in a limited further increase in decomposition rate. The cause and level of this threshold will need to be further investigated; investigations are ongoing.

The relation between groundwater depth and subsidence presented in Figure 3.14 is static. In reality, we know that this relation changes over the years as peat becomes more decomposed ('matures') and subsidence for a given water depth decreases. An approach has been tentatively developed that allows projections of future subsidence on the basis of current subsidence.

Based on the Johor record, cumulative subsidence curves were derived for different drainage depths. This was simply done by scaling the Johor curve (for which a groundwater depth of 0.6m is assumed; section 3.5), with a 'drainage depth factor'. This results in Figure 3.15. For example, a peatland site with a hypothetical average groundwater depth of 1.1 would have an average subsidence rate of 0.087 m/year, which is 1.1/0.6=1.775 times higher than the average subsidence for the Johor site (about 0.05 m/year over 40 years).

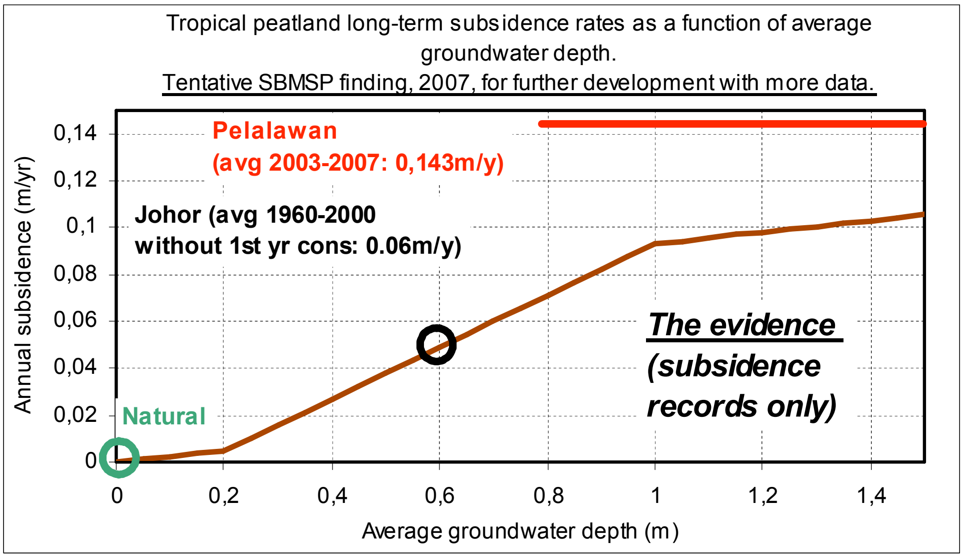


Figure 3.14 Tentative subsidence–water depth curve tentatively applied in the Kampar SBMS Project (from Hooijer, 2008). Note that this relation applies to average subsidence over the first decades after drainage. Also note that the water depth assumed for the Johor subsidence data is an estimate, as no measurements are available for that dataset. The very high subsidence rate observed at Pelalawan plantations in recent years applies to the early years after drainage is implemented, and are the result of drainage to 1.2m water depth on average over this period; this rate will be reduced in coming years as water tables are raised and peat matures.

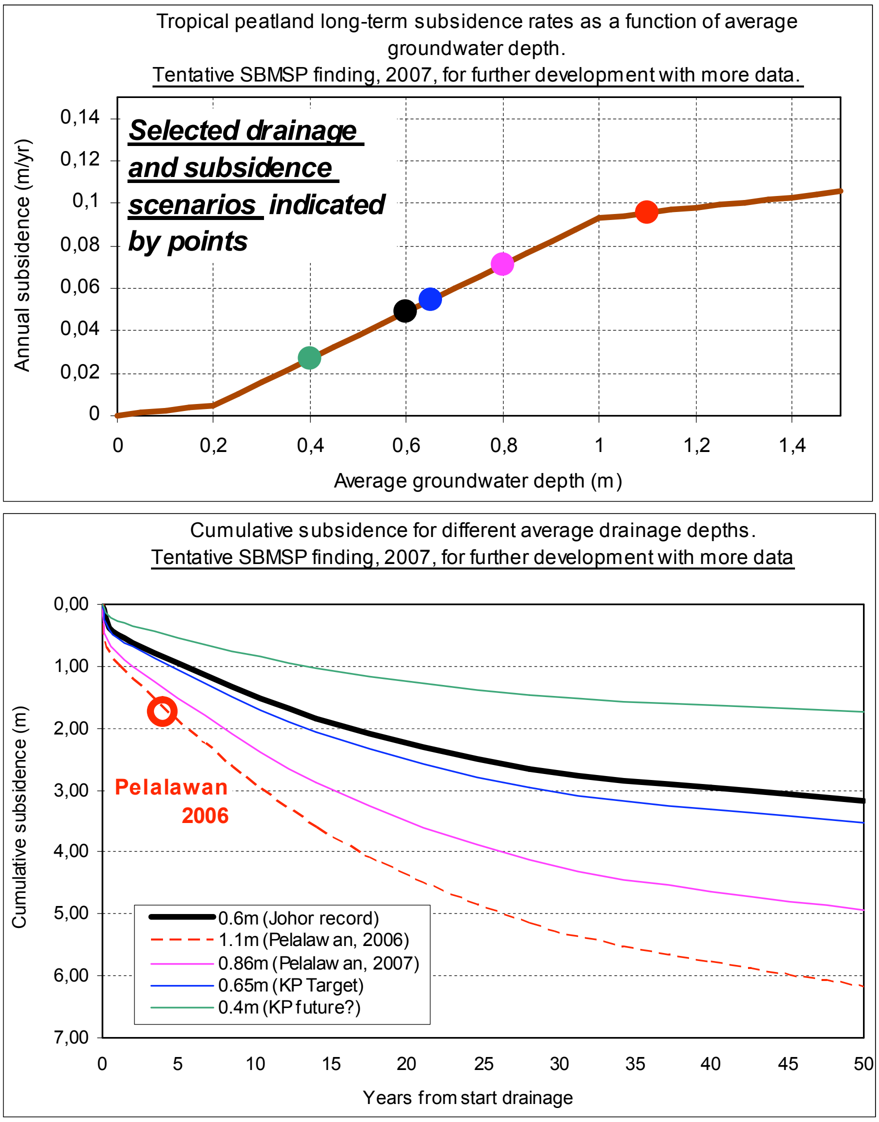


Figure 3.15 Tentative long-term cumulative subsidence for different average groundwater depths.

Long-term records are 'scaled' from the Johor 'base record' (see also Figure 3.12**), by applying relative subsidence rates for different management scenarios as derived from the water depth / subsidence relation shown above (note that point colours in the top figure correspond to line colours in the lower figure).**

4 Some considerations on determining peatland CO_2 emission

Carbon emissions, caused by peatland drainage leading to decomposition and fires, are a major driver for the international interest in improving management of Indonesia's peatlands including the EMRP area. For investments in peatland conservation and rehabilitation it will be crucial to be able to quantify the carbon emission benefits (in terms of avoided or reduced emissions relative to a baseline) of interventions. Tentatively estimating carbon emissions from the EMRP area under different management scenarios is therefore part of the EMRP Master Plan project.

There have been a few carbon emission studies for Indonesia as a whole to date, one of which has been the PEAT-CO2 study (Peatland CO_2 Emission Assessment Tool) (Hooijer et al, 2006). The approach followed for CO_2 emission quantification in this project is based on the PEAT-CO2 approach.

4.1 Measurement methods to determine peatland carbon emission

There are two main sources of CO_2 emission from drained peatlands: decomposition and fires. Both emission types occur in drained and/or degraded peatlands, and both can broadly speaking be quantified in two ways.

CO_2 emission from decomposition of dry peat soil, through biochemical breakdown, can be quantified in the following ways:

1. Gas emission chamber measurements at the plot scale. This has the advantage of yielding direct measurements relatively quickly. *The disadvantages are that it is difficult to distinguish between different sources (decomposition, root respiration), that it does not account for carbon uptake by vegetation, that the measurement applies to a single plot and a short period only, and that expensive and vulnerable equipment is required.*
2. Subsidence monitoring in combination with monitoring changes in peat soil characteristics (bulk density and carbon content) and possibly some checks on carbon removal in discharge (DOC). *The advantage is that these measurements are relatively simple, and that this provides an unambiguous number of the actual net amount of carbon lost from the soil. The main disadvantage is that*

monitoring over a number of years is required to get a meaningful figure.

The two methods both yield significant variation in emission numbers, linked to variations in peat type (more or less decomposed), water management (water depth; average and variation), land management (fertilizers, soil disturbance) and cover (exposure to sunlight). In intensively drained areas however, without specific water management measures to bring water levels up resulting in groundwater around or below 1m on average, there is some consistency: emissions as determined with both methods tend to be in the order of 50 to 150 t/ha/y CO_2 emission, and subsidence in the order of 0.1m/y at least in the first 10 years after drainage. It should be noted that this situation is currently not common in the EMRP area, where peatland drainage canals are mostly quite far apart and groundwater depths mostly far less than 1 m. The drainage has done great damage to the peatland system in terms of ecology and hydrology, and caused significant emissions, but emissions would be even greater if canals were closer together.

CO_2 emission from peatland fires, that also occur at a large scale in dry soils, can be quantified through two different methods:

1. By measuring the burnt area, the depth of the lost peat layer as well as the above-ground biomass carbon lost. *The advantage is that a rough yet unambiguous estimate can be obtained quickly using data that can be collected in the field using simple techniques soon after fires occur. Disadvantages are that all of the measurements required involve major uncertainties, and that the method does not work well for areas that are repeatedly burnt, as is common because burnt areas tend to be most fire-prone.*
2. By using satellite data on atmospheric CO concentrations in areas where fires occur, and translating these to CO_2 emission figures. *The advantage is that a number is obtained that applies to large areas, averaging out spatial variation. But this is also a disadvantage, as this emission estimate applies to large areas covering fires in peatlands as well as non-peatlands, emitting aboveground as well as belowground carbon and that the different sources van not be distinguished. Furthermore, significant uncertainties in the satellite measurements may be assumed.*

A third type of emission from drained peatlands, methane (CH_4) from canals and standing water areas in fire depressions, warrants further investigation. Methane bubbles are commonly observed in such areas. Absolute CH_4 emissions are likely be far lower than CO_2 but it is considered a much stronger greenhouse gas (23 CO_2 equivalents). A study into the significance of this emission source is ongoing in Riau (Hooijer 2008).

4.2 Assessing and projecting peatland carbon emissions for large areas

From the methods summary above it will be clear that accurately determining peatland carbon emission takes much effort and expertise, and that much spatial variation in emissions exists. As a result, such information is only available for a few sites in Indonesia, some of which are in Block C in the EMRP area. As it is unclear to what extent conditions in those sites are representative for the wider EMRP peatlands, and because knowledge on the relations between carbon emissions and controlling environmental parameters is limited as yet (although it is now being developed), the 'safest' and most transparent way to assess CO_2 emissions is still to deduce it from subsidence rate. This is the PEAT-CO2 approach; its application in the EMRP area is briefly explained in section 5.6.

It is expected that, with the new information now being collected in other projects, it will be possible to apply a more process-based and accurate approach to peatland CO_2 emission assessment in the near future.

5 Developing the Peatland Subsidence Scenario Assessment Tool, PSSAT

5.1 Introduction

From the above rapid assessment of different information sources on subsidence rates in the EMRP area, it is clear that there are major knowledge gaps to be filled before accurate subsidence modelling will be possible. Developing this knowledge should be a focus of further work.

However, whatever data is available for the EMRP peatlands does indicate that subsidence has been significant since they were drained, and has already significantly altered their hydrological functioning. The CO_2 emissions that accompany subsidence and fires must, therefore, also be significant.

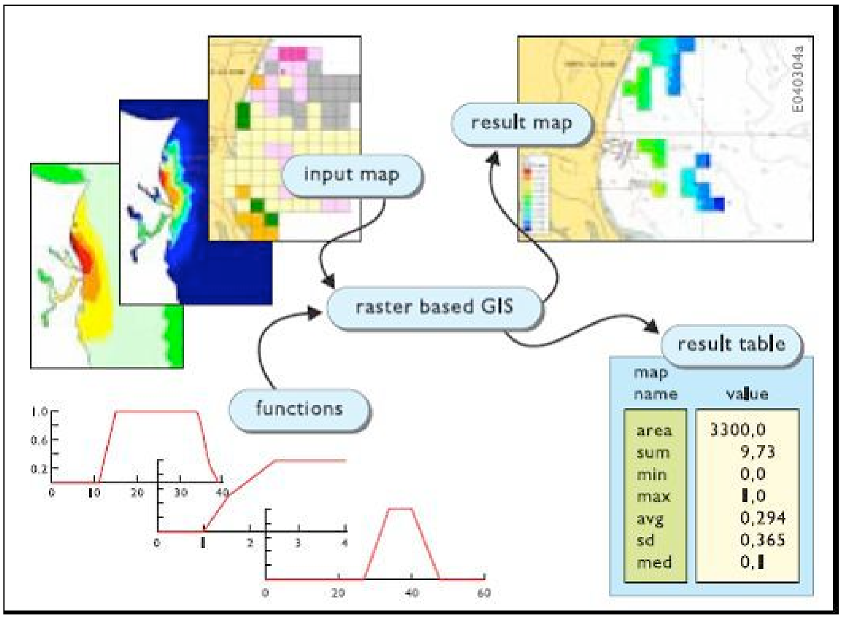
An effort has been made in the EMRP Master Plan projects to quantify future subsidence, hydrological impacts and CO_2 emissions in the area, as accurately as possible considering the data and knowledge limitations. The results presented here serve to give an indication of the magnitude of impacts, and to demonstrate these impacts in a format that is clear to decision makers and other stakeholders. However we estimate that the cumulative uncertainties involved in subsidence quantification, and therefore in quantification of flooding and CO_2 emission impacts, probably exceed 50%. The results can therefore not be used for detailed planning purposes, but they do provide a basis for development of general management strategies for peatlands, and for identifying knowledge gaps that need to be filled in further projects.

5.2 HABITAT spatial analysis tool

The PSSAT calculations were performed in the HABITAT platform. HABITAT is a spatial analysis tool developed to support spatial planning. The tool is developed by Delft Hydraulics and the Netherlands Ministry of Transport, Public Works and Water Management. It is a ‘shell’ around PCRaster, a software package developed at the University of Utrecht capable of advanced map-based calculations (Burrough et al, 2005, and http://pcraster.geouu.nl). It is used for all spatial analyses where grid operations are needed such as ecological assessments, flood risk maps or damages to agriculture or urban areas in case of floods and droughts. The two main advantages of HABITAT are that A) it provides a platform for model development without highly advanced programming skills from the user, and B) it helps the user to systematically follow the full cause-effect chain (see Figure 5.1).

The systematic approach demanded by HABITAT allows for an easy comparison of different strategies and a better understanding the ecosystem and its relevant steering variables. The tool applies knowledge rules to maps (grid cells), using data in different data layers and (if needed) adjoining cells over a specified distance. As the analysis is performed on maps, the heterogeneity of areas is taken into account.

HABITAT contains the Toolbox with decision rules. Rules developed for specific studies can be stored in this database, re-used and adapted for other studies in other areas.



map name	value
area	3300,0
sum	9,73
min	0,0
max	1,0
avg	0,294
sd	0,365
med	0,1

Figure 5.1 Schematic working process of HABITAT.

5.3 Decision rules for the assessment of long-term subsidence

Subsidence in the EMRP area, and its impacts in terms of flooding and CO_2 emissions, were calculated by applying decision rules to combinations of grid maps (100m resolution), in the HABITAT software platform. These decision rules are based on measurements, literature and expert knowledge as presented in the previous chapters. It should be noted that all decision rules developed so far are empirical, i.e. they serve to simulate subsidence as observed, but without taking into account the actual decomposition and shrinkage processes involved. The decision rules applied are based on assessment of subsidence rates in relation to water depth in the EMRP area (section 3.3), combined with a method tentatively developed for subsidence impact assessment for the Kampar Peninsula (section 3.7).

Decision rules were developed for the following calculation steps:

1. Assessment of drainage level, groundwater depth and long-term subsidence as a response to different management regimes.
2. Assessment of changes in peat depth and elevation.
3. Assessment of CO_2 emission.
4. Assessment of impact on drainability in response to subsidence.
5. Assessment of impact on flooding as a result of adjusted elevation.

To quantify the rate of peatland subsidence and CO_2 emission under given management strategies and scenarios, the subsidence of the peat is calculated. The subsidence is derived through the following steps:

- The drainage depth for a particular land use in a particular water management strategy is defined.
- This drainage depth is used to calculate groundwater depths in the areas surrounding plantations, transmigration areas and canals.
- Based on the groundwater depth and the time since the start of drainage, the subsidence rate and the new elevation and peat depth are calculated for all map cells. This is done in time-steps of 5 years.
- Where fires occur, they are assumed to occur once every 10 years, once every 20 years in plantations, and to burn away 0.5m of peat.

This following sections provide a description of the decision rules.

5.3.1 Decision rules for deriving drainage intensity and drainage depth from land and water management

Rules and maps of future drainage intensity and drainage depth are derived from insights in future land and water management, which is a combination of current land and water management (location of current canals) and of planned changes, i.e. plantation concessions (resulting in drainage intensification) or rehabilitation (resulting in drainage reduction).

The rules for drainage intensity and depth are as follows:

- New plantation concessions and transmigration are assumed to be densely drained, resulting in a uniform groundwater depth of 0.8 metre.
- In all land outside of concessions and transmigration areas, existing canals are maintained (as we know them, i.e. a number of smaller ones are not included). In the 'existing drainage' and 'maximum drainage' scenarios (see Chapter 6), canal water depths (relative to the surrounding peat surface) are maintained in coming decades. In the 'modified Inpres' scenario, canals are blocked at a fixed level (of 0.4 m at present) and canal water depth is then reduced a as subsidence proceeds.

5.3.2 Decision rules for deriving groundwater depth from drainage depth in canals

For each drainage canal or water management unit (plantation, transmigration area) the drainage impact is calculated for a zone around it (up to 7km away, assuming the impact of drainage will extend no further). For concessions and transmigration areas it is assumed that the areas will be drained with such a density of drainage canals that the groundwater depth is equal to the drainage depth in canals. For modelling of the subsidence we have used an indicator of canal water depth in the dry season (as this period is most important for subsidence, and as we only have data for that period): the average of all canal water depths as measured in the period of July-August 2007 (section XX). It would be better to differentiate between canals of course, which can have quite different water depths, and to have a measure of average water depth in time, but such data are not available at present.

The drainage level is defined as the depth of the surface water table in the canal relative to the surface level at 1 km from the canal or plantation boundary. Based on measurements of groundwater depths below the surface along 20 transects in the EMRP area (section 3.3), the relation between the drainage level and the groundwater depth at different distances from the drainage canal is calculated by multiplying the drainage level with the so-called groundwater factor which is a function of the distance to the drainage canal. The relation between the groundwater factor and the distance to the drainage canal or plantation boundary is presented in Figure 5.2. The groundwater depth in the surrounding areas is then calculated through:

$$GroundwaterDepth = DrainageLevel * GroundwaterFactor$$

When two or more canals or plantations influence a cell, the lowest groundwater depth is taken (driest conditions).

An example of a result of this decision rule is presented in Figure 5.3.

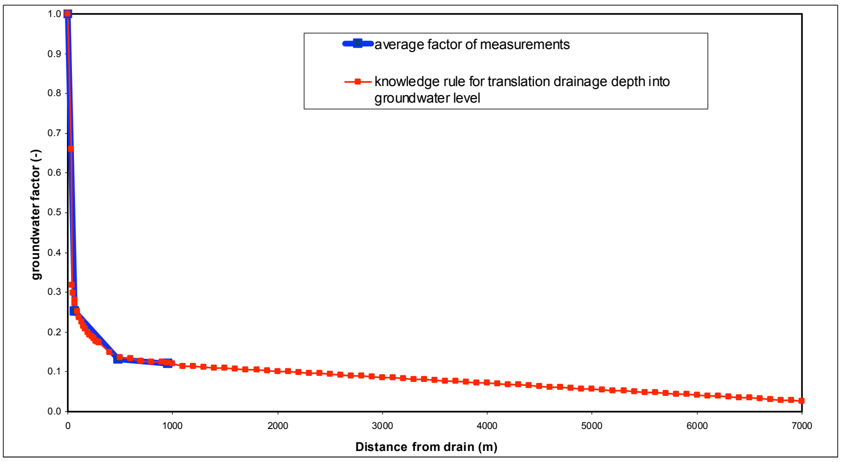


Figure 5.2 Groundwater factor representing the relation between the drainage depth in canals on surrounding groundwater depths below the peat surface. The blue line is the average measured factor in 20 transects and the red line indicates the knowledge rule as applied in the modelling. Note that in model calculations, to limit processing time, the effect of the drainage has been assumed to be negligible (i.e. null) at 7 km from canals.

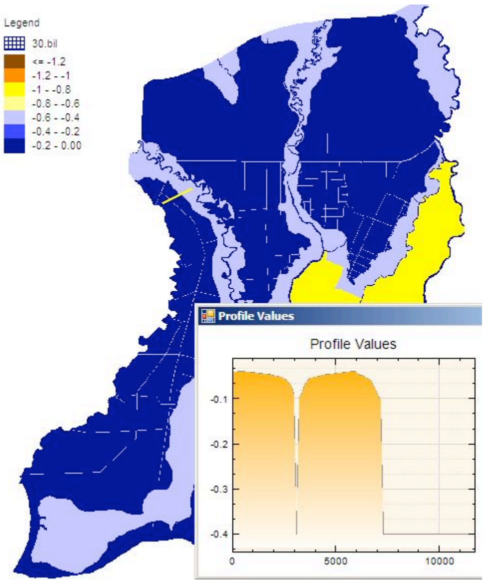


Figure 5.3 Example result of groundwater level decision rules, including a profile figure along the indicated transect in Block C. The profile graph presents the groundwater depths along the yellow line.

5.3.3 Decision rules for subsidence calculation based on groundwater depths

Soil surface subsidence in peatlands is simulated as a function of drainage depth (which is a proxy for soil moisture content, which actually controls peat decomposition), the period after the start of the drainage as the peat matures, and peat type. A second cause of subsidence of the peatland surface is peat loss due to fire, which is influenced by drainage conditions as well (as wet peat does not burn). Decision rules for both subsidence drivers are presented here.

Subsidence due to drainage

When the groundwater depth for a peatland is estimated, the subsidence rate 5 to 10 years after drainage can be tentatively estimated from Figure 3.14. It is then possible to identify the change in subsidence in time using the following equations derived from Figure 3.15, which scales the original curve established for Johor peatland (Figure 3.12) for different water depths:

$$TimeSubsidence = 0.1429 * \exp(-0.0455 * Year)$$

GWDSubsidenceFactor = from GWD and Figure 3.14

$$SubsidenceRate = TimeSubsidence * GWDSubsidenceFactor$$

The outcome of these equations for a number of ground water depths is presented in Figure 5.4.

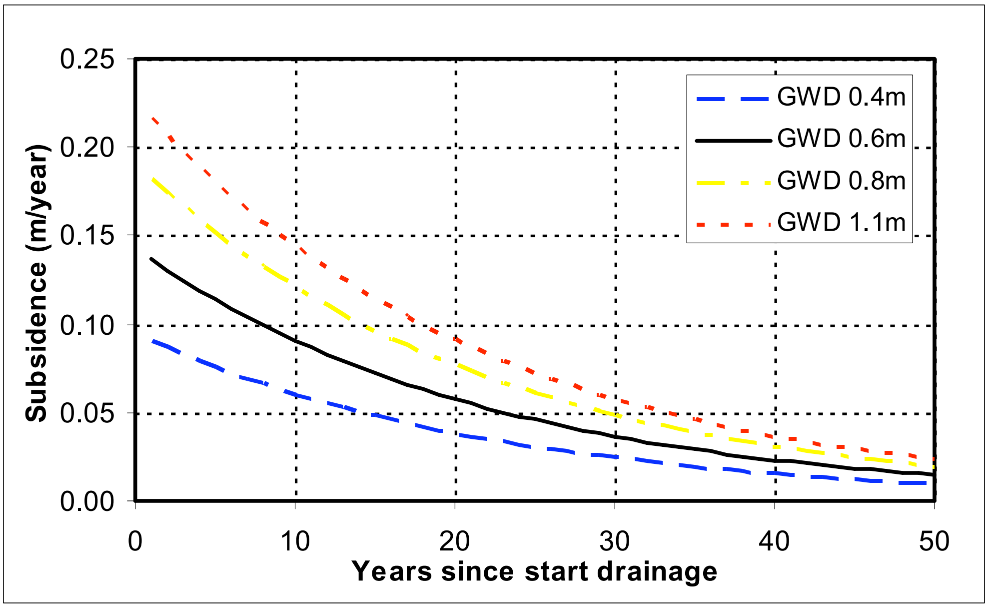


Figure 5.4 Tentative subsidence rate curves for different ground water depths (GWD), derived from the relation with GWD (Figure 3.14) and the long-term cumulative curve for Johor peatland (Figure 3.15).

Besides groundwater depth and recent peat maturation caused by drainage, the original peat type also influences the subsidence rate. More humified peat, which has already underground more decomposition in past centuries, now has a lower decomposition rate for a given groundwater depth.

As we know that the peat in much of the EMRP area is more humified than the peat in the Johor and (especially) Riau sites where our subsidence relations are derived from, the subsidence rate for the EMRP area needs to be corrected for this difference in peat type. A correction factor of 0.7 is derived from calibration with the measured transects in the EMRP area.

The potential subsidence rate due to drainage is then calculated as:

$$SubsidenceRate = SubsidenceRate * 0.7$$

One additional subsidence component that has to be accounted for is the lowering of the peat surface due to peat consolidation, which occurs at a high rate in the first year after drainage (in subsequent years it is now lumped with subsidence due to shrinkage and decomposition).

Based on a tentative estimate for the Kampar Peninsula study sites (section 3.7), the subsidence for the first year is assumed to be a linear function: 0.9 m at the canal side and 0 m at 3 km from the canal. This rule is only applies for the scenarios where new drainage is implemented in Block E. The other EMRP peatlands have been drained already and therefore the initial rapid consolidation phase is not included in forward-looking subsidence projections. Subsidence for this first year is calculated as follows (for cells up to 3km from canals and plantation boundaries):

$$ConsolidationSubsidence = -0.0003 * Distance\ from\ Canal\ (m) + 0.9$$

Estimation of subsidence due to fires

Besides drainage, fires are another major cause of subsidence. One fire event may result in a peat loss of 0. 2 m (Jaya, 2005), which we include as subsidence in this assessment. The drivers of peat fires are not understood well enough to model them in knowledge rules. There is a relation with the:

- groundwater depth: if the water level is at surface level the chance on fire is low,
- population / points of access: the probability of fire is higher where there are more people,
- fire management: the better the fire management in terms of public awareness, enforcement of 'no-burning' laws, presence and preparedness of fire brigades etc., the lower the chance on fire.

In the current subsidence tool an indication of the effect of fire is given in order to get an idea of the sensitivity in relation to the water management driven subsidence (without claiming accuracy for the resulting subsidence figure).

The assumption is that degraded and unmanaged areas close to canals will burn once in every 5 years, and that 1 fire will result in a subsidence of 0.2 m (Jaya, 2005); this results in an additional subsidence (*FireSubsidence*) of 0.04 m/y.

Data from CARE Indonesia (Figure 5.5) show a clear relation between fire frequency and distance from the canals. We have combined this with findings of Jaya (2005) to prepare a decision rule for the relation between subsidence rate due to fire and distance to canals. for the first kilometre the rate is kept constant at the 0.04m/y based on Jaya (2005). Further away from the canal the rate decreases based on the relationship in Figure 5.5 according to the formula:

$$FireSubsidence = 0.04 * 287881 * Distance2Canal^{-1.3403} / 57$$

This results in the relation presented in Figure 5.6.

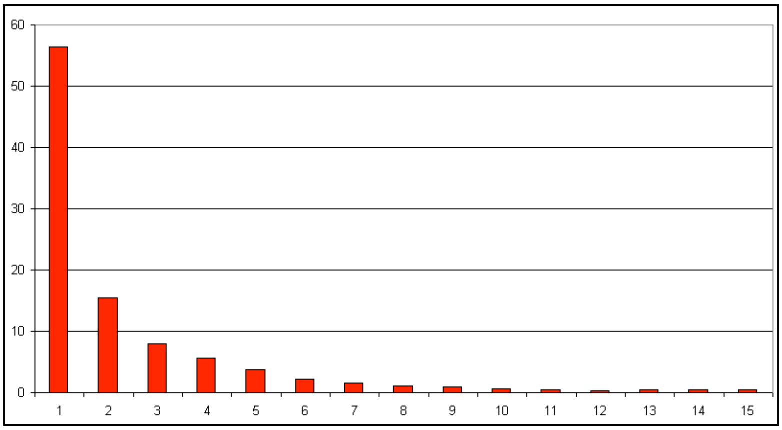


Figure 5.5 Relationship between frequency of fires and distance from canal / river for the period 2002-2006 showing that most fires occur within 1-2km of a canal. *Source*: CARE Indonesia.

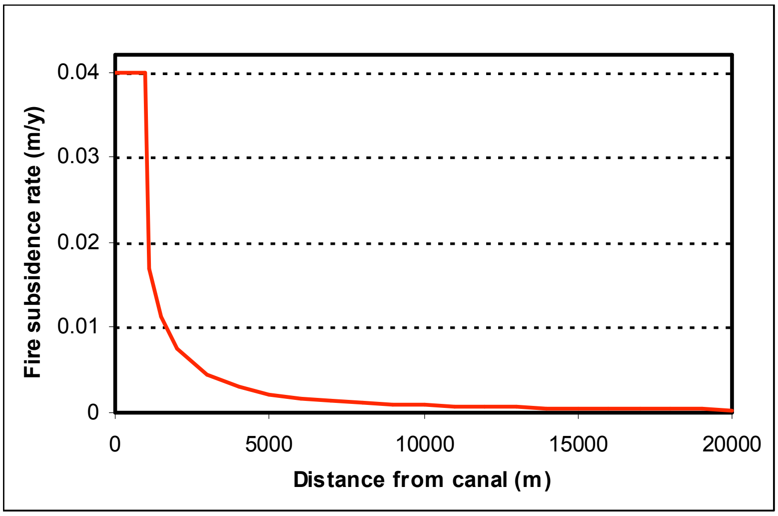


Figure 5.6 Relationship between subsidence rate due to fire and distance from canal

In plantation areas the frequency of fire is assumed to be less because of fire management, namely 1 in 10 years resulting in 0.2 m of subsidence; this results in a subsidence rate of halve that for degraded and unmanaged areas, e.g. near canals 0.02 m/y. In conservation and rehabilitation areas, where groundwater should be more or less as in natural conditions, it is assumed there will be no fires in the future (despite the fact that fires have been common in recent years).

5.3.4 Subsidence calculation steps

The subsidence is calculated in time steps of one year. Over each time step, the total maximum subsidence for each map grid cell is calculated as the annual subsidence rate for the given water depth and the given land use.

Once the total maximum subsidence is calculated, it is checked whether this does not exceed the limits imposed by the natural system. The limits are A) the depth of the peat deposit, below which subsidence is assumed not to continue, and B) a minimum gradients towards the drainage base (rivers and sea) that is required to allow drainage of each cell. It is assumed that once peatlands can not be drained anymore (by gravity, without pumping), they will automatically become very wet and subsidence will be strongly reduced. The minimum gravity drainage gradient applied in the current assessment is 10 cm/km, which is a drainage engineering ‘rule of thumb’.

These subsidence limits are expressed in a ‘Minimal DEM’, representing the lowest elevation model that can result from continued subsidence up to the natural system limits. Feedback mechanisms resulting from management adaptations (especially abandonment of plantations once drainage becomes problematic) are not accounted for.

This ‘Minimum DEM’ is calculated from the original DEM, the peat depth model, and the median river water level in the dry season (June to November) in the period November 1983 to February 2008, derived from SOBEK simulations. For each grid cell the nearest point in the river is determined. The difference in water level between the grid cell and the river is calculated by multiplying the distance with the minimum slope of 10cm/km. This is added to the median dry season water level of the nearest river point to obtain the “minimum elevation”. This results in the DEM presented in Figure 5.7.

The calculated groundwater level (see Section 5.3.2) is also limited to this ‘Minimum DEM’, since ground water level cannot be lower than the minimum DEM based on the drainage criteria descried above.

For the situation including subsidence due to fire, a lower minimal DEM is used as fires occur in the extremely dry conditions and can in principle remove all peat up to the drainage base level. The 'Minimum DEM' including fire impacts is derived from the original DEM, the peat depth model, and the modelled minimum river water levels as calculated for the extremely dry period between October 15 and November 1 1997. Gradients of 10 cm/km towards rivers are calculated as above. The result is presented in Figure 5.7

For each time step the subsidence is then derived through the following formulas:

If drainage starts in this time step:

*DrainageSubsidenceRate = SubsidenceRate * 4+ ConsolidationSubsidence year 1*

else:

*DrainageSubsidenceRate = SubsidenceRate * 5*

*PotentialSubsidencerate = DrainageSubsidenceRate + FireSubsidence * 5*

ActualSubsidenceRate = minimum (PotentialSubsidenceRate, PeatDepth, (DEM-DEMminimal))

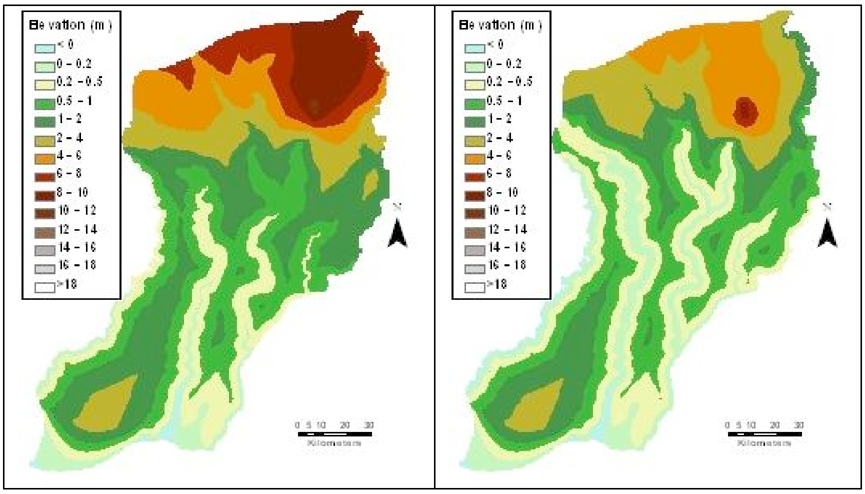


Figure 5.7 'Minimum DEMs', beyond which subsidence can not proceed, without fires (left) and with fires (right).

5.3.5 Decision rules for the assessment of peat depth and elevation

For each time step of 5 year the peat depth and a new elevation model (DEM) is calculated with the following formulas:

Peatdepth (year x) = peatdepth (year x-5) – subsidence (year x)

Elevation = elevation (year x-5) – subsidence (year x)

For each time step a new DEM with and without the subsidence due to fire is calculated. These DEMs are then input for further calculations.

5.4 Verification of decision rules for subsidence

The outcome of application of decision rules for the assessment of the subsidence was verified against the original measurement from which the decision rules were derived: the average peat surface slope and water level over 26 transects perpendicular to canals in the EMRP area in July/August 2007.

This verification serves to check if the decision rules were correct insofar that they could replicate the source data. This is not a full calibration of the subsidence model of course, for which we would need to compare model outputs with long-term time series of subsidence (and water depths) in the EMRP area, as such records are not available.

For a hypothetical peatland with a horizontal starting surface, groundwater depth and subsidence was modelled for the 10-year period 1997-2007. This period starts (more or less) with onset of drainage of the area, and ends with the elevation survey of 2007. The comparison was done following the next steps and assumptions:

- For each transect the original surface elevation was reconstructed by taking the highest elevation in the transect and adding 50cm to account for subsidence since the start of the drainage. For the points within 3km of a canal, the estimation of the initial consolidation as described in section 5.3.3 was added to the measured elevation
- The drainage level was taken from the measurements and is the difference of the water level in the canal and the surface level at 1000 m from the canal.
- The groundwater level was modelled according to the formula in section 5.3.2 with the drainage level as input. The function of Figure 5.2, which is used for this calculation, is based on the average groundwater level from 26 transects (see Figure 3.7).
- The subsidence for the first year after the start of drainage was calculated according to the formula for initial consolidation in section 5.3.3. This subsidence was subtracted from the assumed original surface level to achieve the modelled surface level after one year of drainage.
- The subsidence due to drainage for year 5 and 10 was calculated with the formulas in sections 5.3.3 and 5.3.4
- The correction factor for the subsidence rate was used as calibration parameter, which was finally set on 0.7.

The verification of model results against measurements is presented in Figure 5.8.

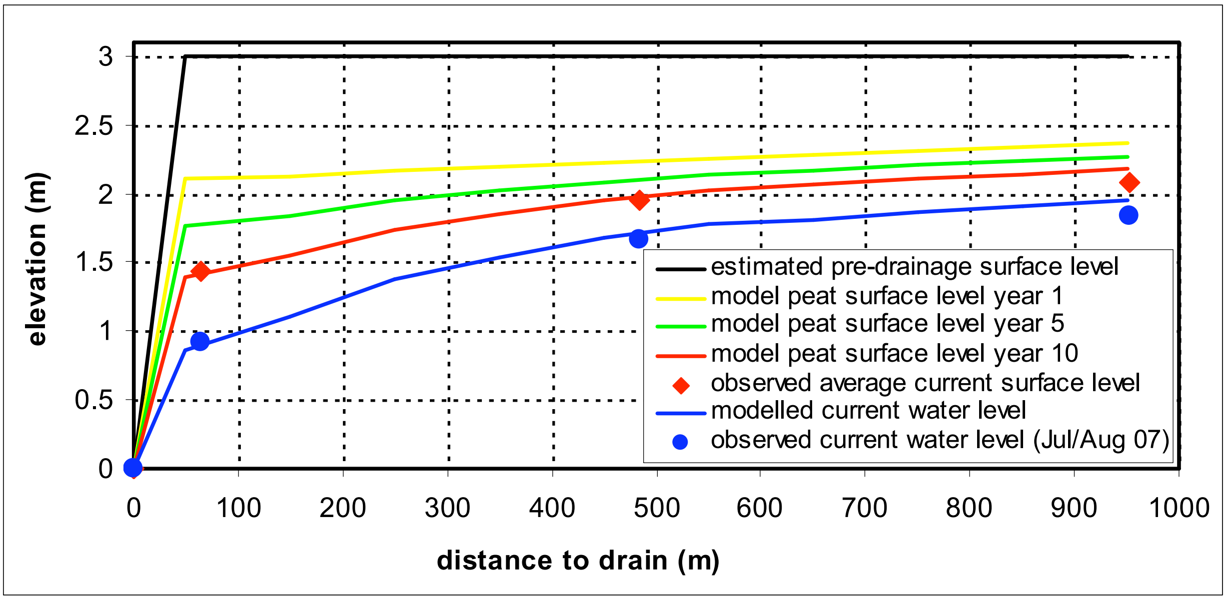


Figure 5.8 Verification of decision rules for subsidence (due to decomposition alone, without fires), for the average current (July/August 2007) measured peat surface and water level along 20 transects perpendicular to canals.

5.5 Decision rules for the assessment of drainability and potential flood risk

5.5.1 Drainability

For our tentative estimation of peatland drainability, we have assumed that any part of any peatland can be connected to the nearest rivers by straight canals. Therefore, drainage slope could be determined by searching the nearest river cell from each peat cell, finding the optimum drainage slope.

As in reality it is not possible to connect each peatland to the best drainage base, actual drainability of the area, now and in the future, may be worse than simulated.

To derive an idea of peatland drainability, now and in the future, slope maps are classified with this index:

< 10 cm/km (0.01 %)	*severely inundated*
10-20 cm/km (0.01 - 0.02 %)	*frequently inundated*
> 20 cm/km (0.02 %)	*infrequently inundated*

The slope thresholds of 10 and 20 cm/km are ‘rules of thumb’ applied in drainage engineering. Common wisdom is that drainage requires optimization of the drainage system and intensification of maintenance when surface water slopes in canals are below 20 cm/km, and drainage becomes very problematic when slopes are below 10 cm/km.

5.5.2 Potential flood risk map

For the Flood risk map the maximum river water levels in the period November 1983 – February 2008 have been interpolated between the rivers and combined with the DEM.

Land that is below the highest interpolated river water levels is considered to be potentially at risk of flooding. It should be noted that this method overestimates the total potential flooding extent, as potential water levels in any cell will depend on whether other cells upstream of it are flooded as well. The river water levels used apply to the current situation, where peatland subsidence has only yet resulted in limited increase in the potentially flooded area. As a larger area gets flooded by river water in the future, the river discharge volume will be spread over a larger area and flood levels will be lowered. The potential flood risk should therefore be seen as an absolute maximum, probably not very likely to occur in practice. However the more accurate modelling of present and future flood extent using the SOBEK 1D-2D flood model (see EMRP Master Plan Hydrology report) shows that the potential flood risk results do indeed overestimate flood depth and extend, but that they accurately indicate the general areas where flood risk will increase in future.

5.6 Decision rules for the assessment of CO_2 emission

The CO_2 emission is calculated from subsidence using the following formula:

*CO_2 emission per grid cell = ActualSubsidencerate (m) * cellarea (m2) * bulk density (g/m3) * 60% (part of subsidence due to oxidation) * carbon content (50%) * 3.667*

For the bulk density a value of 0.15 g/m3 is taken as indicated by measurements (see section 3.1). The value of 3.667 is used to convert the values from C to CO_2 emission. In case of subsidence due to fire 100% of the soil is oxidised (instead of 60%).

The initial consolidation taking place in the first year after the start of the drainage is mainly due to shrinkage and not to peat decomposition. Therefore, subsidence due to initial consolidation does not contribute to CO_2 emission and has been subtracted in the above decision rule for CO_2 emission from the actual subsidence rate.

6 Results of subsidence scenario modelling; PSSAT application

Cluster 3 has provided input to development of the overall land use scenarios for the EMRP Master Plan, by helping develop the scenarios and by demonstrating their long-term impacts on the physical environment of the area. The Peatland Subsidence Scenario Assessment Tool (PSSAT), described in the previous section, was the analysis platform.

The impacts of 3 land and water management scenarios over the coming 50 years, in terms of subsidence, hydrology (drainability, flooding) and CO_2 emissions, were calculated as presented below.

The scenarios were selected to demonstrate the ultimate effects of 3 extreme planning and management strategies: changing nothing to the current situation, maximize drainage i.e. implementing all currently planned plantation concessions and transmigration schemes, or end drainage in all peat and forest conservation areas designated in the Inpres.

The impacts demonstrated here are relevant in economic terms: reduced drainability and flooding have direct impacts on agricultural sustainability prospects in the area, while CO_2 emissions present a negative value on the global carbon market. There are further impacts, such as ecological degradation (as areas get increasingly flooded). It should be noted that any impact assessment will be highly tentative at this stage, considering the lack of field data and the need for process-based (rather than empirical) subsidence modelling.

With the Peatland Subsidence Scenario Assessment Tool three management scenarios (or strategies) were modelled and analysed for their effects on soil subsidence, peat depth, CO_2 emission, flood risk (risk on flooding from the rivers) and inundation risk (risk on inundation by rain water due to lack of drainability).

6.1 Subsidence scenarios for the EMRP

The following EMRP management scenarios were examined:

1. **Existing drainage** (reference) scenario: the current drainage canals are maintained at a drainage depth of 2 m. If the

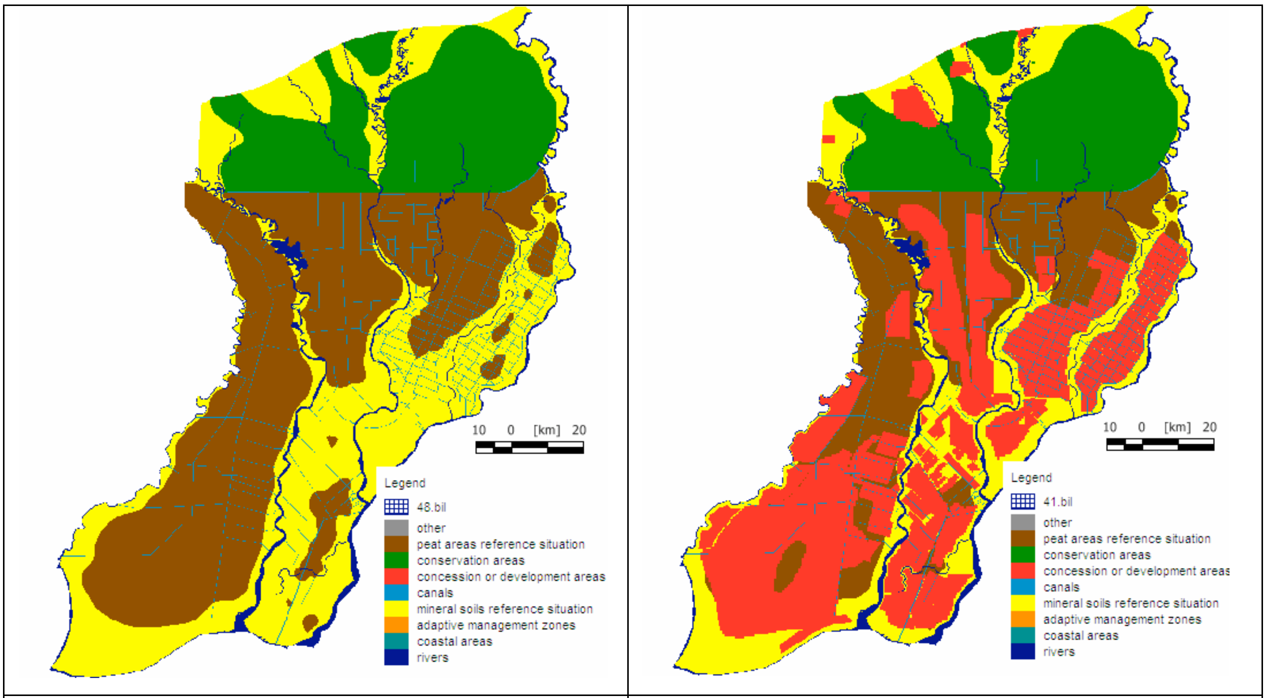
subsidence results in lower drainage depth, the drainage depth is adapted. In the adapted management zone it is assumed that a dense drainage system keeps the groundwater depth at 0.4 m on average. In these areas the drainage depth is adapted after soil subsidence. In the development zones a dense drainage system keeps the groundwater levels at 0.8 m. Drainage levels are adapted after subsidence. There is no extra development of plantations and transmigration schemes.

2. **Maximum drainage** scenario: all known plantation concessions and transmigration plans are implemented. For both it is assumed that a dense drainage system will be implemented resulting in average groundwater depth of 0.8 m. For the currently existing drainage canals in the remaining areas a drainage depth of 2 m is maintained. Drainage depth is maintained at this level, meaning that the canals will be deepened further after subsidence. In the adapted management zone a drainage level of 0.4m is maintained and in the development zone a level of 0.8m.
3. **Modified Inpres** scenario with maximum conservation area and minimum drainage: for the conservation zones a water depth of 0.4 m is implemented in the current drainage canals. The drainage depth is not adapted after soil subsidence, resulting in a diminishing drainage depth after subsidence. In the adapted management zone a drainage level of 0.4m is maintained and in the development zone a level of 0.8m.

As a description of the current situation it has been assumed that the adapted management and development zones have the same drainage status now as under the modified Inpres scenario. This is used as a minimum drainage level for the other scenarios, since no more accurate description of current drainage status is available.

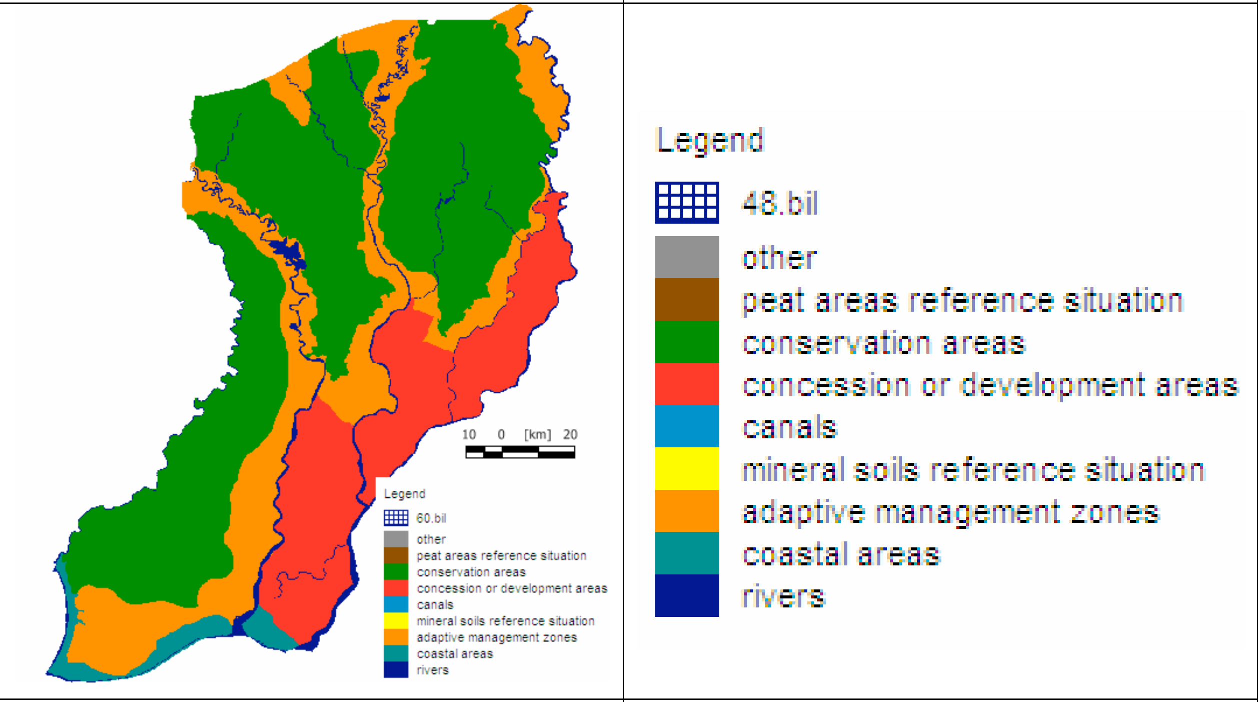
The long-term impacts of each of these scenarios have been evaluated with and without the effects of fires, and over 25 and 50 years.

Figure 6.1 presents the land use maps for the different management scenarios.



Existing drainage (reference) scenario

Maximum drainage scenario



Modified Inpres scenario with maximum conservation area and minimum drainage

Figure 6.1 Land use maps for the three scenarios.

The land use and water management scenarios described above result in different distributions of groundwater depths and consequently also in different soil subsidence and CO_2 emission. The initial groundwater depths are presented in Figure 6.2.

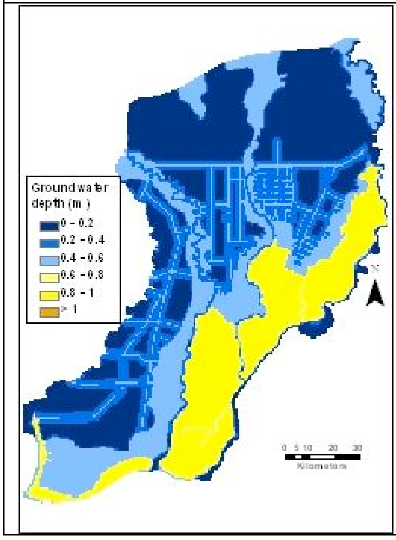
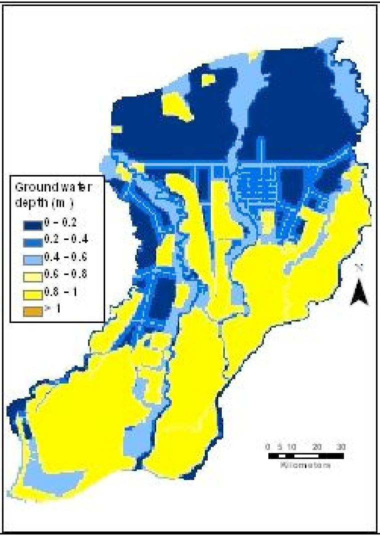
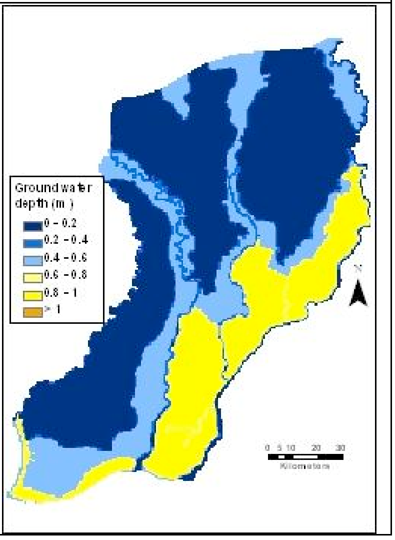
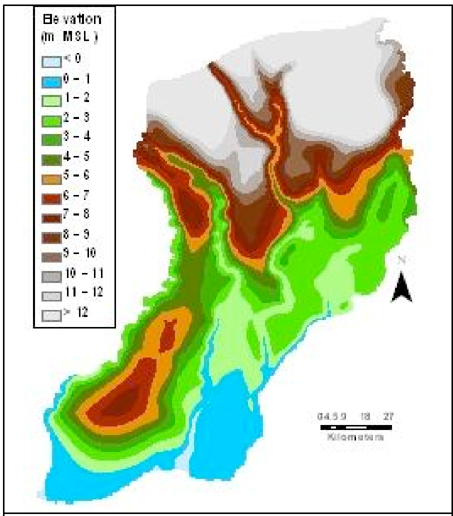
existing drainage scenario	maximum drainage scenario	modified Inpres scenario
		

Figure 6.2 Initial groundwater depths (in meters) for each scenario.

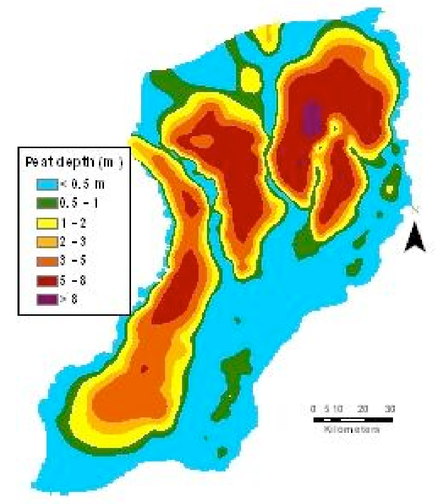
6.2 Input maps to EMRP scenario assessment

In the subsidence, drainability, flood and CO_2 emission modelling the following digital input maps were used:

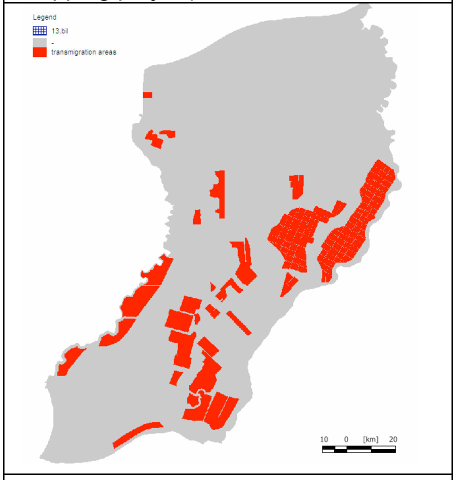
1. DEM
2. Peat depth
3. Planned transmigration areas
4. Concession areas
5. Main rivers
6. Maximum water levels, average dry season water levels and minimum water levels between October 15 and November 1, 1997, in main rivers and sea, calculated by SOBEK
7. Management zone map
8. Existing drainage canal map
9. MRP (Mega Rice Project) zones map



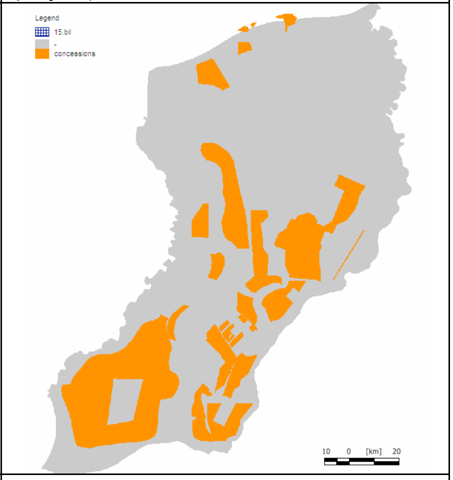
Digital Elevation Model (modified in Master Plan project from CKPP mapping project)



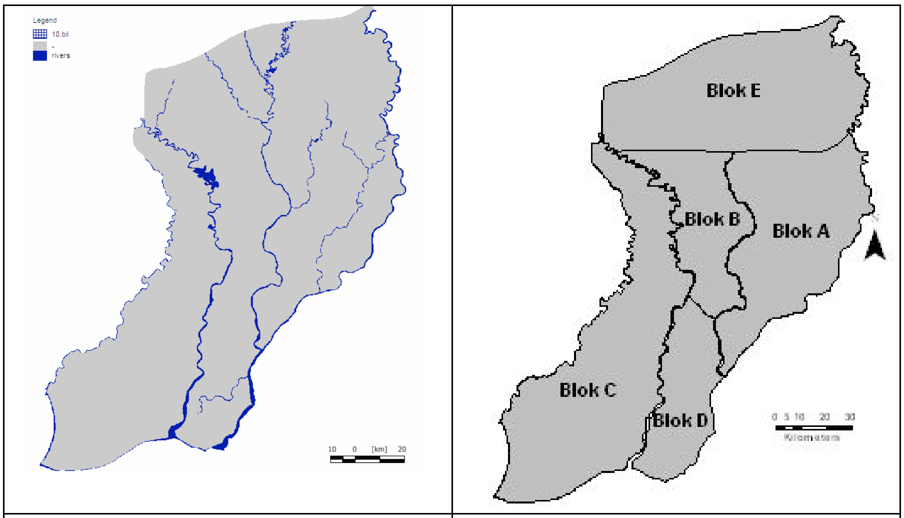
Peat Depth Model (modified in Master Plan project from CKPP mapping project)



Planned Transmigration areas (Bappeda and other sources)

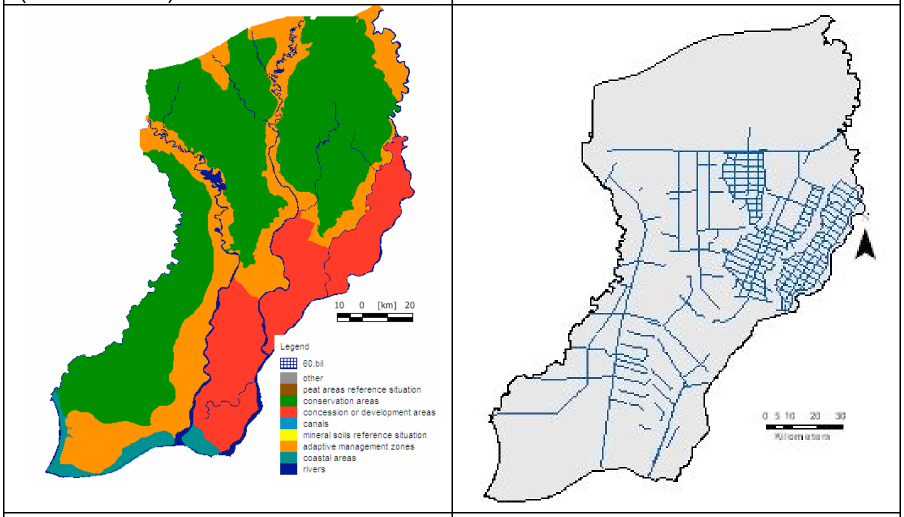


Planned Concession areas (Bappeda and other sources)



Main Rivers (Bakosurtanal)

MRP zones



Management zone map with Conservation zones (EMRP Master Plan outcome)

Existing Drainage Canals (Bakosurtanal)

Figure 6.3 Input maps to EMRP scenario assessment.

The peat depth map has been modified in this project from the results of the CKPP Mapping Project based on new data. The map and its constraints is more fully described in the Cluster 3 report. The accuracy and reliability of the map is limited by the spatial extent of available data, their accuracy and reliability and the nearly complete lack of data for Block E. Peat depths described for Block E should therefore be interpreted as highly tentative.

6.3 Scenario assessment result maps

The results of the scenario analysis are presented is the following figures. Both the results including and excluding subsidence due to fire are presented as the decision rules on fire are very uncertain. The first set of figures present the DEM in the current situation, after 25 years and after 50 years.

The maximum drainage scenario results in the largest subsidence. After 50 years only patches of peat are left in the EMRP area (except for block E). This may be an underestimation as the subsidence decision rules should be further improved by taking into account the maximum possible slope of peat (see section on further improvements). Also after 25 years a lot of the peat is gone. The same accounts more or less for the existing drainage scenario: much of the peat is gone, but the patches which are left have a larger peat depth than in the concession scenario. The maximum drainage scenario causes the largest effects as the drainage pattern is very dense, but the existing drainage scenario results in a significant subsidence as well as the water tables in canals remain at below 2m below the peat surface (which is rare in most plantations).

In the modified Inpres scenario subsidence occurs mainly close to the drainage canals, like in the reference scenario, but the drainage levels are not adjusted after subsidence in the conservation zones. Because of this the subsidence diminishes fast and after 10 years the subsidence is only visible in an area close to the canals. After 50 years the subsidence stops as the surface level is more or less equal to the water level in the canals. Most of the peat is saved in the conservation zones.

The CO_2 emission due to drainage is highest in the concession and transmigration zones and close to the canals. The dense drainage pattern in part of Block A results in relatively higher emissions.

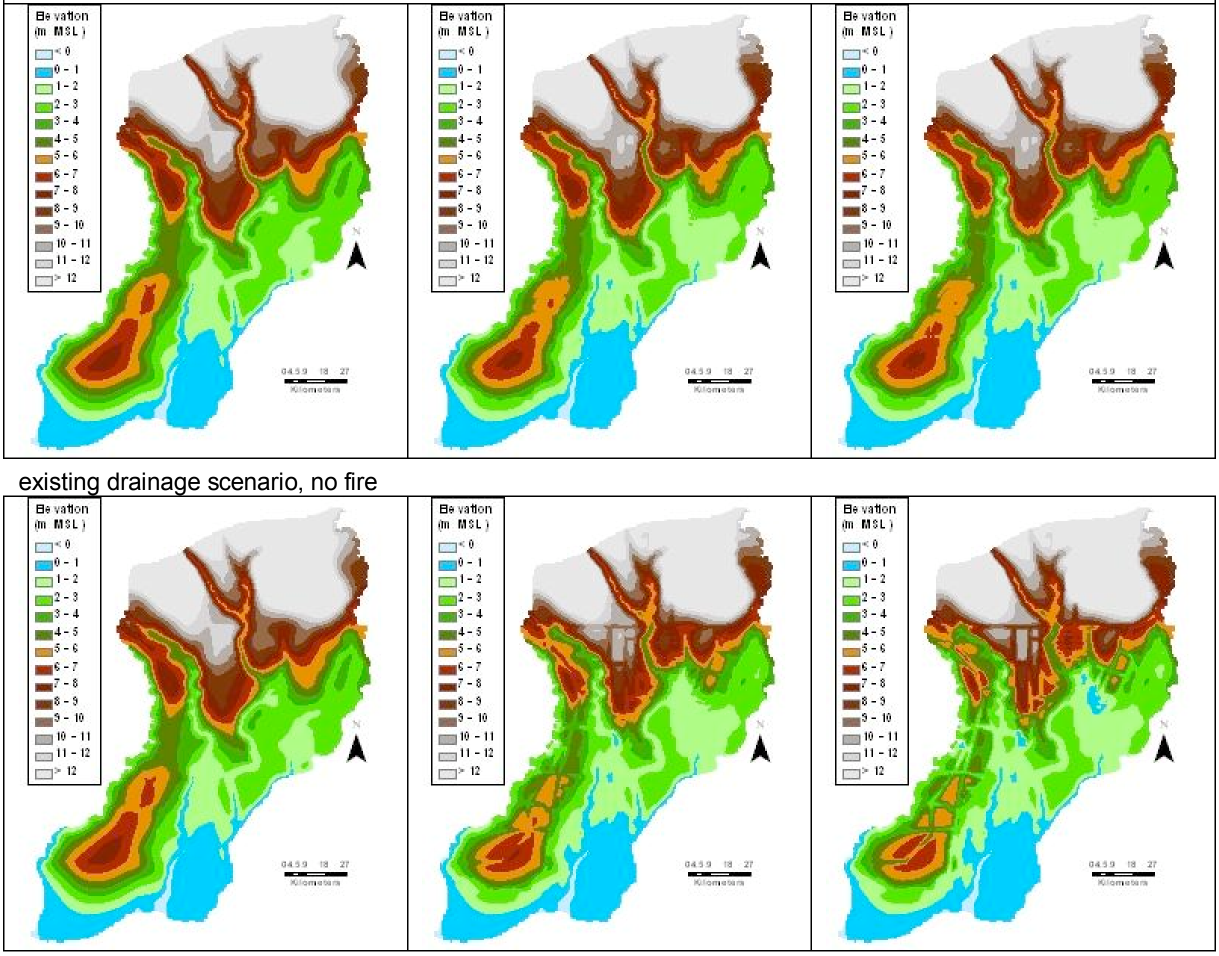
The CO_2 emission diminishes over time as a result of peat depletion, especially after 25 years and in the scenario’s which include fires. In the modified Inpres scenario the emission is larger in the first years compared to the other scenarios and to other areas. This is caused by the initial large subsidence when the sort of pristine peat area is drained for the first time. Although the drainage depth is less in concession and transmigration areas than in the reference situation, the dense drainage pattern resulting in a lowering of the groundwater levels in large areas causes a much higher CO_2 emission than in the reference scenario.

Subsidence may cause a higher frequency of inundation due to a lack of drainability. A steep slope makes it easier to drain the area and discharge water to the rivers via canals, while it is more difficult to discharge water under gravity to the rivers in areas with a gentle slope, resulting in frequent inundation after heavy rain. In the existing drainage scenario this occurs at the borders of block A and C after 25 years, while after 50 years large areas of this block may be frequently to very frequently inundated.

Effects are much more severe in case of the maximum drainage scenario. In the modified Inpres scenario the effects are limited to the south and eastern part of block C and eastern borders of block A.

Besides flooding from rainwater, flooding from river and seawater may increase with lower surface levels. In the modified Inpres scenario the flooding stays more or less the same. There is not much difference between the existing drainage and the maximum drainage scenarios. After 50 years large areas will be frequently flooded.

Current Situation	After 25 years	After 50 years



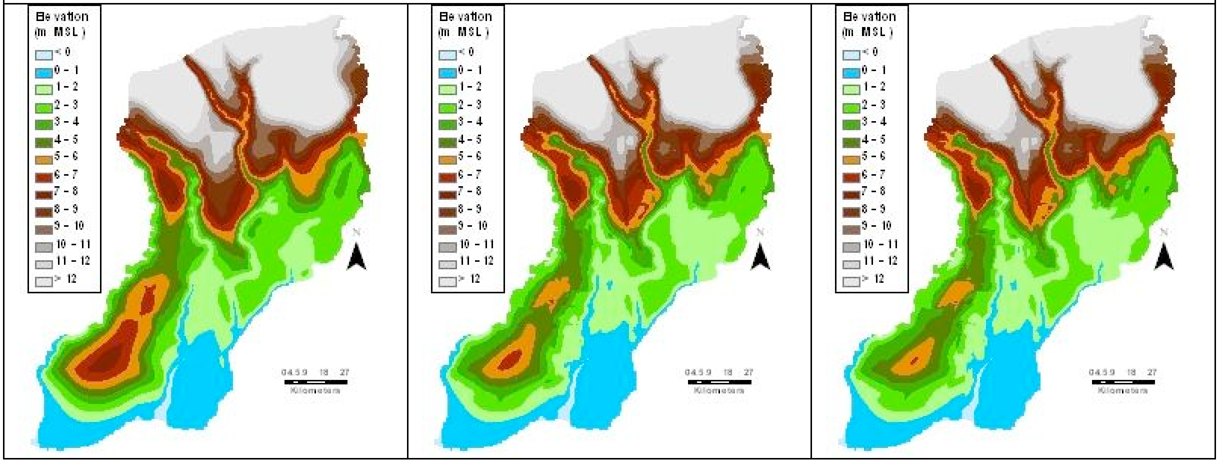
existing drainage scenario, no fire

existing drainage scenario, with fire

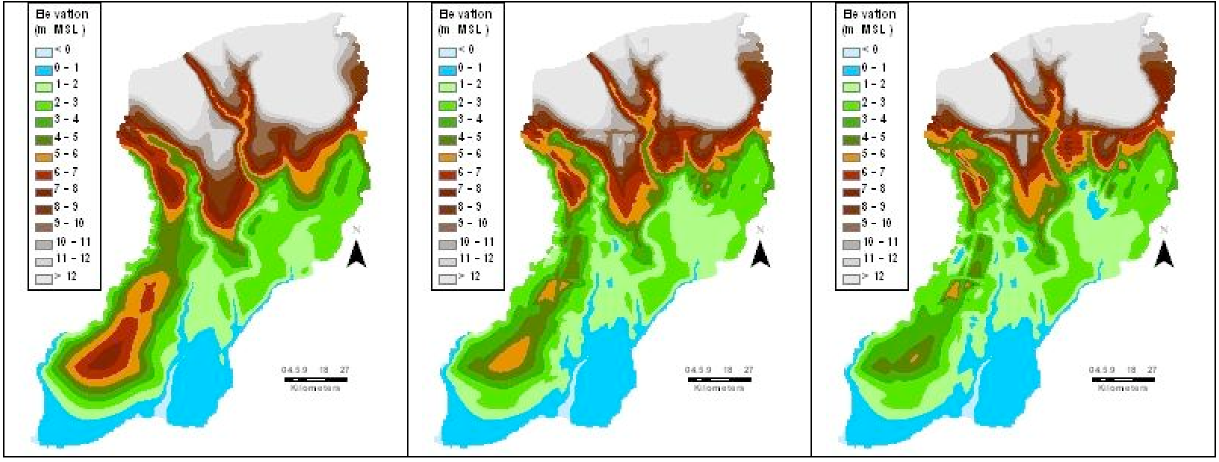
modified Inpres scenario

Figure 6.4 DEMs for the Existing drainage (reference) scenario, in the current situation, after 25 years and after 50 years.

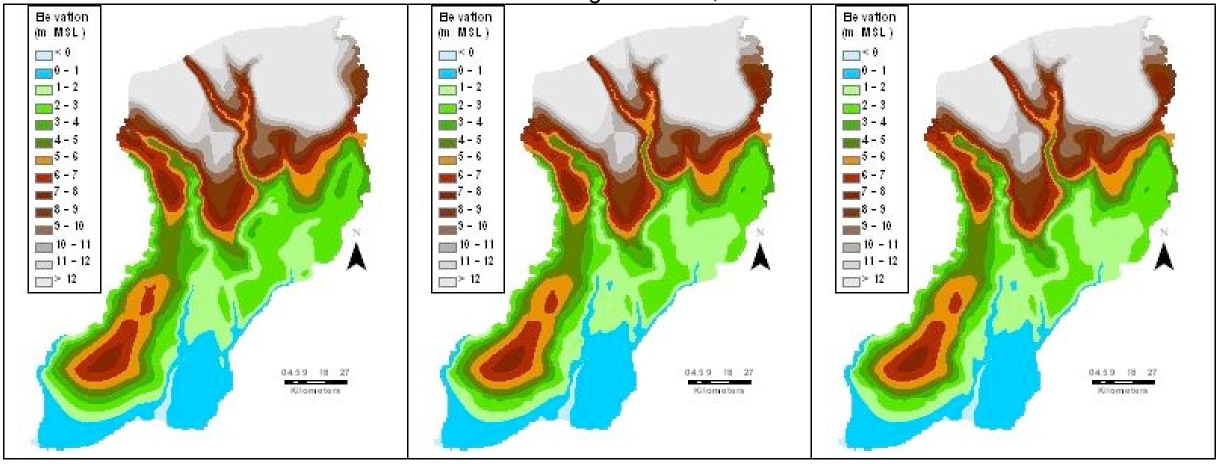
Current Situation | After 25 years | After 50 years



maximum drainage scenario, no fire

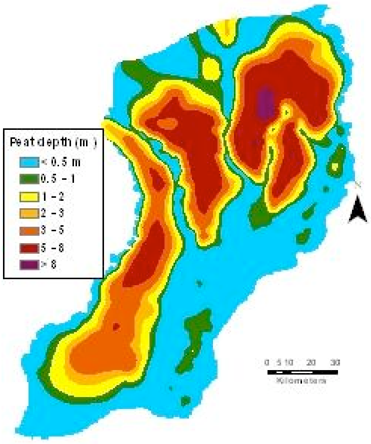
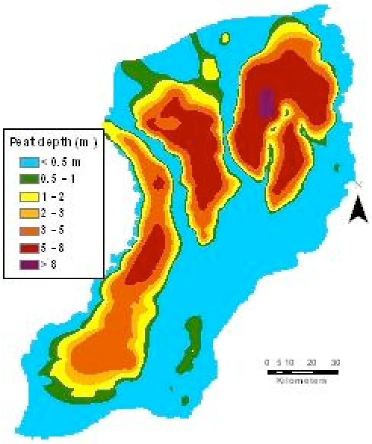
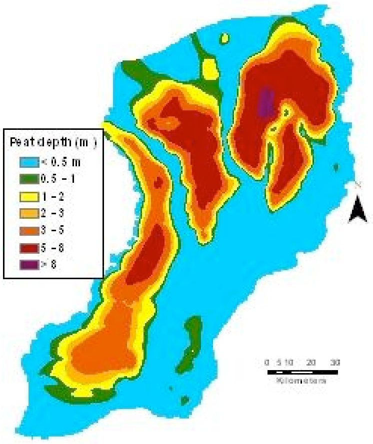


maximum drainage scenario, with fire

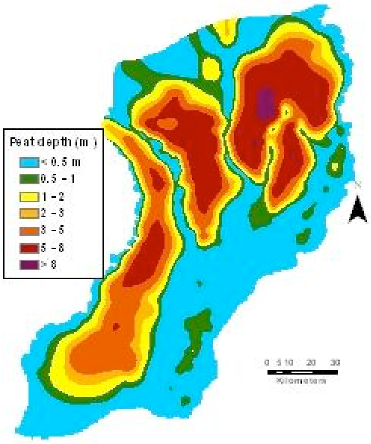
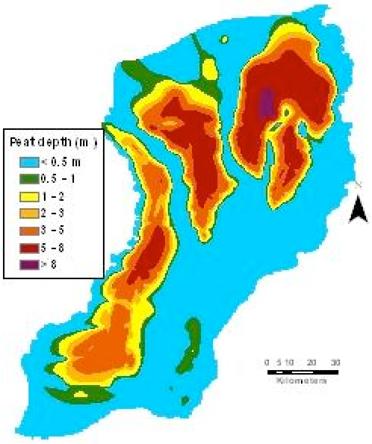
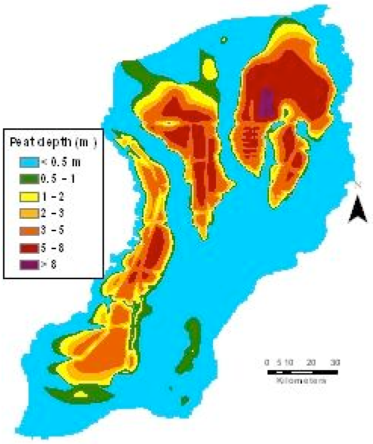


modified Inpres scenario

Figure 6.5 DEMs for the maximum drainage (without and with fire) and modified Inpres scenarios, in the current situation, after 25 years and after 50 years.

Current Situation	After 25 years	After 50 years
		

existing drainage scenario, no fire

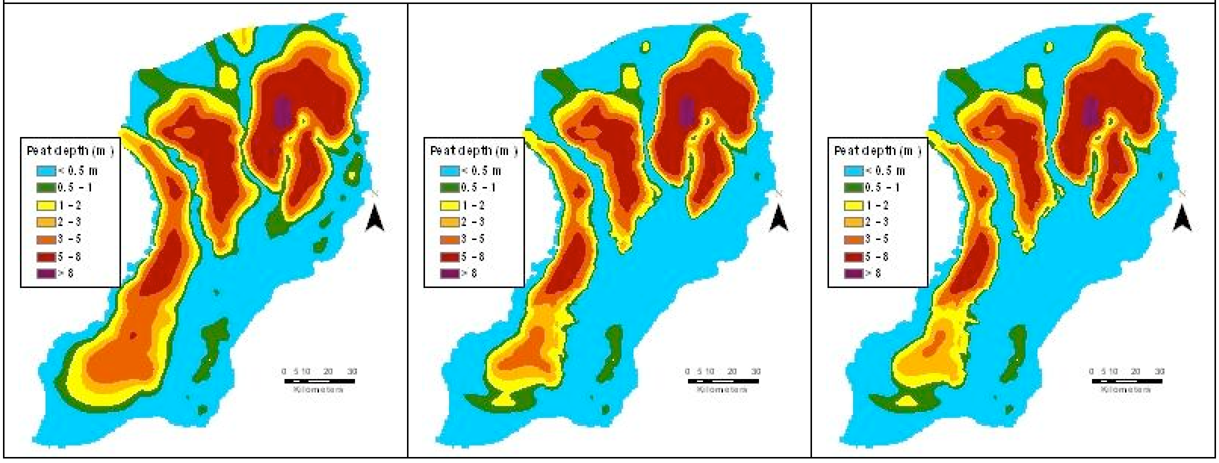
existing drainage scenario, with fire

Figure 6.6 Peat depth for the reference scenario in the current situation after 25 years and after 50 years.

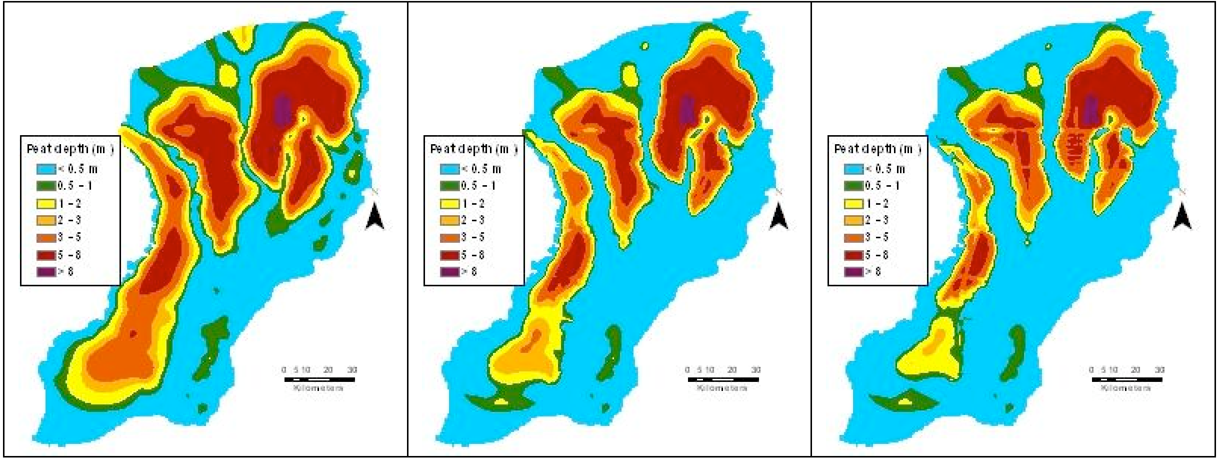
Current Situation

After 25 years

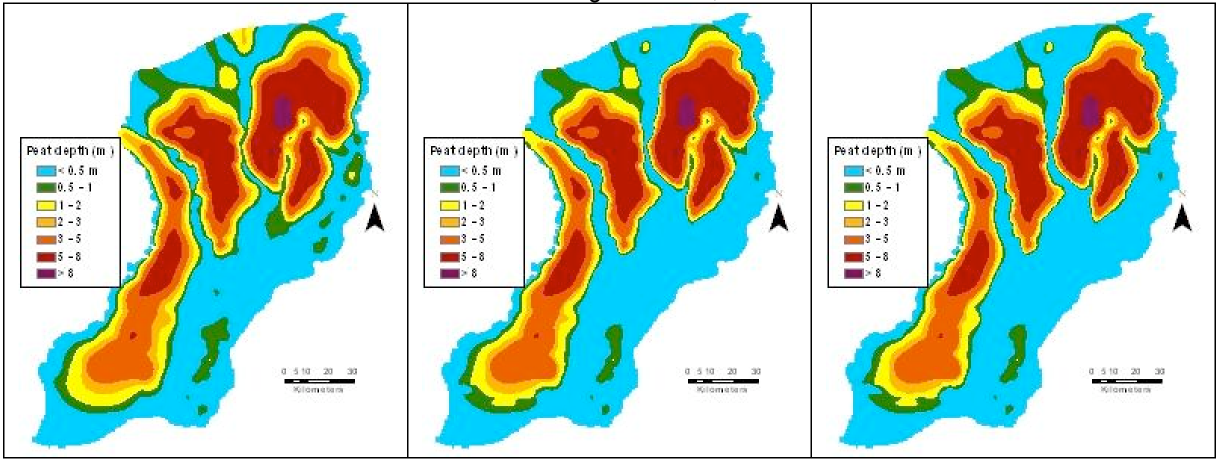
After 50 years



maximum drainage scenario, no fire



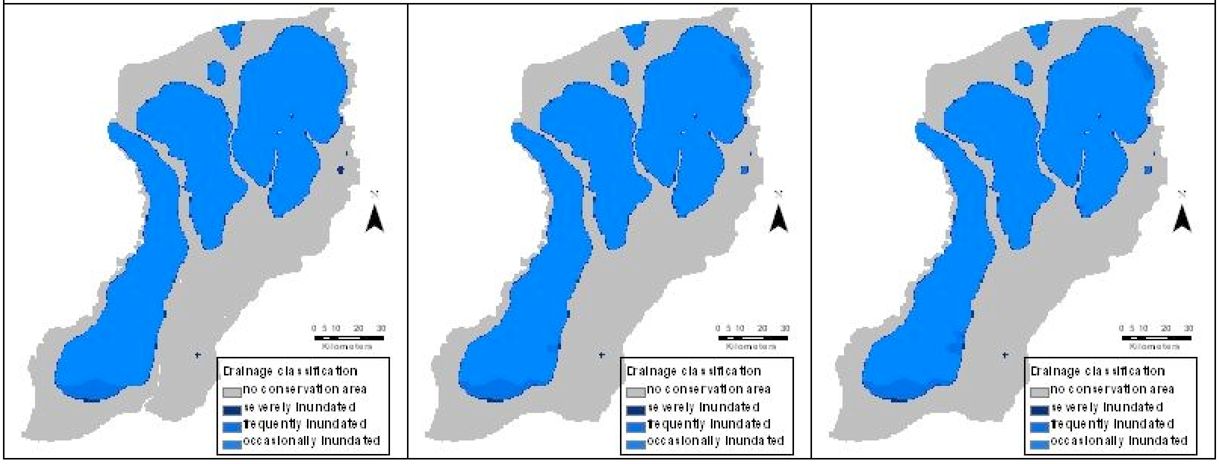
maximum drainage scenario, with fire



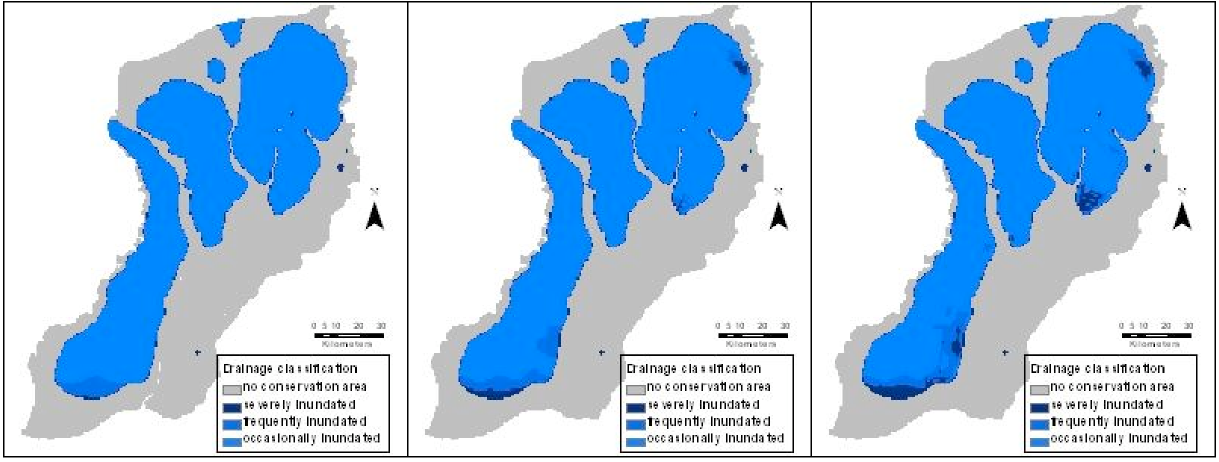
modified Inpres scenario

Figure 6.7 Peat depth for the maximum drainage scenario and modified Inpres conservation area & minimum drainage scenario in the current situation after 25 years and after 50 years.

Current Situation	After 25 years	After 50 years



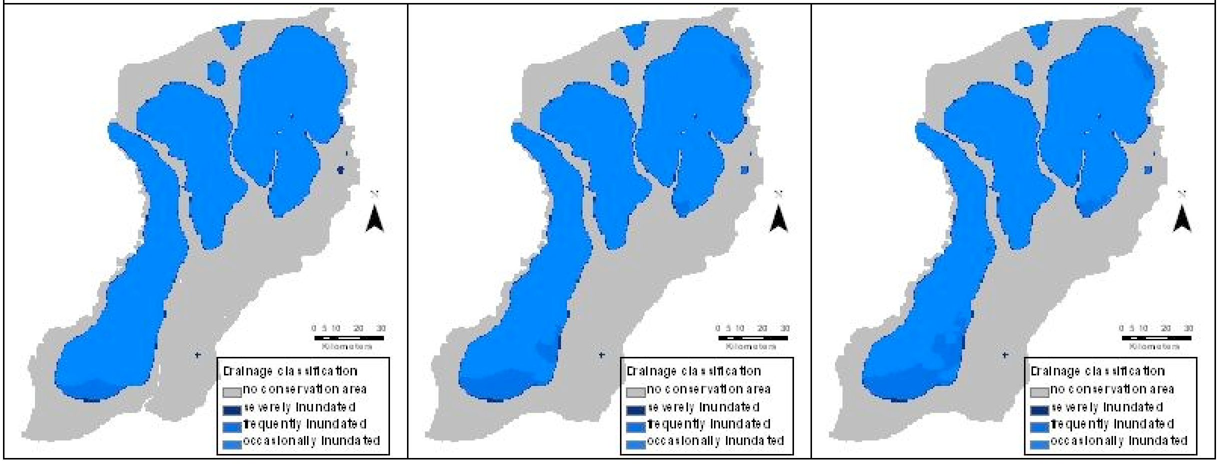
existing drainage scenario, no fire



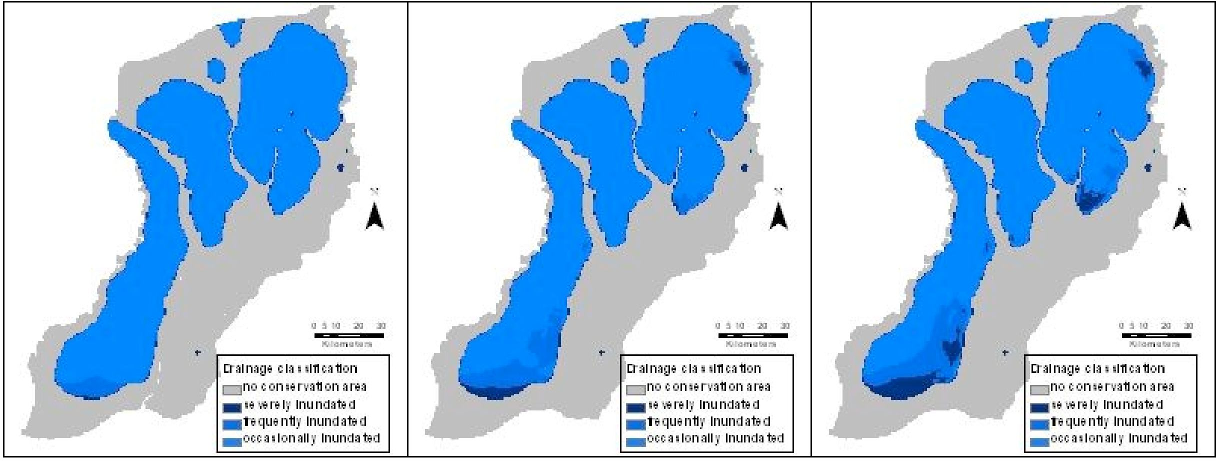
existing drainage scenario, with fire

Figure 6.8 Risk on inundation by rain water (due to impeded drainage as gradients get too low) for the reference scenario, in the current situation, after 25 years and after 50 years.

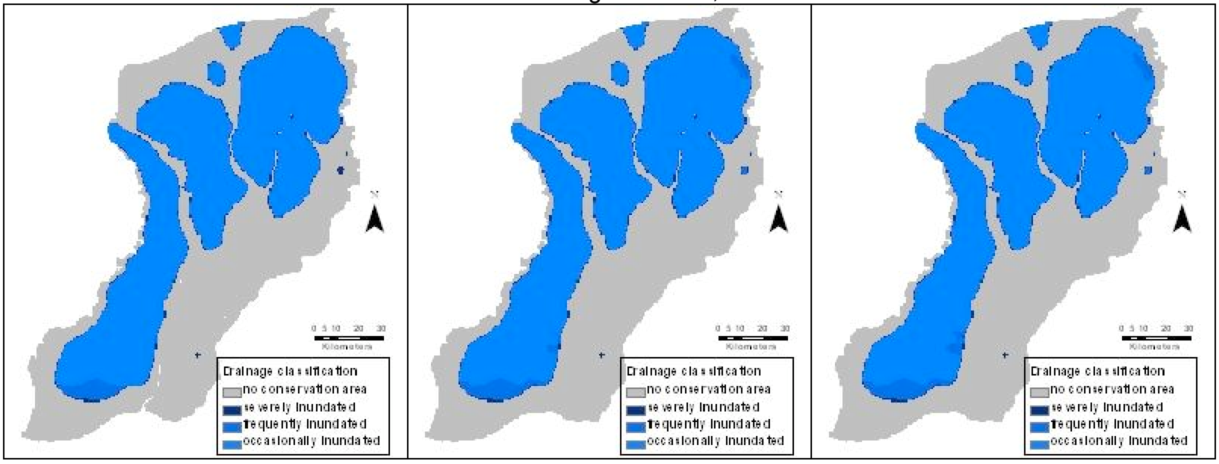
Current Situation	After 25 years	After 50 years



maximum drainage scenario, no fire



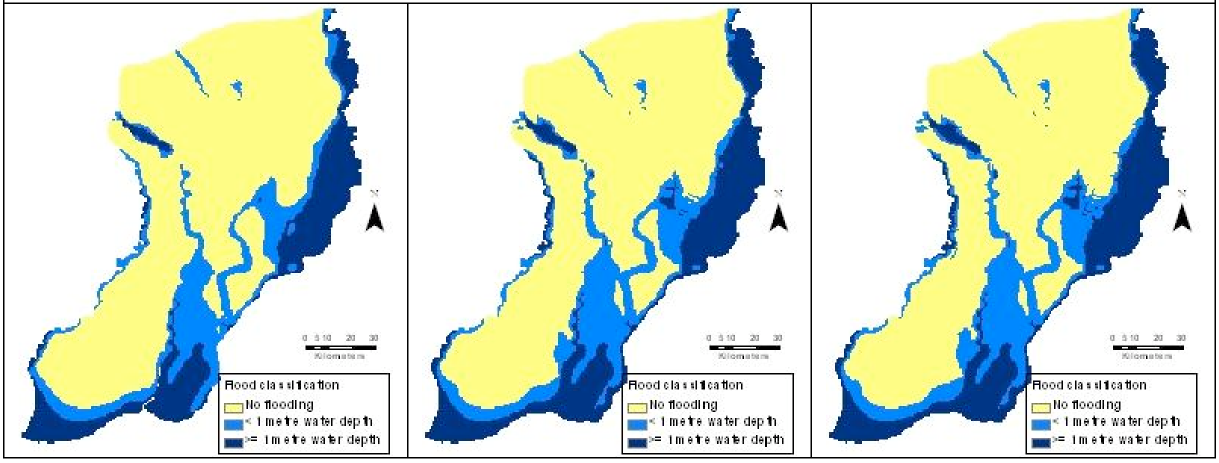
maximum drainage scenario, with fire



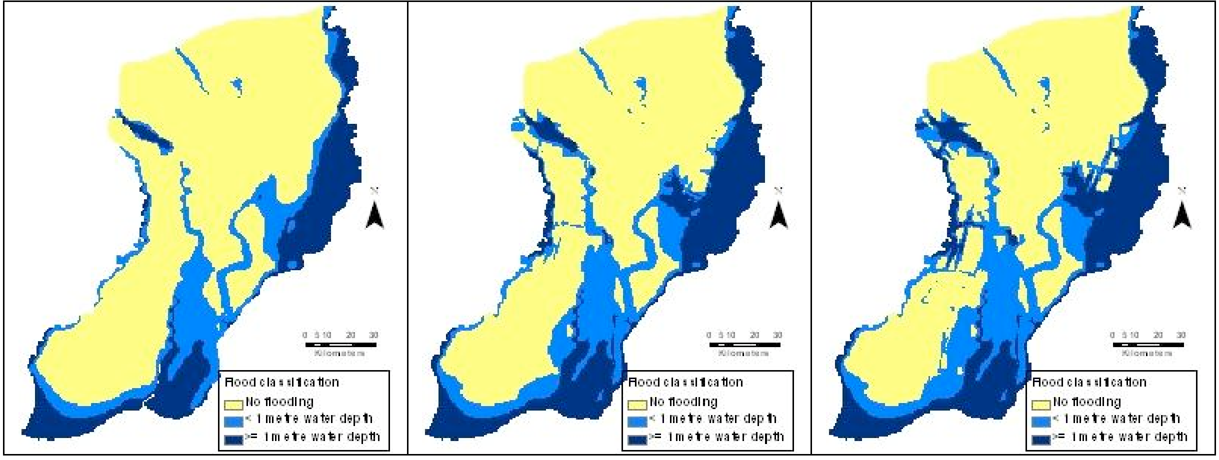
modified Inpres scenario

Figure 6.9 Risk on inundation by rain water (due to impeded drainage as gradients get too low) for the maximum drainage scenario and modified Inpres conservation area & minimum drainage scenario, in the current situation, after 25 years and after 50 years.

Current Situation	After 25 years	After 50 years



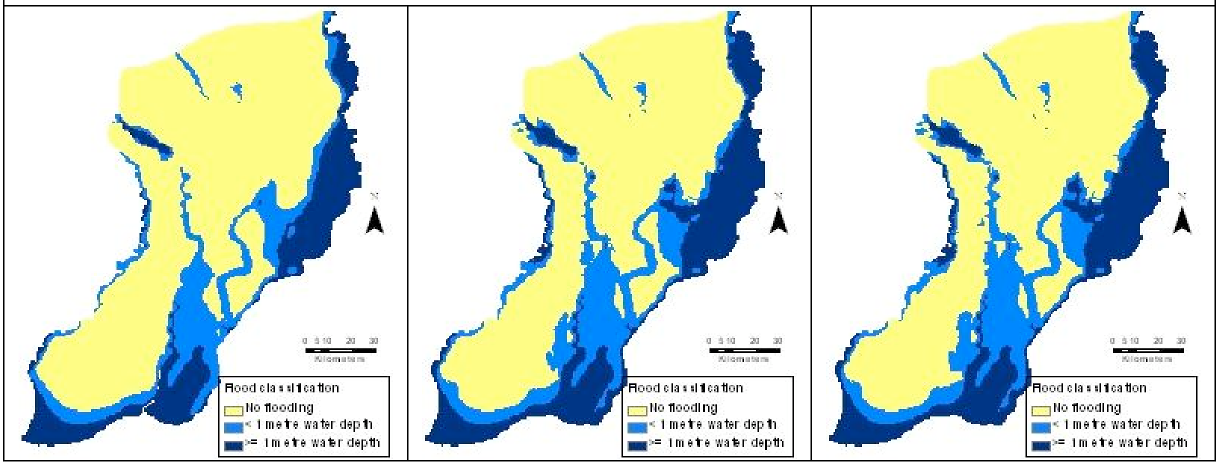
existing drainage scenario, no fire



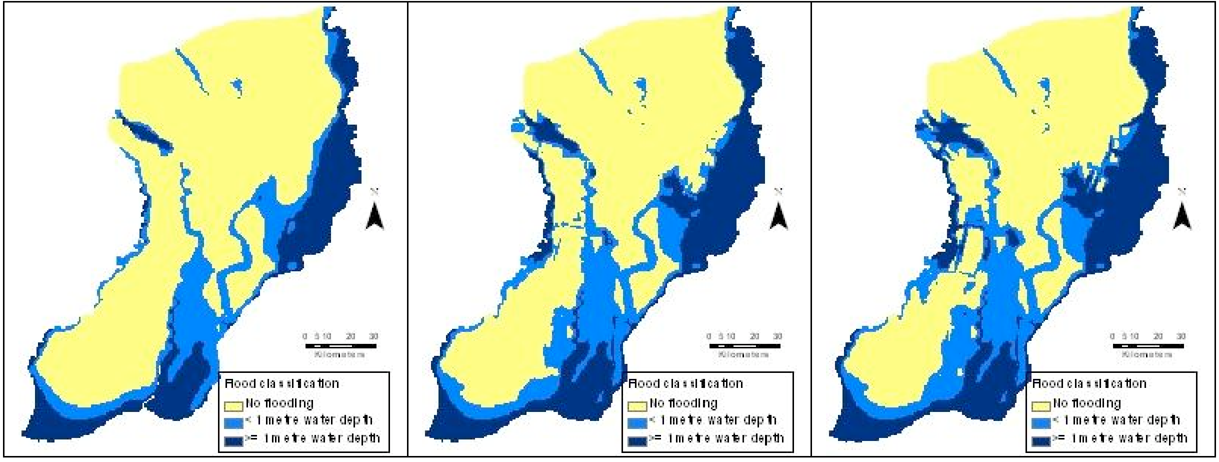
existing drainage scenario, with fire

Figure 6.10 Risk of flooding by River or Sea water, in the reference scenario, in the current situation, after 25 years and after 50 years.

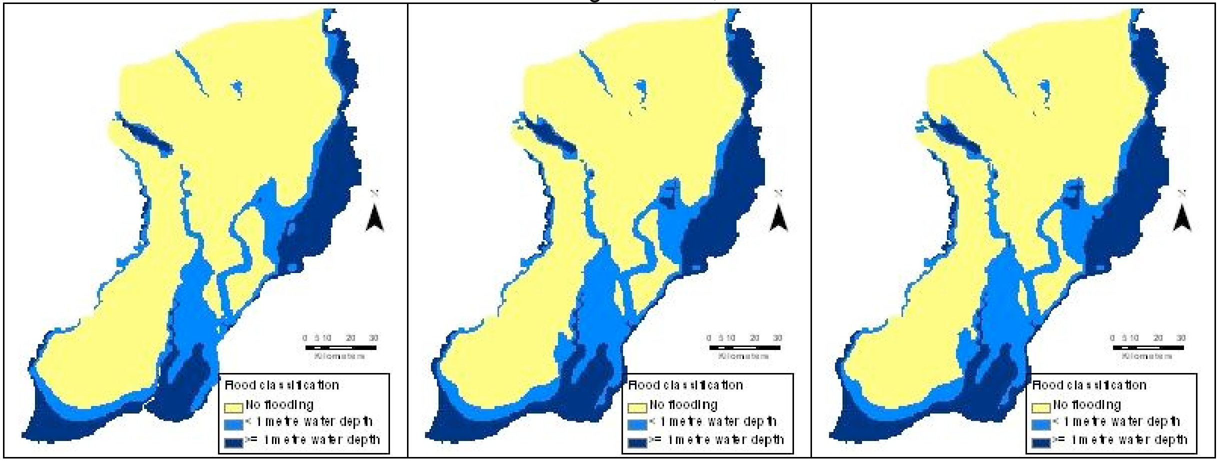
Current Situation	After 25 years	After 50 years



maximum drainage scenario, no fire

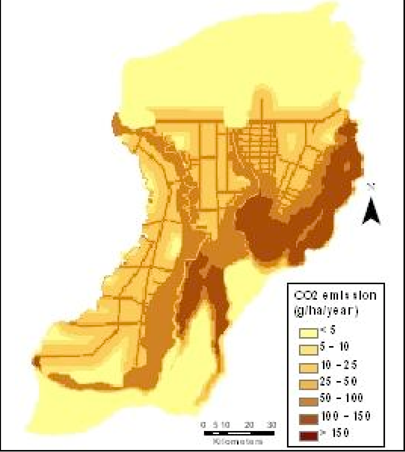
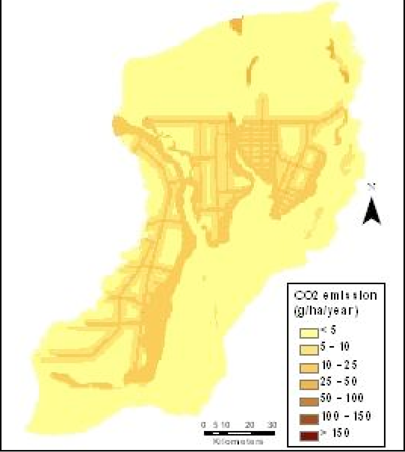
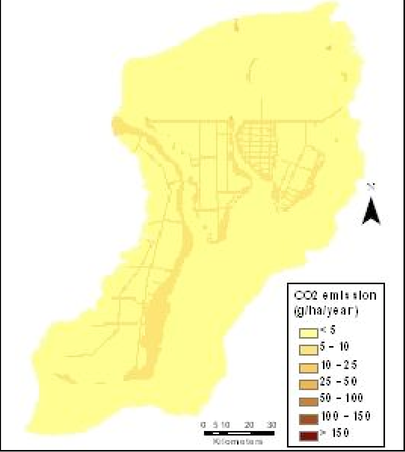


maximum drainage scenario, with fire

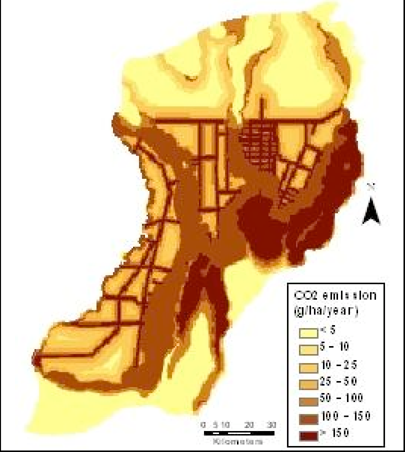
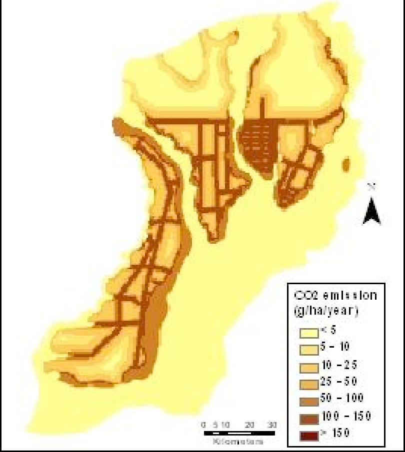
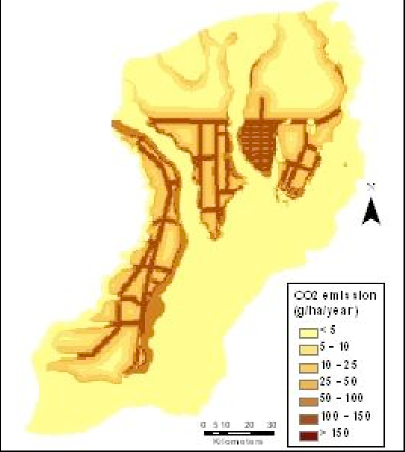


modified Inpres scenario

Figure 6.11 Risk of flooding by River or Sea water, in the maximum drainage scenario and modified Inpres conservation area & minimum drainage scenario, in the current situation, after 25 years and after 50 years.

Current Situation	After 25 years	After 50 years
		

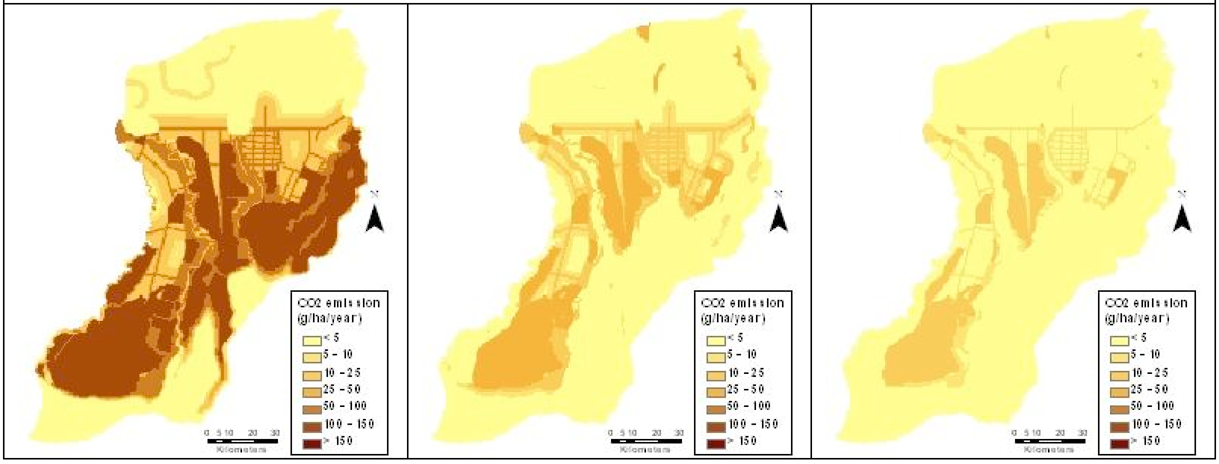
existing drainage scenario, no fire

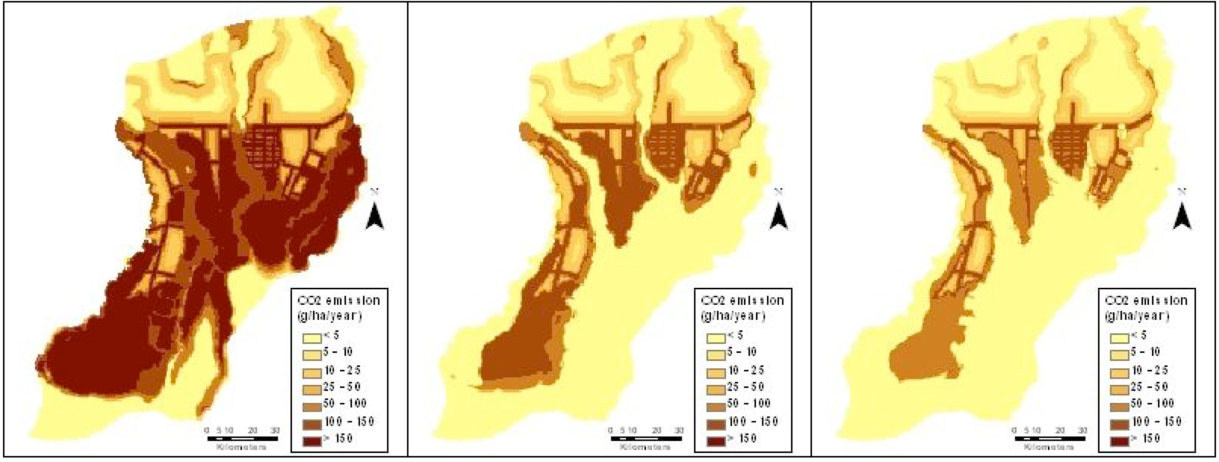
existing drainage scenario, with fire

Figure 6.12 CO_2 emissions for the reference scenario in the current situation (5 years from now), after 25 years and after 50 years. In each case, average emission over the previous 5 years is shown.

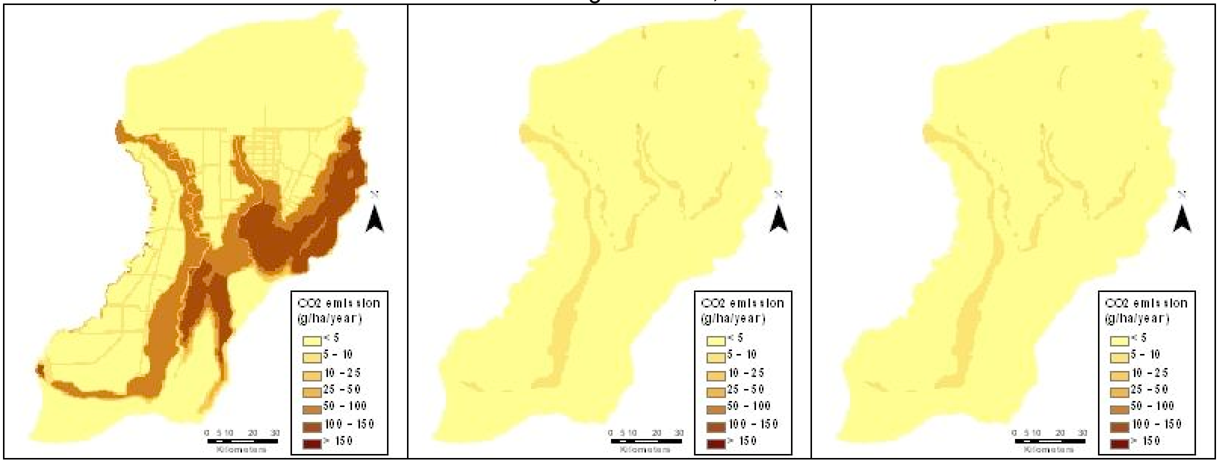
Current Situation	After 25 years	After 50 years



maximum drainage scenario, no fire



maximum drainage scenario, with fire



modified Inpres scenario

Figure 6.13 CO_2 emissions for the maximum drainage scenario and modified Inpres conservation area & minimum drainage scenario, in the current situation (5 years from now), after 25 years and after 50 years. In each case, average emission over the previous 5 years is shown.

6.4 CO_2 emissions

The calculations presented in earlier maps also yield numbers of CO_2 emissions under different scenarios. The results below show that emissions are ultimately declining in all scenarios, with or without fires, but that both emissions and changes in time are very different. Emissions are calculated as explained in chapter 2. It should be noted that these results provide not more than an indication of possible emission levels. No accurate assessment is possible with the currently available data and knowledge, as explained in Chapter 4.

Changes in emissions are the result of two factors:

1. the reduction in subsidence and decomposition rate given a certain drainage depth, as the peat matures,
2. depletion of increasingly deeper peat deposit as emission proceeds.

Table 6.1 Emission estimates of carbon dioxide (CO_2) in million tonnes per year, with and without fires, for the EMRP area excluding Block D (which has little peat left) and Block E (where there is limited data availability).

	Emissions without fires (Mt/y)			Emissions with fires (Mt/y)		
	Existing drainage	Maximum drainage	Modified Inpres	Existing drainage	Maximum drainage	Modified Inpres
	1 year from now					
Block A	24	26	21	40	42	21
Block B	6	15	4	16	24	4
Block C	12	35	8	32	57	8
Total	**42**	**76**	**32**	**87**	**123**	**32**
	25 years from now					
Block A	2	2	0.7	9	9	0.7
Block B	1	4	0.7	8	10	0.7
Block C	3	8	2	16	20	2
Total	**6**	**14**	**3**	**34**	**40**	**3**
	50 years from now					
Block A	0.5	0.6	0.2	6	6	0.2
Block B	0.4	1	0.2	6	6	0.2
Block C	1	2	0.6	12	12	0.6
Total	**2**	**4**	**1**	**24**	**25**	**1**

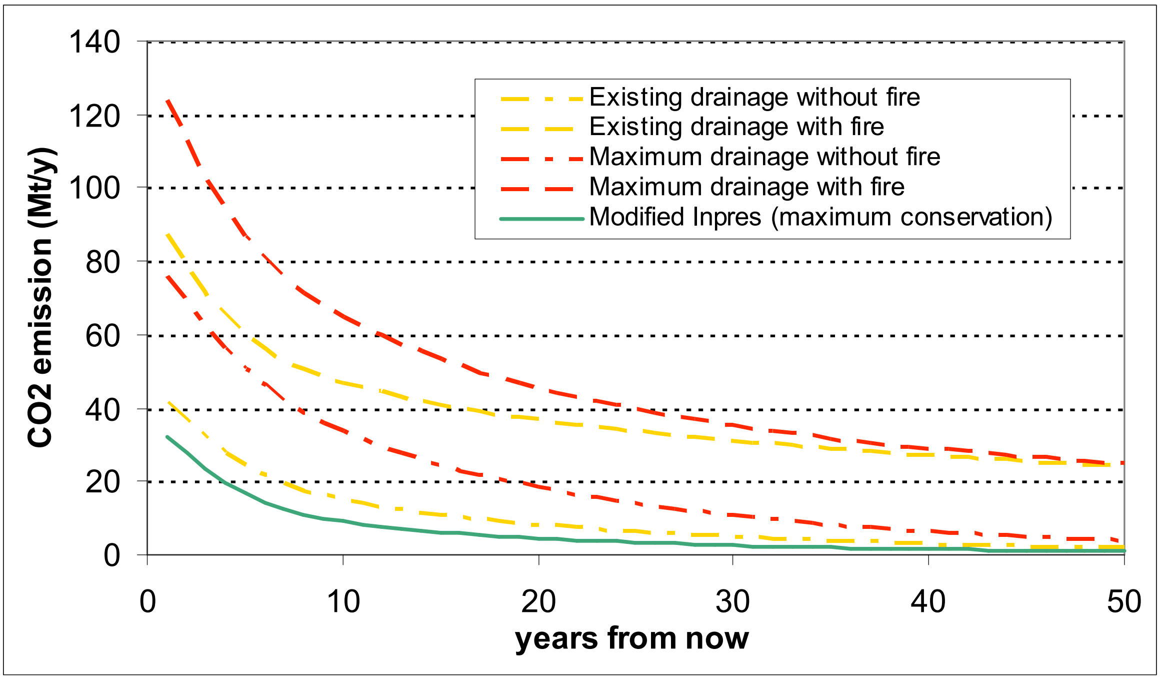


Figure 6.14 Change in CO_2 emissions over time, for different scenarios.

7 Discussion and recommendations

7.1 Discussion

The activities described in this report were aiming to A) demonstrate the principles involved in subsidence caused by drainage, B) demonstrate the speed and scale of subsidence impacts under different management scenarios, C) explore the data gaps and the further data collection and research required to reduce those. The results of these activities have a high associated degree of uncertainty, as this has been a rapid assessment with limited data. During the project (and in ongoing peatland research projects elsewhere), it was found that knowledge gaps were greater than expected. Therefore, all results should be considered highly tentative.

7.1.1 Methodology and data

A method was developed and applied that allowed assessment, based on a set of decision rules, of the impact of future changes in water management (increase or decrease of drainage) on peatland subsidence, CO_2 emission, drainability and flooding. The Peatland Subsidence Scenario Analysis Tool (PSSAT) was developed in the Habitat software package prepared by Delft Hydraulics for water and ecology related GIS applications.

A review has been carried out of existing data on peat characteristics, hydrology, subsidence and CO_2 emissions for the EMRP area and for peatlands in South East Asia in general. As far as possible within the time frame of the EMRP MP project, additional data have been collected. For the EMRP area limited data exist on peat characteristics, ground water dynamics and subsidence. No longer-term subsidence records exist for the area.

Peat characteristics determine the rates of loss of groundwater and peat material under given drainage conditions. Data on peat characteristics for the EMRP are limited. Almost all peat in Blocks A, B and C appears to be moderately or highly humified (hemic to sapric), and to have moderate to low hydraulic conductivity. No evidence of spatial differentiation in peat characteristics has been found and therefore the peat was treated as homogenous. However, it is not unlikely that less humified (fibric) peat is present in Block E, where distances between rivers and forest cover are greater. Fibric peat generally has a higher hydraulic conductivity making it even more susceptible to subsidence caused by drainage than other peat types.

For two transects between drainage canals in Block A it has been shown that groundwater levels are mostly at or near the surface during the wet season. The impact zone along canals where groundwater depth is lowered significantly seems to be limited by the low hydraulic conductivity to a few hundred metres. However, the drainage canals in the EMRP area already exist approximately ten years. Local topography has adapted to the drainage by subsiding, creating small domes between the drainage canals of up to two meter height. This also explains the almost uniform groundwater depths found.

The CKPP Mapping Project and the EMRP MP Project have collected elevation data for 26 one kilometre transects perpendicular to drainage canals in Block A, B and C. At 20 of these transects groundwater depth has been surveyed as well. Average gradients for both elevation and groundwater depth have been determined based on these data describing the general relation between water level in the canal, distance to the canal and groundwater depth and subsidence.

Very few measurements of subsidence have taken place in the EMRP area. Available measurements suggest a subsidence rate of about 1cm per year 10 years after the start of drainage, well away from canals in highly decomposed (sapric) peat in degraded peatland with relatively high water tables. Rates will be higher where peat is less decomposed or has lower groundwater tables. No clear relation is found between subsidence and average groundwater depth. However, a relation may exist between subsidence and a measure of minimum groundwater depth. This suggests that average groundwater depth is probably a poor descriptor of the soil moisture regime that controls peat decomposition and subsidence.

No long term subsidence records exist for the EMRP area. Therefore, data from Johor (Malaysia) have been used to describe the relation between time after drainage (i.e. peat maturation) and the annual subsidence rate. This relation shows an exponential decline of subsidence rate over time.

Based on the Johor long term subsidence record, previous studies have mostly used the rule that subsidence equals 10% of the average water depth. In the current project, because of uncertainties in both measured groundwater depths and subsidence rates, it has been decided to apply a different approach, by developing a tentative non-linear relation between groundwater depths and subsidence rate as derived from the Kampar Science Based Management Support Project which studies the Kampar Peninsula in Riau, Indonesia.

It is tentatively assumed that peatland in the EMRP burns on average once every five years and loses on average 50cm of peat when it first burns, and 20cm during subsequent episodes. This results in an average annual subsidence due to fires of 4cm per year.

The assessment of CO_2 emission from peat lands follows the PEAT-CO2 approach which calculates the carbon content of the annual subsidence and assumes for subsidence due to drainage that 60% is caused by oxidation resulting in CO_2 emission. For subsidence due to fires all carbon lost is assumed to be emitted as CO_2.

The decision rules described above have been applied to reproduce the apparent subsidence in the past ten years for the average 1 km transect perpendicular to the drainage canals as determined from measurements in the EMRP area. This allowed calibration of the Kampar-based relation between groundwater depth and subsidence rate for the EMRP area.

Based on knowledge and data presented above an empirical model to assess subsidence and emission has been implemented in the form of the Peatland Subsidence Scenario Assessment Tool (PSSAT). Uncertainties in results are easily as high as 50% for the calculations without fires, possibly greater for the calculations with fires. The locations of actual flooding and potential flooding under the different management scenario seem to be modelled correctly. However, the total area flooded is clearly overestimated due to the calculation methods used.

7.1.2 Results of scenario analysis

The following EMRP management scenarios were examined with PSSAT:

1. **Existing drainage** (reference) scenario: the current drainage canals are maintained at a drainage depth of 2 m. If the subsidence results in lower drainage depth, the drainage depth is adapted. In the adapted management zone it is assumed that a dense drainage system keeps the groundwater depth at 0.4 m on average. In these areas the drainage depth is adapted after soil subsidence. In the development zones a dense drainage system keeps the groundwater levels at 0.8 m. Drainage levels are adapted after subsidence. There is no extra development of plantations and transmigration schemes.
2. **Maximum drainage** scenario: all known plantation concessions and transmigration plans are implemented. For both it is assumed that a dense drainage system will be implemented resulting in average groundwater depth of 0.8 m. For the currently existing drainage canals in the remaining areas a drainage depth of 2 m is maintained. Drainage depth is maintained at this level, meaning that the canals will be

deepened further after subsidence. In the adapted management zone a drainage level of 0.4m is maintained and in the development zone a level of 0.8m.

3. **Modified Inpres** scenario with maximum conservation area and minimum drainage: for the conservation zones a water depth of 0.4 m is implemented in the current drainage canals. The drainage depth is not adapted after soil subsidence, resulting in a diminishing drainage depth after subsidence. In the adapted management zone a drainage level of 0.4m is maintained and in the development zone a level of 0.8m.

For each scenario the tool provided an assessment after 25 and 50 years of:

- Groundwater depth and level;
- Subsidence rate;
- Surface elevation;
- Remaining peat depth;
- Drainability;
- Extent of flooding; and
- CO_2 emission

Scenario results provide a clear indication of potential impacts and are a strong tool for communication and comparison between management scenarios. The effect of drainage on subsidence through shrinkage and decomposition in EMRP peatlands is found to be significant, but because of the apparent low hydraulic conductivity of the peat, it appears mostly confined to a zone of a few kilometres from drainage canals with the worst effects confined to the first kilometre or so. Present annual subsidence rates are estimated to be 66 mm/y at 50m from a canal, 23 mm/y at 500m, 18 mm/y at 1000m, 12 mm/y at 2000m and 6 mm/y at 5000m. The result is that the extent of the long-term subsidence impact of isolated canals is also relatively limited compared to some other peatland areas, whereas in densely drained areas like plantations the surface subsides faster and more uniformly over large areas.

Extending the drained area in the EMRP peatlands will result in severe soil subsidence and consequently also CO_2 emission. In the coming decades large areas of peat will disappear if all planned concessions and transmigration areas will be implemented. However, continuation of the actual situation will result in a significant amount of subsidence as well.

Not only does this influence global climate and biodiversity of peatlands negatively, the use of the area for agricultural purposes will also be limited in time. Our current projections for the existing drainage and maximum drainage scenarios foresee in the future a sharp increase of water management problems related to a lowering elevation such as poor drainability and frequent flooding by water from the rivers.

Sustainable development of the EMRP area as investigated under the “modified Inpres scenario” seems the best of the examined scenarios if results are evaluated on flood risk, CO_2 emission and peat conservation. The latter implies the best possible results for peat related biodiversity as well.

These preliminary results of the PSSAT allow for a comparison and demonstration of the effects of different scenarios. For quantification of the possible market value of reduced/avoided emissions, more refined calculations are required. The presented results are highly tentative, because the underlying science is very much in development.

7.2 Recommendations for enhancing the knowledge base

More accurate assessments of the impact of different management regimes on subsidence and CO_2 emission are required for more detailed design in the framework of implementation of the EMRP Master Plan. Improved modelling of subsidence is especially important to assess the long term sustainability of developments in the adapted management zone with respect to increased flooding and drainage problems. Improved modelling of CO_2 emission is required to provide an assessment of avoided emissions if peatland is conserved.

Improvement of model descriptions of subsidence and CO_2 emissions require first of all monitoring to overcome current data limitations. It is therefore recommended to start a comprehensive monitoring programme which should include the following elements:

- Collect more data on the horizontal and vertical distribution of peat characteristics throughout the EMRP area, especially the bulk density.
- Continue and intensify groundwater level monitoring along transects parallel to the drainage direction and under different drainage regimes;
- Install a number of subsidence poles along the different groundwater transects under different drainage regimes to monitor subsidence in the coming decennia;
- Measure CO_2 emission for selected locations under different drainage regimes.

The current approach aimed to define knowledge rules that are consistent with the scarce subsidence data available. These knowledge rules are entirely empirical. For more accurate subsidence modelling, what is needed is a process-based model that takes into account the actual processes that determine peat shrinkage and carbon loss. This will also allow more accurate modelling of carbon emissions. It is recommended for further developments to focus on two models for different scales.

A process based model should be developed to describe the interaction between surface water-groundwater interactions, soil moisture in the unsaturated zone, land management aspects (vegetation cover, fertilization, tilling etc), peat decomposition and shrinkage, subsidence and CO_2 emission for well-monitored pilot areas of limited extent. This model will serve as a research tool to test methods for quantification of the processes involved, and to calibrate process coefficients on measurements.

A simpler GIS-based model is required to assess subsidence and CO_2 emissions for larger areas, since detailed process based modelling is not feasible and not useful at this scale. This model should be based on the relations derived from process based modelling.

The hydrological impacts of subsidence, i.e. reduced drainability and increased flooding, are best modelled using a 2-dimensional hydrological modelling approach. The assessment of flood extent and frequency as used in the current PSSAT tool could be improved by taking into account storage of flood water in upstream flooded areas.
Although time and data to do this fully were lacking in the current project, the basis for doing this is now available as explained in the EMRP MP Hydrology Technical Report.

It is recommended to evaluate whether the current PSSAT model can be extended with an assessment of the impact of management scenarios on habitats of key species and biodiversity in general.

8 Acknowledgements

This study was carried out by Deltares | Delft Hydraulics in the EMRP Master Plan project, funded by the Royal Embassy of the Netherlands in Jakarta. The study was supported by Alterra in the area of subsidence assessments and by CIMTROP and CKPP with data. In the area of development of the subsidence modelling tool (PSSAT), input was provided by the Singapore Delft Water Alliance (SDWA) Peatland Programme.

9 References

Burrough, P.A., D. Karssenberg, and W.P.A. van Deursen, 2005, Environmental Modelling with PCRaster , in D. J. Maguire, M. F. Goodchild, and M. Batty, eds., GIS, Spatial Analysis and Modeling: Redlands, California, ESRI,480 pp.

Hooijer, A., Silvius, M., Wösten, H., Page, S., 2006. PEAT-CO2, Assessment of CO2 emissions from drained peatlands in SE Asia. Delft Hydraulics report Q3943.

Hooijer, A. (ed.), 2008. Introduction to the SBMS Project and preliminary results to date. Kampar Peninsula Science Based management Support Project. Summary Interim Report, April – December 2007.

Jaya, A., 2005. Study of carbon and water on tropical peatlands for ecological planning (Case study of the ex Mega Rice Project in Central Kaliumantan, Indonesia). PhD Thesis University of Nottingham.

Page, S. E. Page, F. Siegert, J.O. Rieley, H.D.V. Boehm, A. Jaya and S. Limin, 2002. The amount of carbon released from peat and forest fires in Indonesia during 1997. Nature. vol. 420, pp. 61-65.

Page, S.E., Wüst, R.A., Weiss, D., Rieley, J.O., Shotyk, W., Limin, S.H., 2004. A record of Late Pleistocene and Holocene carbon accumulation and climate change from an equatorial peat bog (Kalimantan, Indonesia): implications for past, present and future carbon dynamics. Journal of Quarternary Science 19(7):625–635.

Wösten, J.H.M., A.B. Ismail and A.L.M. van Wijk, 1997. Peat subsidence and its practical implications: a case study in Malaysia. Geoderma 78, pp. 25-36.

Wösten, J.H.M., Ritzema, H.P., 2002. Challenges in land and water management for peatland development in Sarawak. In: Rieley, J.O., Page, S.E. (eds.), Peatlands for People - Proceedings of the International Symposium on Tropical Peatlands, 22.-23.08.2001, Jakarta, pp 51-55.

Wösten, J.H.M. 2008. Relation between subsidence / CO2 emission and water table level for tropical peatlands. Memo to the EMRP Master Plan project (February 2008).

Bappenas
Secretariat
Inpres 2/2007

Jl. Taman Suropati
No.2,
Jakarta 10310

www.bappenas.go.id

Bappeda
Central
Kalimantan
Secretariat Inpres
2/2007

Jl. Diponegoro 60,
Palangka Raya
73111,
Kalimantan Tengah

www.kalteng.go.id

Royal
Netherlands
Embassy

Jl. H.R. Rasuna
Said Kav. S-3,
Kuningan
Jakarta 12950

indonesia.nlembassy.org

Euroconsult
Mott MacDonald

S. Widjojo Centre, lt. 3
Jl. Sudirman Kav. 71
Jakarta 12190

www.euroconsult.mottmac.com

Deltares | Delft
Hydraulics

P.O. Box 177
2600 MH Delft
The Netherlands

www.wldelft.nl