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Canal blocking strategies for hydrological restoration of degraded tropical peatlands in Central Kalimantan, Indonesia

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ABSTRACT

In the 1990s the Government of Indonesia decided to develop one million hectares of peatlands for agriculture in Central Kalimantan on the Island of Borneo. The construction of thousands of kilometres of canals resulted in over-drainage and targets for agricultural production failed. Abandoned, the area has been subject to severe forest and peat fires. Restoration of degraded peatlands normally starts with restoring the water table to rewet the surface in order to control fire and to initiate reforestation. Canal blocking strategies are a potential means for accomplishing this. In a test plot in the Northern part of Block C of the former Mega Rice Project (MRP), a series of dams were constructed and (ground)water tables and subsidence rates were monitored to assess the effects of dam construction on peatland hydrology. The resulting higher water tables did not completely compensate for the negative effects of increased subsidence near the canals. The canals, which are "eating" themselves into the peatland, create depressions in the peatland surface leading to interception of overland- and interflow and increased risk of overtopping of dams during extreme rainfall events. The lessons learned are being used to improve blocking strategies and dam design. The changes in peatland topography caused by drainage, however, need to be better understood in order to further refine strategies for hydrological restoration of degraded peatlands in Indonesia.

1. Introduction

Tropical peatlands have an important role in the ecosystem in many parts of the world, primarily because they are (i) a major carbon stock (Page et al., 2011); (ii) have a rich biodiversity, including populations of endemic, rare and endangered species (Rieley et al., 2002); (iii) have an important hydraulic function in storing excess rainfall (Wösten et al., 2006), and; (iv) an economically valuable function in the livelihoods for local communities as a source of timber and non-timber forest products (Rieley et al., 2002). In Southeast Asia, owing to a scarcity of agricultural land, there is an increasing interest to invest in the development of lowland peat swamps. Some of these peatlands have become degraded with negative environmental and socio-economic consequences. In this paper, restoration of tropical peatlands in Central Kalimantan, Indonesia through blocking of drainage canals is explored.

1.1. Tropical peatland characteristics

Tropical peatlands have formed under a high precipitation–high temperature climatic regime. An important consequence of high temperature is that peat degradation proceeds rapidly when there is a change in the peatland ecosystem and its water regime, either as a result of natural climatic changes (reduced precipitation or extended dry season) or human-induced ones (for example, on- and off-site drainage and fire) (Page et al., 2009). This leads to an increase in subsidence and CO_2 emission rates and loss of biodiversity and livelihood functions.

Peatlands in Southeast Asia cover about 24.8 million ha, 56% of the total area of the world's tropical peatland (Page et al., 2011), with approximately 11 million ha located in Borneo (Hooijer et al., 2010). The lowland peatlands of Borneo, including those in Central Kalimantan, are purely rain-fed and under natural conditions they are waterlogged throughout the year. Drainage is needed to make these waterlogged lands suitable for agriculture or other land uses (Ritzema, 2007). For successful development there is, however, a need for an integrated approach, based on effective water management in combination with adequate land use and environmental considerations (Ritzema, 2008; Suprianto et al., 2010).

Compared to temperate peat, formed primarily from mosses and sedges, tropical peat has a higher hydraulic conductivity, especially in the upper layer. This is a result of the larger, more open pore structure due to the hemic and fibric remains of rain forest trees (Silvius et al., 1984). The hydraulic conductivity of tropical peat is typically more than 10 m d^{-1}, whereas for a boreal Sphagnum bog it is only around 0.01 m d^{-1} (Takahashi and Yonetani, 1997). The bulk density is around

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0.1 g cm^{-3} in the more decomposed hemic topsoil and lower in the less decomposed fibric subsoil (Wösten and Ritzema, 2001).

Although the water balance of a tropical peat dome may seem rather simple, since it can be expressed in just 4 terms (rainfall, evapotranspiration, storage, and runoff), its hydrology is complex (Ritzema, 2007). In undrained peat swamp forests, water movement mainly takes place in the wet season (Takahashi et al., 2002). Deep percolation is rather low as more than 90% of the excess rainfall runs through the top peat layer, the so-called interflow (Department of Irrigation and Drainage, 2001). Owing to the convex character of tropical peat domes, this water flows in various directions as radial, widely spread sheet flow rather than channel flow.

In dry periods, the lower water table causes oxidation of the peat layer above the water table resulting in subsidence and CO_2 emissions (Jauhiainen et al., 2008). During the dry season in Central Kalimantan, the water table can fall to more than 1 m below the peat surface, even in undisturbed natural forest (Takahashi et al., 2002). In undrained peat swamps, CO_2 emissions decrease when the water table rises to above −0.2 m of the peat surface (Hirano et al., 2009). By contrast, in drained peatlands, CO_2 emission and subsidence increase markedly with falling water tables. The subsidence rate is linearly related to the depth of the (ground)water table, i.e. subsidence rate (cm per year) = 0.1 × depth of the water table (cm) (Wösten and Ritzema, 2001). In addition, Wösten et al. (2008) reported that fire risk increases if the water table falls below 0.40 m and contributing further to CO_2 emissions from the peat.

1.2. Peatland development in Central Kalimantan

The development strategy for the peatlands in Central Kalimantan is based on Presidential Decree No. 32/1990, which allows for the development of both agriculture and nature areas in the same peat dome: peat with a thickness of less than 3 m was to be used for agricultural development and peat with a thickness of more than 3 m should go into conservation. In 1995, the Government of Indonesia initiated the Central Kalimantan Peatland Development Project to convert up to 1 million ha of peat and lowland swamp in Central Kalimantan to rice cultivation (Presidential Decree No. 82/1995). This project became known as the Mega Rice Project (MRP). After construction of a 187 km long main canal connecting the rivers in the region, another 771 km of main canals, 973 km of secondary canals and 900 km of tertiary canals (in Block A alone) were constructed (Fig. 1) (Houterman and Ritzema, 2009). One of the main canals in Block C, which is located between the Sebangau and Kahayan rivers, is the Kalampangan Canal where the study reported in the paper was conducted.

The main canals often cut through the centre of peat domes resulting in excessive drainage, subsidence, irreversible drying, loss of habitat and increased risk, frequency and severity of fire (Diemont et al., 2002; Page et al., 2002). The canal systems also provided easy access for people, especially illegal loggers. To transport the illegally logged timber out of the forest to the main canal system numerous small canals were dug by local people. This network of small canals accelerated the drainage of the peat forest leading unavoidably to irreversible loss of peat through subsidence (Wösten and Ritzema, 2001).

The land in the MRP area, mainly peat soils, proved to be largely unsuitable for rice cultivation (Government of Indonesia, 2009) with the result that the poor agricultural prospects in combination with the continuing subsidence threatened the livelihood of local inhabitants, including long-term residents. As a result, roughly 50% of the 15,594 transmigrant families that originally moved to the area have left it again (Government of Indonesia, 2009; Rieley et al., 2002). After the devastating fires during the extremely long El Niño dry spell of 1997,

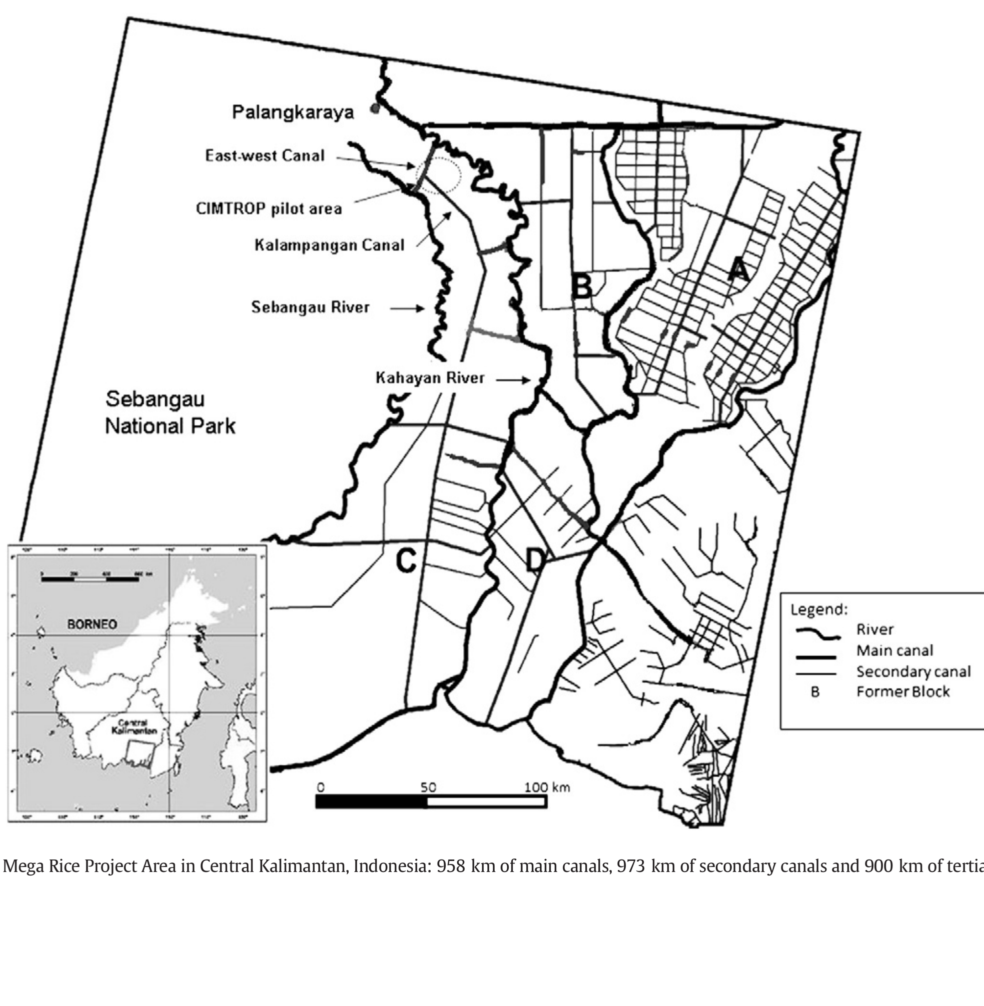

Fig. 1. Map of the Former Mega Rice Project Area in Central Kalimantan, Indonesia: 958 km of main canals, 973 km of secondary canals and 900 km of tertiary canals (in Block A) were constructed.

the MRP was terminated in 1999 (Presidential Decree No. 80/1998). Since that time, several restoration and rehabilitation activities have been initiated (Page and Graham, 2008).

1.3. Peatland restoration

Peatland rehabilitation aims to repair ecosystem processes, productivity and services of the former peatland, but does not imply the re-establishment of the pre-existing biotic integrity in terms of species composition, community structure and ecosystem functions (Clarke and Rieley, 2010). Peatland restoration, i.e. the process of assisting the recovery of peatland that has been degraded or damaged to its original natural condition, goes one step further. Unlike the well-established studies of ecological restoration of temperate peatlands (Kozulin et al., 2010), knowledge of tropical peatland restoration is still in the early stage (Erwin, 2009; Jaenicke et al., 2010; Page et al., 2009). It is clear, however, that appropriate water management is the key to restoration as it minimizes carbon losses due to oxidation and fire, and allows vegetation to regrow (Ritzema and Wösten, 2002; Ritzema et al., 2003). Although in open restored degraded areas the vegetation component of the carbon-sequestration capacity is still too small to compensate for carbon losses from peat decomposition, improved hydrology could be an important factor for reducing fire hazard and creating conditions for forest vegetation re-establishment (Jauhiainen et al., 2008; Page et al., 2009).

Research on appropriate methods for controlling water tables in tropical peatlands used for agriculture was initiated in Western Johor, Malaysia in the 1990s (Land and Water Research Group, 1996) and resulted in guidelines for agricultural development in tropical peatlands (Department of Irrigation and Drainage, 2001). In Central Kalimantan, these guidelines were not followed during the construction of the Mega Rice Project, although the Provincial Public Works Department used robust structures to control water levels in agricultural areas. These structures are made of concrete and geotextile and are equipped with adjustable stop logs.

The first efforts to restore the hydrology in degraded peatlands in Central Kalimantan started in Block A of the former MRP where Wetlands International built 20 dams in deep peat (>3 m). These dams have a width up to 30 m and consist of two rows of poles alongside bags filled with sand in the core (Suryadiputra, 2005). The dams were built by a local contractor in co-operation with the local community using building materials from outside the area (such as concrete and sand). The same type of dams were built by WWF-Indonesia to block illegally dug canals in the Sebangau National Park; since 2005 more than 176 canal sections have been blocked (Maya, 2009). Numerous problems were encountered during these efforts, in particular: (i) transport of the materials is extremely difficult because of the waterlogged conditions and the low bearing capacity of the peat; (ii) misalignment and excessive settlement caused by the use of imported materials with a unit weight exceeding the bearing capacity of the peat; and (iii) seepage and internal erosion caused by the high permeability of the peat.

The restoration study discussed in this paper was conducted by the Centre for International Cooperation in Sustainable Management of Tropical Peatland (CIMTROP), based at the University of Palangka Raya, Central Kalimantan. The overall objective was to investigate how peatland hydrology can be restored by blocking drainage canals. The hypothesis is that construction of dams will raise the water levels in canals, thus reducing forest drought stress and helping to maintain the ecosystem carbon-storing capacity (Hirano et al., 2007; Suzuki et al., 1999). The specific objectives were to test the use of locally available materials for the construction of dams and to study the effect of these dams on water tables in adjacent peat domes.

2. Site information

The CIMTROP pilot area is located in a peat dome in the northern part of Block C of the former MRP (2°18–20″ S and 114°0–2′ E) (Fig. 1). The peat dome is lens-shaped, elongated and irregular rather than the 'oval shape' that is characteristic of peat bogs. Near the study area the dome is approximately 10 km wide with a maximum elevation of approximately 3 to 4 m above the water levels in the two adjacent rivers. The surface slope declines from 1 to 2 m km^{-1} near the rivers to less than 0.5 m km^{-1} in the centre of the dome (Jaya, 2005). Peat thickness increases from 1 to 3 m near the rivers to around 10 m in the centre. The subsoil consists of a mixture of marine and riverine deposits. Two main canals cut through the dome: the East-west Canal that connects the Sebangau and Kahayan Rivers, and the Kalampangan Canal that runs parallel to the top of the peat dome. On the Sebangau River side, the East-west Canal has a gentle slope, on average 0.5 m km^{-1}, while on the Kahayan River side the slope is relatively steep, on average 1.5 m km^{-1} (Jaya, 2005). The Kalampangan Canal, which is situated along a contour about halfway between the top of the peat dome and the Sebangau River, has a more gentle slope varying between −0.6 and +0.4 m km^{-1}. Both canals have a top width varying between 15 and 20 m and a depth varying between 3 and 4 m.

On the south bank of the Kalampangan Canal the original peat swamp forest has remained intact, although it has been logged over at least once. The vegetation is comparable to the relatively undisturbed peat swamp forest in the adjacent Sebangau National Park (Shepherd et al., 1997). On the north bank the entire forest was destroyed by fires in 1997/98 and again in 2002. Information on vegetation change under different fire frequency and severity has been reported by Page et al. (2009). The parts of the area that have been subjected to only one low-intensity fire undergo progressive succession to secondary forest, with initial tree species diversity values comparable to those for the adjacent, relatively undisturbed Sebangau peat swamp forest (Page et al., 1999). With increased intensity and frequency of fire, the number of tree species and individual trees, saplings and seedlings are greatly reduced, with only two dominant recolonizers, namely *Combretocarpus rotundatus* and *Cratoxylum glaucum*. At the highest levels of fire related degradation, secondary succession back to forest is prevented and is replaced by retrogressive succession to lower growing, less structured plant communities dominated by ferns (species of *Stenochlaena*, *Lygodium*, *Polypodium* and *Pteris*) and sedges (*Cyperus* and *Scleria* spp.) with very few or no trees (Hoscilo et al., 2008, 2011).

3. Methods

3.1. Dam construction

Peat soils have low bearing capacity and high permeability (Wösten and Ritzema, 2001). These characteristics have been taken into account in the design and construction of the dams, i.e.:

- Dams were not designed to store water, which is not possible because of the high permeability, but rather to increase resistance to flow to maintain high water levels. Thus dams were designed as weirs to allow overflow during high rainfall events.
- Differences in water levels upstream and downstream of the dams were kept to a minimum to avoid seepage through and underneath the dams. Model studies and field research indicated that the head difference should be less than 0.50 m (Beekman, 2006; Ritzema et al., 1998).
- Indigenous building materials were used, i.e. *galam* timber (*Melaleuca cajuputi* or swamp tea tree) and peat (*gambut*). The benefits are threefold: (i) locally available, thus transport costs are kept to a minimum; (ii) the unit weight is lower than that of commonly used building materials (sand, gravel and concrete), and (iii) local craftsmen are familiar with these materials.
- Dams are of the so-called cofferdam type, consisting of a frame made of galam poles filled with compacted peat (Fig. 2). The poles extend several metres into the peat subsoil.
- To reduce subsidence, building materials with a similar unit weight as the surrounding peatland were selected. Consequently, the (on-going)

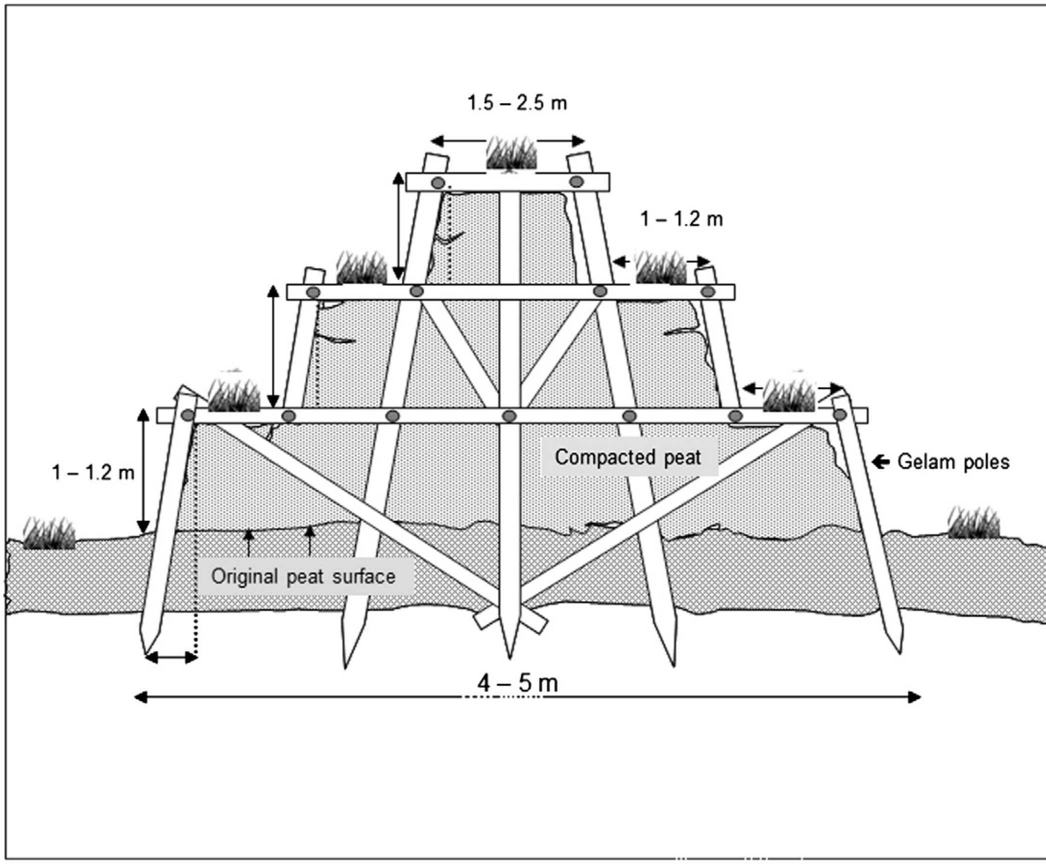

Fig. 2. The dams were built using locally available materials: peat (*gambut*) and *galam* poles.

consolidation of the peat layer under the structure is approximately equal to the total, unavoidable, subsidence of the surrounding peat area. A practical consequence of this design is that the pressure caused by a potential overburden should be very low, e.g. for a head difference of 0.50 m the pressure should not exceed about 2 kPa or 200 kg m^2 (Department of Irrigation and Drainage, 2001).

- Dams were designed to allow easy vegetation establishment on the dam as well as in the blocked canal sections between dams. The dams built from compacted peat and galam poles will disintegrate with time. The peat above the water table will oxidize and those parts of the galam poles that are not saturated have a limited lifetime (3 to 5 years). Thus eventually the natural vegetation should take over. Vegetation on the dam itself will help to stabilize the side slopes and thus reduce the risk of erosion. Vegetation in the canal sections will reduce water flow and the decomposed remains will slowly fill up the canal, initiating the re-growth of the peat layer.

Six dams were constructed: four in the East-west Canal and two in the Kalampangan Canal (Fig. 3). Construction was done using manual labour because the contractors found it too risky to bring in machinery. In Sarawak, under similar conditions, for example, a number of excavators were lost due to the very low bearing capacity of the peat (personal communication Tom Chong, 2008). The dams were constructed under waterlogged conditions since dewatering in these highly permeable peat soils was ineffective. Construction started at the beginning of the dry season of 2005, with dams No. 5 and No. 6 being constructed in May and the other dams being completed in September 2005.

The dams in the Kalampangan Canal (Nos. 5 and 6) were constructed without spillway (Fig. 4A), because the canal runs parallel to the contour lines of the peat dome and not much flow was expected, even during extreme rainfall. The dams in the East-west Canal (Nos. 1, 2 and 4) were built as weirs with a spillway on top to provide for safe discharge of flood water during extreme rainfall (Fig. 4B). For dam No. 3 another type of dam with extended side wings was selected to direct the water away from the canal back to the peatland (Fig. 4C). The

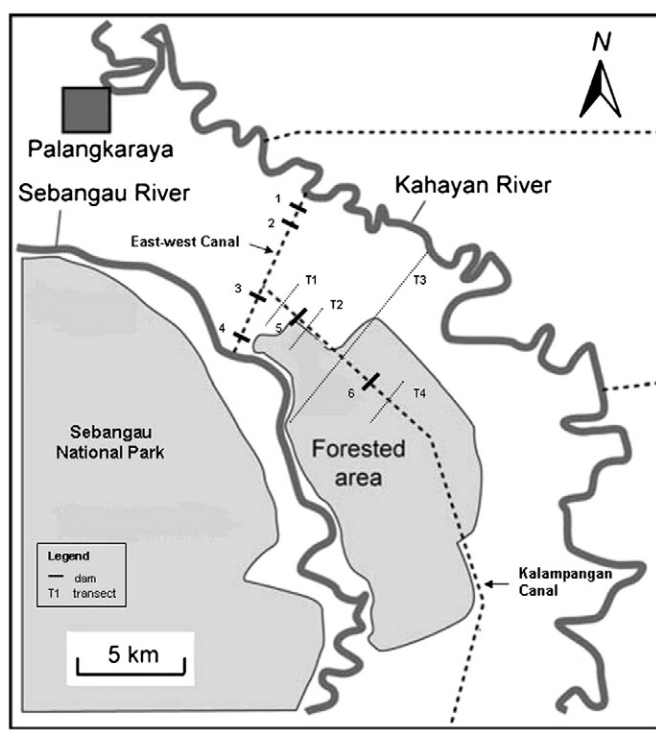

Fig. 3. Location of the dams and transects in the study area.

Fig. 4. A: Dam (No. 5) without spillway just after construction; B: Dam (No. 1) with spillway 2 years after construction after a heavy rainfall event; C: Dam (No. 3) with side wings after construction; and D: Dam (No. 3) with side wings damaged after a heavy rainfall event.

compaction of the subsoil and the construction of the foundation of the dams proved to be very problematic. Furthermore, the galam poles, with a maximum length of 6 m, were too short to reach the mineral subsoil. The original plan was to fill the canal sections between the dams by pushing the soil from the embankment back into the canal but this idea had to be abandoned because of the risk of losing machinery. The side slopes, tops and banks were planted with Red Balau (*Shorea balangeran*), an indigenous (peat)-swamp forest tree (Fig. 4B and C).

3.2. Water table monitoring programme

To monitor water tables and corresponding subsidence rates, four transects, each with 11 observation wells and 2 subsidence poles were

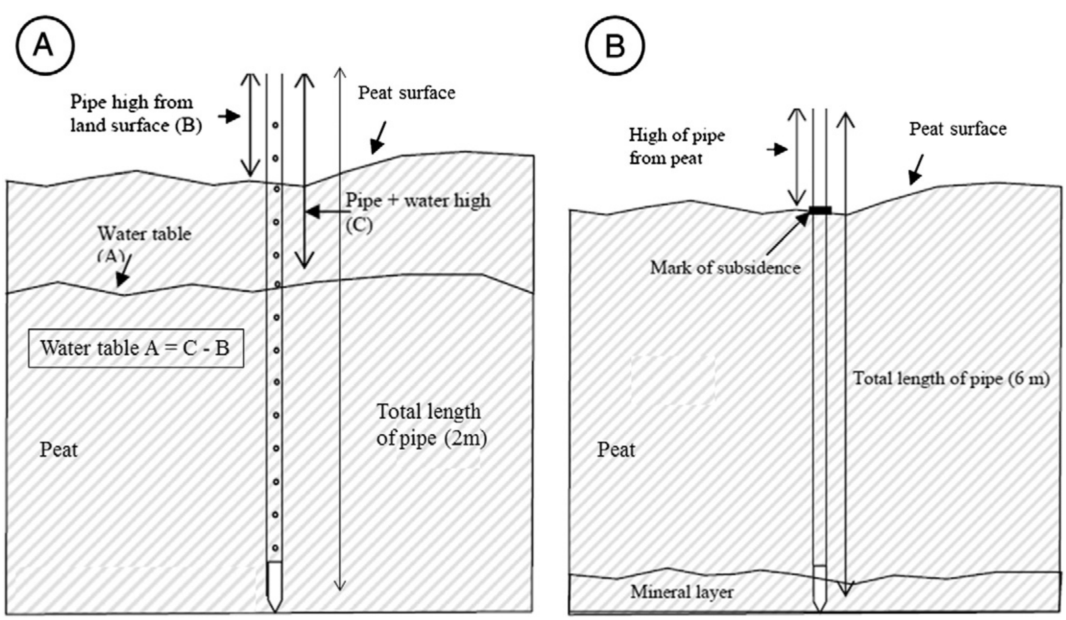

Fig. 5. A: Groundwater table depths/levels were measured using observation wells; and B: Subsidence was measured with subsidence poles.

installed on each side of the Kalampangan Canal up to a distance of 500 m (Fig. 3). Two transects were located in the degraded part of the area (T1 and T2), and two in the original peat forest (T3 and T4). To monitor the water tables over the complete peat dome, transect T3 was extended to the Sebangau River (about 3 km) and to the Kahayan River (about 7.5 km). In these extended sections, subsidence poles and observation wells were installed next to each other at 500 m intervals. The groundwater table was measured relative to the peat or land surface (Fig. 5A) and subsidence levels relative to the elevation of the mineral subsoil (Fig. 5B). The monitoring programme included measurement of the following parameters: (i) daily rainfall; (ii) daily water tables in the 500 m transects; (iii) water tables 3 times per month in 22 observation wells in the extended transect; and (iv) subsidence levels once per year. The monitoring programme started in September 2004 and continued up to June 2009.

4. Results and discussion

4.1. Dam performance

In December 2005, after an extreme rainfall event, the two dams in the Kalampangan Canal (No. 5 & No. 6) were damaged by water seeping underneath and along the sides. The dams were repaired in March 2006, but were damaged again in August 2006.

During an extreme rainfall event in August 2007, dam No. 3 in the East-west Canal was also damaged during a flash flood. In a short period of time, the water level in the canal rose by several metres. Although the dam was not overtopped, seepage flow eroded one of the side wings of the dam (Fig. 4D) (personal communication Suwido Limin, 2007). The lesson learned from this disaster was that the extended side wings type of dam should not be built in canal sections perpendicular to the contour lines, but only in canal sections that run parallel to the contour lines. Only then will it be possible to divert the water safely downhill.

4.2. Effect of dams on groundwater table

In a peat dome, the depth of the (ground)water table varies in place and in time. The water table had the same dome shape as the peat but was less irregular, meaning that it was in some places above and in other places below the peat/land surface (Fig. 6). The water table fluctuated over the year depending on the rainfall, the only source of water in these elevated domes (Table 1). In the rainy season (December to April) the water table was near or above the surface, but in the dry season July–October) it fell to well below the surface.

There is a clear relationship between the depth of the water table and rainfall: in 2006, an El Nino year, there was hardly any rainfall from August to November and the water table dropped to more than 0.8 m below the ground surface (Fig. 7). These fluctuations are comparable to the fluctuations of the water table in the natural forest in the adjacent Sebangau National Park (located on the opposite side of the Sebangau River). In Sebangau National Park, the average depth of the groundwater table is around 0.4 m −GL during a normal year, but can fall to as low as 1.0 m below the surface in a dry year. In the rainy season it can rise up to 0.2 m +GL (Takahashi et al., 2002).

The construction of the dams raised both the water levels in the upstream canal sections and the groundwater table in the surrounding peatland (Table 2). In the first few months after construction, the average water table along the transects T1, T2 and T3 varied between 0.26 and 0.35 m −GL, significantly higher than before the construction of the dams when it varied between 1.02 and 1.22 m −GL. In the following dry season (July–November 2006), the water tables dropped again to well below 0.40 m indicating that the dams cannot maintain high

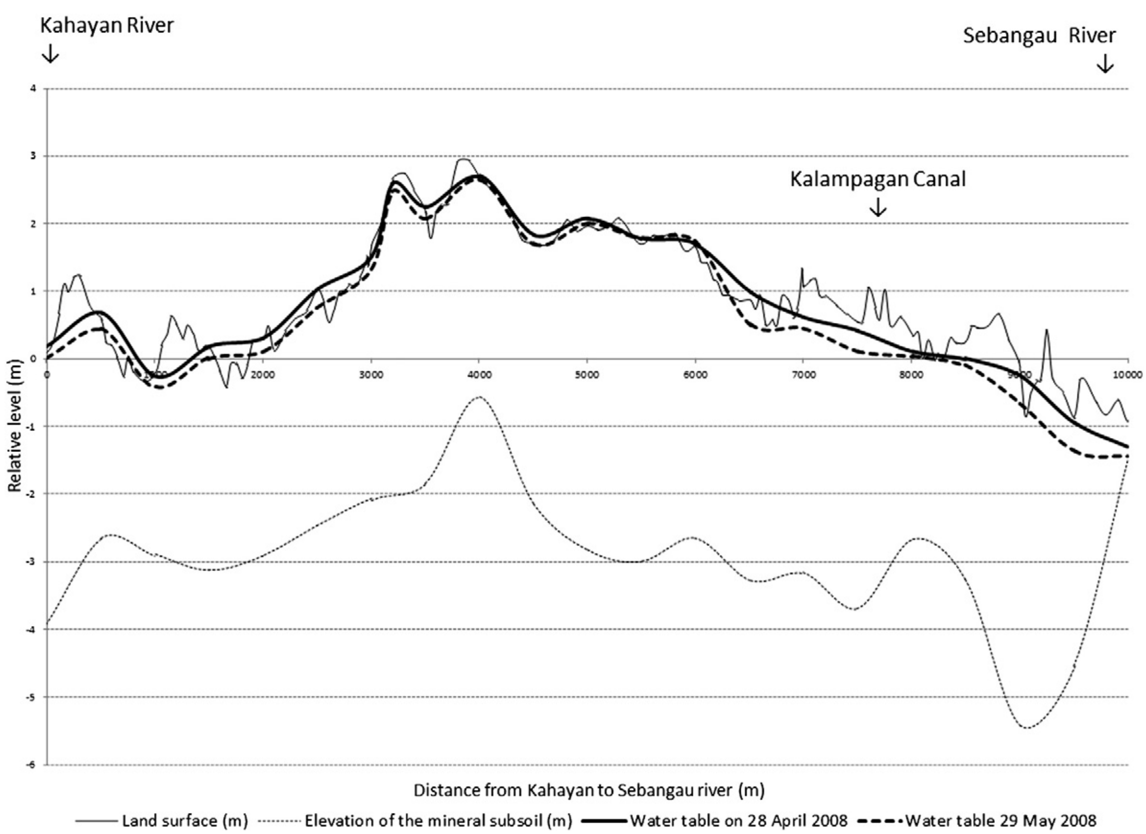

Fig. 6. Cross section of the peat dome at the north side of Block C near Kalampangan showing the elevation of the peat dome and the depth of the water table (Transect 3: 22 observation wells at a distance of 500 m).

Table 1
Monthly average depth of the water table across the peat dome at the north side of Block C at Transect 3 (average of 3 observations per month in 22 observation wells).

	2005	2006	2007	2008	2009	Average 2005–2009
January		−0.08	−0.06	0.15	0.08	0.02
February		0.01	0.11	−0.14	0.09	0.02
March		−0.06	−0.01	0.36	0.05	0.09
April		0.01	−0.06	−0.05	−0.03	−0.03
May		−0.08	−0.12	−0.24	−0.14	−0.15
June		0.05	−0.03	−0.2	−0.4	−0.15
July		−0.31	−0.04	−0.36		−0.24
Augustus		−0.52	−0.22	−0.32		−0.35
September		−0.78	−0.49	−0.3		−0.52
October		−0.87	−0.18	−0.39		−0.48
November	−0.14	−0.73	−0.02	0.07		−0.21
December	−0.15	−0.01	0.09	0.11		0.01
Yearly average		−0.28	−0.09	−0.11		−0.14

Note: In March 2008 Kahayan river bank was flooded.

Table 2
Average depth of the water table along the three transects on peatland before and after the construction of dams in Block C (Limin et al., 2008).

	Depth of the water table (m)		
Year	Transect 1	Transect 2	Transect 3
Before dam construction			
Sep-04	−0.84	−0.87	−1.08
Oct-04	−1.51	−1.34	−1.45
Nov-04	−1.04	−0.86	−1.12
Average	−1.13	−1.02	−1.22
After dam construction			
Jun-05	−0.59	−0.83	−0.41
Jul-05	−0.34	−0.27	−0.29
Aug-05	−0.12	−0.38	−0.09
Average	−0.35	−0.49	−0.26

water tables during prolonged dry periods. This is likely due to the high permeability of the peat which results in lateral seepage along and below the dams. Similar results are reported for the monitoring site in the Sebangau National Part (Maya, 2009). Overall, the level of the water table in the pilot area remained higher after construction of the dams. The effects of this are further discussed below.

4.3. Effects of dams on subsidence

The relation between the depth of the water table as effected by the dams and the subsidence rate in the Kalampangan site is difficult to establish accurately because long-term data records are needed and only the 4 years of monitoring data from this study are available (Table 3). Over these years the average subsidence across the peat dome was 1.2 cm y^{-1}. As the average depth of the water table was 0.14 m (Table 1) the rate of subsidence is surprisingly close to the linear relation established by Wösten and Ritzema (2001).

The canals increased the drainage of the peat dome as the water table close to the canals was 0.40–0.50 m deeper compared to the water table at a distance of 1000 m away from the canal (Table 4). This difference is consistent throughout the year, although in the dry season, the water tables are, on average, 0.30 m deeper than in the rainy season. As the water table in the peat close to the canals is lower, the rate of subsidence near the canals is higher. Consequently, the canals are "eating" themselves into the peat dome, creating depressions (Fig. 8). These higher subsidence rates cannot be confirmed with the limited data from the four year monitoring period, but they can be clearly seen from the cross-section of the Kalampangan Canal in Fig. 8. The deeper the canal "sinks" in the peat the higher the rate of subsidence will be. Blocking the canal with dams cannot stop this process because the dams are not watertight; in the dry seasons the water table will always drop well below the peat surface.

Another effect of the higher subsidence near the Kalampangan Canal is that the canal intercepts part of the overland flow and interflow that moves from the top of the peat dome towards the Sebangau River. This has two effects: (i) lower water tables at the downstream (Sebangau) side of the canal, and (ii) higher discharges into the canal during extreme rainfall events. The first effect was indeed observed: the difference in the depth of the water table at Sebangau side of the canal was deeper than at the peat dome (Kahayan) side of the canal (Table 5). The second effect was not measured but as discussed in Section 4.1, the dams No. 5 and No. 6 were damaged during extreme rainfall events in December 2005 and again in August 2006, probably as a result of high discharges in the canal.

4.4. Effects of dams on peatlands

The previous discussion clearly indicates that the Kalampangan Canal has a pronounced influence on the water table in the surrounding peat land. In both the degraded open non-vegetated area as well as in the natural forest area on the Kahayan side of the canal, water tables were higher and prevailed longer than on the Sebangau side, both in the rainy and dry seasons (Table 6).

The construction of the dams did not change this situation. Field observations indicate that the forest area at the Sebangau side still has a 15–30 cm deep highly porous and fibric peat horizon (almost a decade after the initial drainage). Thus it is likely that in the degraded forest and

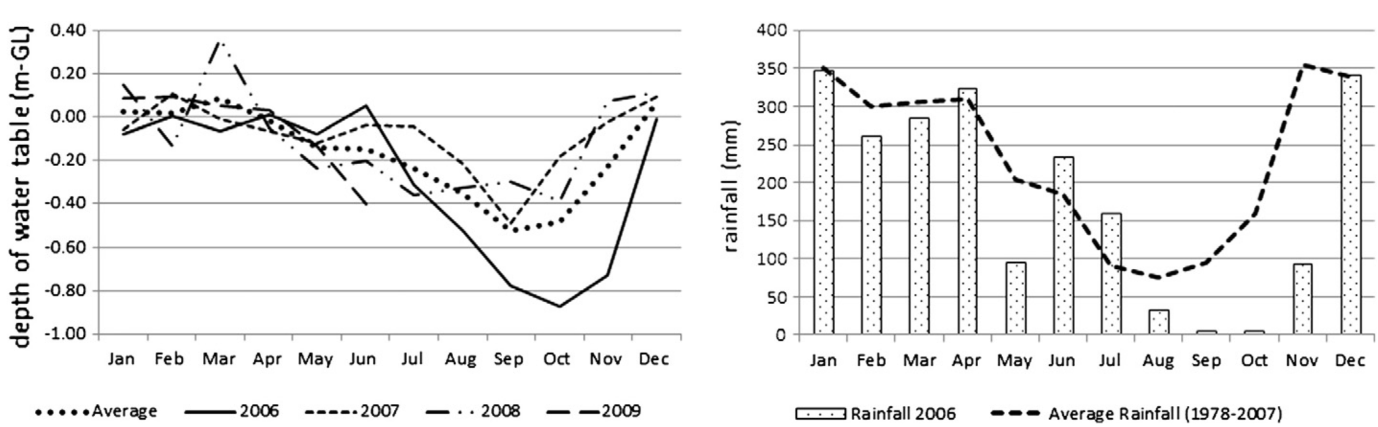

Fig. 7. Relation between the depth of the water table and the rainfall: Left: depth of the water table over the years 2006–2009 (average of 22 observation wells in Transect T3). Right: long-term average rainfall (1978–2007, Palangka Raya, Source: Meteorology and Geophysics Office) and the rainfall at the study site in the El Niño year 2006.

Table 3
Subsidence along Transect No. 3 across the peat dome measured from the Kahayan River to the Sebangau River over the period 2006–2009.

No.	Distance from Kahayan River	Peat thickness	Elevation of the peat surface (cm + RL)		Subsidence over the period 2006–2009	
	(m)	(cm)	26-02-2006	31-03-2009	(cm)	(cm yr^{-1})
1	0	400	80	Lost		
2	500	323	274	278	4	1.3
3	1000	270	213	217	4	1.3
4	1500	330	224	228	4	1.3
5	2000	320	170	176	6	2.0
6	2500	349	137	142	5	1.7
7	3000	375	190	195	5	1.7
8	3500	400	216	219	3	1.0
9	4000	327	108	112	4	1.3
10	4500	386	144	148	4	1.3
11	5000	480	159	163	4	1.3
12	5500	470	148	152	4	1.3
13	6000	432	249	253	4	1.3
14	6500	415	111	116	5	1.7
15	7000	424	104	106	2	0.7
16	8000	303	138	140	2	0.7
17	8500	350	219	222	3	1.0
18	9000	527	85	85	0	0.0
19	9500	367	219	220	1	0.3
20	10,000	58	141	143	2	0.7
					Average	1.2

open area on the Kahayan side of the Kalampangan Canal, surface runoff in the top layer of the peat profile exceeded the surface runoff in the original forest at the Sebangau site. The surface peat in the degraded areas has a collapsed peat macropore structure due to the effects of repeated fires (lost surface peat), compaction and increased peat decomposition. Periodicity and duration of oxidation–reduction conditions in drying or wetting peat are the most important abiotic factors in the tropical peat carbon cycle (Inubushi et al., 2003; Ueda et al., 2000). In the undrained natural peat forest waterlogging can last for several months, which, together with the litter deposited from the vegetation (above ground- and root litter), slows down the onset of aerobic decomposition. By contrast, in a drained forest with porous surface peat, waterlogged periods were shorter or non-existent (Table 6), and aerobic decomposition continued relatively intensely throughout the year. Comparison of the CO_2 emission in the drained forest in the study area with CO_2 emission in the undrained Sebangau National Park indicates that in the former decomposition takes place within a relatively thick unsaturated upper peat zone leading to very high rates of CO_2 emission (Jauhiainen et al., 2005, 2008). Because of the high rate of root respiration, raising the (ground)water level hardly results in any emission reduction in peat surface CO_2 fluxes. Nonetheless, using dams to improve hydrological conditions by keeping dry season water tables closer to the peat surface and roots in these forests can be expected to create better conditions for vegetation (re-)growth. This is confirmed by the subsidence data, which indicates that in the natural forest, despite the lower water table, there is still accumulation of organic matter contrary to the degraded peat area where subsidence was observed (Table 6). The period over which subsidence was monitored is, however, too short to draw firm conclusions.

Table 4
Relation between the depth of the water table and the distance from Kalampangan Canal (average of transects T1, T2, T3 & T4 over the period September 2004–April 2007).

	Depth of the water table (m)			
	Distance from canal			
	10 m	100 m	400 m	1000 m
Dry season (Jul–Oct)	−0.88	−0.54	−0.35	−0.33
Rainy season (Nov–Apr)	−0.50	−0.13	−0.05	−0.06
Year (dry & rainy season)	−0.56	−0.24	−0.12	−0.15

5. Conclusions and recommendations

The experiments conducted at the Kalampangan area taught us the following lessons:

- Dams can permanently raise the water table in a degraded peat dome. The higher water table reduces subsidence and CO_2 emissions. It should be remembered, however, that although the average water table along the transects rose from 1.12 m −GL to 0.37 m −GL, water tables in the dry season may still fall to below 1 m −GL.
- Dams built with locally available construction material, i.e. peat (*gambut*) and *galam* poles, perform reasonably well. Construction however is problematic, especially on deep peat, because (i) the locally available *galam* poles are generally too short to stabilize the foundation; and (ii) compaction of the peat is difficult, especially if the base of the dam becomes waterlogged during construction.
- The intended regrowth of vegetation, both on the dams as well as in canal sections between the dams, did indeed take place. It is assumed that the vegetation on top of the dams reduced the risk of erosion and that the vegetation in the canal sections decreased flow velocities. It is expected that the increases in litter deposition into drainage systems have led to reduced water outflow from the area and this is considered a positive step towards structural rehabilitation of surface peat.

Next to these positive effects, some drawbacks were observed:

- The low water levels in the canals have accelerated peat subsidence alongside the canals. Subsidence during the dry season is clearly much greater than (re-)growth of the peat in the wet season. As a result, the canals “eat” themselves into the peat creating local depressions. This leads to the interception of overland- and interflow by the canals, which increases the flow rates in the canals and the risk of overtopping during extreme rainfall events.
- The interception of overland- and interflow during extreme rainfall events can cause flash floods in the canals. At several locations this resulted in damage to the dams.
- Interception of overland- and interflow by canals built along the contour lines of a peat dome results in significantly lower water tables downhill of the canals.
- Due to the high permeability of the peat, seepage flow underneath and alongside the dams presents a major threat which can result in the collapse of dams.

Based on these experiences, improvements in canal blocking strategies for drained tropical peatlands can be recommended. It is important to remember that the main objectives of the blocking strategies are: (i) to raise water tables in the peat land; (ii) to reduce runoff through the canals and instead to re-establish the natural overland flow from the top of the dome towards the adjacent rivers, and; (iii) to reduce the flow velocity in the canals as much as possible to avoid erosion. Depending on the location of the canals with respect to the gradient/slope of the peat land the following canal blocking strategies are recommended:

- Canals running perpendicular to the contour lines of the peat dome and connecting the rivers. Because of the high gradients, flows and velocities in these canals, and the low bearing capacity of the peat, the difference in the upstream and downstream water level (head difference over the dam) should be kept to a minimum (<0.5 m). Consequently a cascade of multiple robust dams, each with a bypass, is required. The main function of the dams is not to divert the water, which is almost impossible as the canals have “sunken” into the peat, but to act as a drop structure to reduce flow velocities and safely discharge the excess water over the dam (or bypass) into the downstream section.
- Canals that run more or less parallel to the contour-lines of the peat dome and have a more gentle slope with lower flow rates. Because

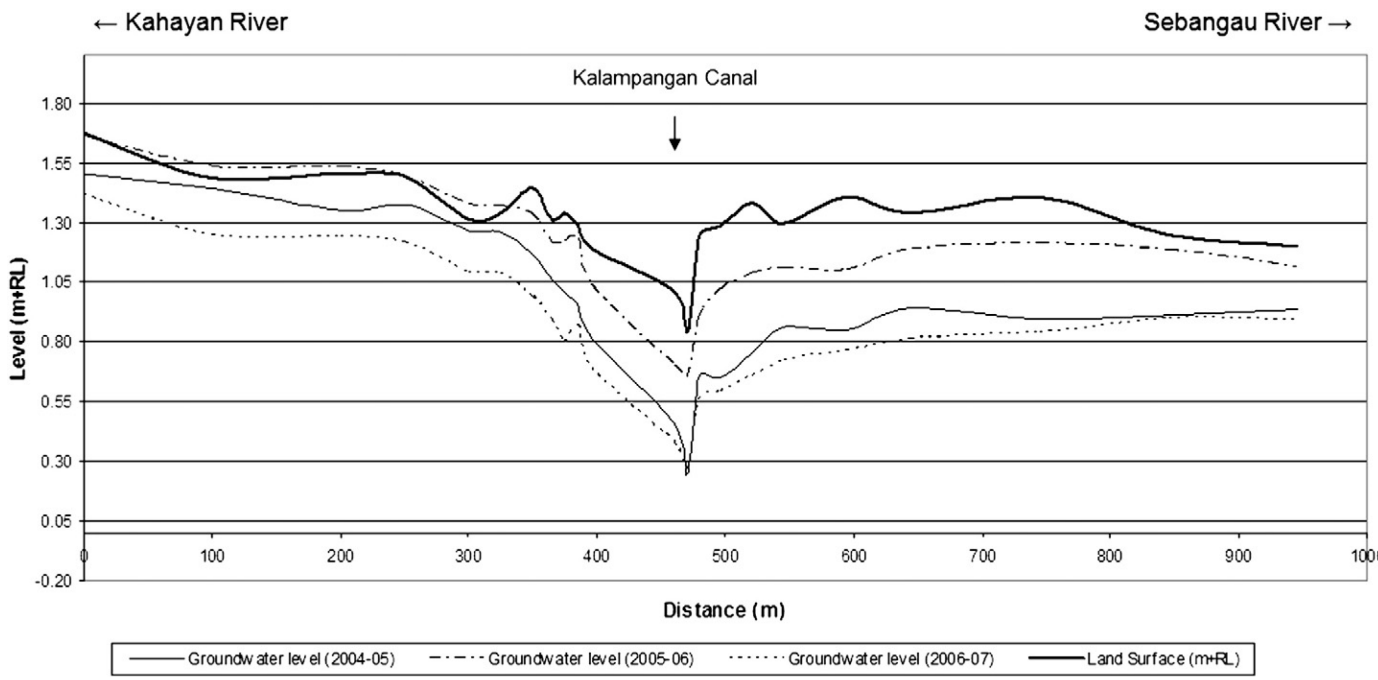

Fig. 8. Close to the Kalampangan Canal water tables are lower and, due to the resulting higher subsidence, the canal is "eating" itself into the peat dome.

the primary goal in this situation is diversion of the water from the canals to re-establish the overland flow and interflow, the elevation of the dams should be above the elevation of the surrounding peatland (>0.30 m) and side wings should be constructed to allow the water to be diverted in a downhill direction as overland or interflow. While overtopping is not a great concern, seepage through, underneath or along the sides of the dam is a major risk. This type of dam will only be successful if the head difference between the water level in the canal and the peat surface is not too large and if the surface runoff water can be safely diverted away from the canal.

It is important to note that the construction of dams, however effectively done, cannot prevent water tables in the surrounding peat from dropping as low as 1.0 m below the surface in the dry season. Thus canal blocking has only a limited impact on (ground)water tables. Canal blocking should be seen as a long-term rehabilitation measure. The resulting improvement of the hydrology creates conditions for suitable forest vegetation regeneration that over a long period of time will create opportunities for improved peat carbon store maintenance or even the re-establishment of carbon sequestration.

Additionally, canal blocking should not be seen as a standalone measure or an objective in itself; nor as only an instrument for the restoration of the natural peat forest. Rather canal blocking is best seen as just one part of an overall strategy to restore peatlands and minimize carbon emissions, fire and haze. This study clearly indicates that both the strategies for long-term restoration and research into the rehabilitation of tropical peat lands need further refinement.

Table 5
Depth of the water table and corresponding subsidence on both sides of the Kalampangan Canal along transects T1, T2, T3 and T4.

	Sebangau side (obs. well 12–22)	Kahayan side (obs. well 1–11)	Δ (Seb-Kah)
Transect 1:			
Land type	Degraded	Degraded	
Depth of the water table (m)	0.41	0.17	0.24
Subsidence (cm yr^{-1})	0.7	0.9	−0.2
Transect 2:			
Land type	Natural forest	Degraded	
Depth of the water table (m)	0.4	0.14	0.26
Subsidence (cm yr^{-1})	0.1	0.2	−0.1
Transect 3:			
Land type	Natural forest	Natural forest	
Depth of the water table (m)	0.62	0.30	0.32
Subsidence (cm yr^{-1})	0.4	0.4	0
Transect 4:			
Land type	Natural forest	Natural forest	
Depth of the water table (m)	0.41	0.20	0.21
Subsidence (cm yr^{-1})	n.a.	n.a.	n.a.

Note: at each transect there were 11 observation wells and 2 subsidence poles on each side of the canal up to a distance of 500 m.

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Table 6
Average depth of the water table in the degraded and natural forest in the dry (July–October) and rainy (November–June) seasons (calculated from the daily water levels in the 22 observation wells and 4 subsidence poles for each transects).

	Average depth of the water table (m)			
	Sebangau side		Kahayan side	
	Degraded	Natural forest	Degraded	Natural forest
	(T1)	(T2, T3 & T4)	(T1 & T2)	(T3 & T4)
Rainy season	−0.25	−0.45	−0.03	−0.19
Dry season	−0.84	−1.04	−0.52	−0.62
Year	−0.41	−0.48	−0.16	−0.25
Subsidence (cm yr^{-1})	−0.7		−0.3	
Accumulation (cm yr^{-1})		0.03		0.4

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