Hydrogenetic Aspects of Peatland Restoration in Tibet and Kalimantan

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Abstract

Living peatlands are often intricate systems with important self-regulation mechanisms to maintain the balance between ‘vegetation,’ ‘water’ and ‘peat.’ An important part of this self-regulation is directly associated with vegetation, which is generally ignored or insufficiently acknowledged in hydrological approaches to peatland restoration. This paper illustrates the ecohydrological complications of restoration of recently degraded peatlands in Tibet (China) and Kalimantan (Indonesia).

On the Ruoergai Plateau (China), long-term grazing has changed many original percolation mires into more vulnerable surface-flow mires that since the 1950s have become subject to overgrazing and drainage. In Kalimantan, especially since the 1990s, peat swamp forests have been disturbed by drainage and deforestation. For both areas, different peatland degradation stages are distinguished with their own restoration perspectives and approaches. Because restoration of severely degraded peatlands is extremely difficult to achieve, the highest priority is the identification and protection of undisturbed mires and the prevention of further degradation. In both areas the restoration of the water retaining and storing role of vegetation is indispensable to prevent the peat body from further erosion and to provide adequate conditions for the regeneration of living mires. As the vegetation in both peatland areas is the main object of human exploitation (overgrazing, deforestation), peatland restoration is not only a matter of technical management, but has an important social dimension.

Key words: degradation, ecohydrology, mires, self-regulation, vegetation

1. Introduction

Although the majority of the mires of the world is still in pristine condition (Joosten & Clarke, 2002), in some regions the degradation of peatlands has – in addition to affecting the livelihoods of local communities – effects of global dimensions. The Ruoergai peatlands on the Tibetan Plateau constitute the headwaters of the Yellow River and are vital for regulating water supply to many millions of people in its extensive downstream areas. Peat oxidation by drainage and peatland fires in Southeast Asia is currently responsible for CO₂ emissions of over 2 Gigatonnes per year (Hooijer et al., 2006) which constitutes a substantial part of global anthropogenic CO₂ emissions. Restoring these peatlands and their regulation functions is therefore a task of highest urgency.

Peat is sequestered and conserved as a result of permanent waterlogging. Consequently restoration must pay much attention to hydrological aspects. In praxis, however, hydrology often focuses on rather static geohydrological aspects and insufficiently acknowledges the hydrological role of vegetation and the dynamic hydraulic properties of vegetation and peat. In this paper we illustrate the hydrological complications of peatland restoration from two case studies from Asia (Fig. 1): the Ruoergai Plateau, Tibet, and the Ex-Mega...
2. Mire Ecology and Peatland Degradation

Crucial for understanding peatlands and especially mires (actively peat accumulating peatlands) is the awareness that ‘plants,’ ‘water,’ and ‘peat’ are very closely connected and mutually interdependent (Fig. 2). The plants determine what type of peat will be formed and what its hydraulic properties will be. The hydrological conditions determine which plants will grow, whether peat will be stored, and how decomposed the peat will be. The peat structure determines how the water will flow and fluctuate. The close interrelations imply that when any one of these components changes, the others will change too. Not necessarily at once, but in the longer run inevitably.

Not all components react with the same speed. Generally the vegetation is affected more easily than the hydraulic properties and those again react much faster than the composition of the peat. Indeed peat, unlike sand, is alterable: as an organic substance it changes its properties and can even totally disappear as a result of decomposition and oxidation. When it is not protected by vegetation, peat easily erodes, because it is much lighter than sand. However, peat is a ‘slower’ component than plants: it is more difficult to change, but when it has changed, it is more difficult to reverse the change.

Therefore we can distinguish peatland degradation stages according to the ‘inertia’ of the components affected (Table 1). As a general rule, components that are more difficult to affect are also more difficult to restore.

3. Peatland Degradation and Restoration on the Ruoergai Plateau (Tibet)

In contrast to the drier western and central parts of the Tibetan Plateau, the Rouergai Plateau in North east Tibet (32.20° - 34.10° N / 102.15° - 103.50° E, 3,400 to 3,900 m asl) has a cold and wet climate with long winters and rather short summers. Since the end of the last Ice Age this humid climate facilitated the development of the world’s largest extent of high altitude peatlands.

The slightly humified radicel (sedge) peats in the deepest layers of many peatlands suggest that during the first part of the Holocene ‘sloping percolation mires’ were the predominant mire type, whereas palynological, soil, and recent vegetation records indicate that most hills and mountains of the Plateau were at that time covered by trees. ‘Sloping mires’ impede water flow, enable their own continuous upward growth, and cause a rise of the groundwater table in their catchment area. ‘Percolation mires’ develop in areas where groundwater supply is large and evenly distributed over the year. Their little decomposed peat is highly permeable, which

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Table 1 Peatland degradation stages.

<table>
<thead>
<tr>
<th>Degradation stage</th>
<th>Peatland components</th>
<th>Site characteristics</th>
<th>Peat accumulation rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimal</td>
<td>plants / flora</td>
<td>Natural spontaneous vegetation: undrained, human impact restricted to hunting/ gathering; possibly some change in flora and fauna</td>
<td>&gt; 0 (≤ 0)</td>
</tr>
<tr>
<td>Minor</td>
<td>vegetation</td>
<td>Change in vegetation because of low-intensity grazing/mowing or forestry; not/ slightly drained; no peatogenesis</td>
<td>&gt; 0 (≤ 0)</td>
</tr>
<tr>
<td>Modest</td>
<td>hydrology</td>
<td>freshly deeply drained; spontaneous vegetation changed through recent drainage or regular harvesting; no peatogenesis yet</td>
<td>≤ 0</td>
</tr>
<tr>
<td>Moderate</td>
<td>peat hydrates</td>
<td>Long-term very shallow or recent deep drainage; some peatogenesis or change in peat type; spontaneous vegetation changed by long-term use</td>
<td>≤ 0 - &gt; 0</td>
</tr>
<tr>
<td>Major</td>
<td>form and relief</td>
<td>Long-term deeply drained or inundated, strong peatogenesis; peatland shape modified by subsidence and oxidation</td>
<td>≤ 0 - &lt;&lt; 0</td>
</tr>
<tr>
<td>Maximal</td>
<td>peat deposits</td>
<td>Intensively drained; strong peatogenesis or compact peats surfacing; peat body severely affected by peat erosion, oxidation or extraction</td>
<td>&lt;&lt; 0 - &lt;&lt;&lt; 0</td>
</tr>
</tbody>
</table>

Fig. 2 The interrelations between plants, water, and peat in a mire.
leads to water flowing through the peat body, and flexible, which enables them to respond to changing water supply by shrinking and swelling of their peat body. In this way percolation mires reduce downstream flooding and guarantee stable base flow. Their ability to oscillate allows for stable relative water levels, constant vegetation productivity, high peat accumulation rates, and makes percolation mires to the most stable peatlands in existence.

### 3.1 Change of peatland character

It was the domestication of the yak (Bos grunniens) that made permanent occupation of the harsh environment possible. Initially the percolation mires will have been only marginally used as grazing ground because their load-bearing capacity is too low to support yaks. Since about 5,000 years ago grazing has led to deforestation of the mineral uplands. Whether this deforestation was solely attributable to human impact or also caused by a changing climate is still a matter of debate. In any case the recurrent traces of charcoal in the upper horizons of the peat profiles reveal that fires became more frequent.

The deforestation resulted in increased erosion of mineral substances from the uplands. Precipitation water that was previously absorbed by upland forests and soils rushed more rapidly into the valleys. In most peatlands an increase in clastic materials is visible in the upper peat horizons, sometimes even as obvious sand or silt layers. Highly compacted radicel peats below layers with a higher clastic component illustrate that the increased load caused compaction of the hitherto accumulated peat. This improved the load-carrying capacity of the peatlands, enabling the cattle to switch from the (then overgrazed?) upland meadows to the peatlands for forage. The new peat became much stronger decomposed (because of regular animal tread and stronger water level fluctuations) and less permeable for water. This prevented water from further percolating through the peat body and forced it to flow over the peatland. As a result the ‘surface-flow mires’ originated that currently dominate many valleys of the Ruoergai Plateau.

In contrast to percolation mires, surface-flow mires hardly shrink and swell with fluctuating water supply. They show stronger peak discharge and less base flow. The only way to store substantial amounts of water is above the surface among the vegetation. The strongly humified peats of the surface flow mires are susceptible to erosion because of their higher degree of decomposition.

On the Ruoergai Plateau the water regulation function of the peatlands thus has become less effective for two reasons:

1. The upland water supply to the mires has become less regular due to deforestation and increased run-off.
2. The water regulation capacity of the mires has decreased through the change of percolation mires to surface-flow mires.

As the incoming water now has to be transported ‘over’ the peatland surface, the importance of vegetation for water regulation has strongly increased. This has made the system more fragile and vulnerable to climate change and overgrazing.

### 3.2 Peatland erosion

With the construction of roads in the 1950s the Ruoergai Plateau was opened to settlers. To enhance meat and milk production, traditional husbandry was replaced by a more market-oriented economy. Life stock numbers on the Ruoergai Plateau increased dramatically as a result of population growth and a lack of regulation. Increased overgrazing and the resulting decrease in pasture quality fuelled the demand for new rangeland. Since the 1970s, almost 50 % of the Ruoergai peatlands have been drained with severe consequences. Oxidation and mineralization of the uppermost peat layers lead to larger emissions of carbon dioxide and nitrogen. The increased water level fluctuations cause the formation of cracks that impede capillary water flow and lead to more frequent drying out of the soil. Through increased activity of soil organisms, drained peat becomes loose and fine-grained, and may eventually become hydrophobic and very easily erodable because of its low weight. Small burrowing mammals like pikas (Ochotona curzoniae, O. daurica, O. pallasi) and zokors (Myospalax fontanierii) colonized the dry areas and - with up to 300 animals per ha - boost peat erosion and oxidation by digging holes and burrows (Fig. 3).

Recognising the severity of the situation, the Chinese authorities introduced a ban on draining wetlands and stopped forestry activities in the region in 1999. In addition, they have started to fill in drainage ditches and have designated five nature reserves covering about 0.5 million ha.

### 3.3 Restoration perspectives

As a result of these developments, the majority of the Ruoergai peatlands is currently showing moderate to major degradation (cf. Table 1, Schumann et al., 2008). Next to flora, fauna and vegetation, also hydrology, peat properties and peat hydraulic conditions have changed substantially and in most cases irreversibly.

Thousands of years of grazing have created a new landscape of surface-flow mires that is recognized as a beautiful natural and cultural heritage. Although the origin of surface-flow mires from the original percolation mires must be considered to be degradation in itself (a transition of minimal to moderate degradation), it cannot be the aim to restore the former percolation mires over large extents. Firstly this would require the removal of most animals and herdsmen and would fundamentally change the physical and social character of the Plateau. But also, and more importantly, large scale restoration of percolation mires has become impossible because over large areas the peat hydraulic properties have changed irreversibly and it will take many hundreds years of peatland development to get them back.
3.4 Percolation mires

Many peatlands of the Ruoergai Plateau currently are surface-flow mires. Percolation mires of minor or modest degradation have, however, survived or regenerated locally. This is probably due to exceptional hydrologic conditions (strong seepage) and to a low intensity of grazing at these sites. It is of utmost importance to rapidly locate, protect, and restore the mires that are still in a good condition (Schumann et al., 2008).

Grazing should be restricted as trampling compacts the loose structure of the peat and may rapidly lead to degradation and erosion. New drainage must be strictly forbidden. Existing drainage ditches must be closed. In mires that have only recently been drained or that are situated in an area with abundant groundwater supply, soil hydraulics and relief may not have been severely affected yet (degradation stage ‘modest,’ Table 1). They can easily be restored fully by closing the drainage constructions. To disperse the water and reduce its volume, damming should proceed starting from the highest part of the peatland. By guiding the water over the largest possible area, flow velocity and erosive power are reduced, vegetation can more easily re-establish in the ditches (‘self-recovery’ by terrestrialization), and pressure on downstream dams decreases. Concentration of water in preferential pathways has to be prevented because its force may lead to erosion. It is crucial to raise the water table above the surface, so that as much area as possible is optimally rewetted. Therefore, dams have to be constructed at such distances from one another that the water level difference between adjacent dams does not exceed 5-10 cm in the wet season.

The ditches may be dammed/filled with peat, wood or bales of hay or straw. It is not necessary to make the constructions fully impermeable. It is sufficient to substantially hamper water flow: percolation mires are characterized by water slowly percolating through and over the peat. Sand, clay or stone should not be used, because they are too heavy and will eventually sink in the loose, watery peat. Care has to be taken that the vegetation close to the dam is not damaged, as it plays an important protective role to prevent the water from eroding the peat.

3.5 Surface-flow mires

Many peatlands of the Ruoergai Plateau are currently surface-flow mires. These mires are a degradation stage of the original percolation mires (degradation stage ‘moderate,’ Table 1): the peat hydraulic properties (porosity, storage coefficient, hydraulic conductivity and capillarity) have substantially and largely irreversibly changed. As a consequence the peatland’s capacity for water storage and regulation has decreased. But as peat accumulation has continued for some thousands of years, they can be considered as a new type of mire. Surface-flow mires belong currently to the most important grazing lands on the plateau.

Most important for the management of surface-flow mires is to avoid peat erosion by water cutting into the peat body. For that purpose it is necessary to slow down water flow and to disperse the water so that it flows off diffusely over the surface. This implies:

- retaining the water upstream,
- no construction of new and closure of existing drainage gullies, and
- conducting the water diffusely over the surface. It is crucial that no preferential flow pathways of water develop. This can be brought about by
  - maintaining dense vegetation in the wet season to hold back and spread the water and to protect the peat body and
  - diffuse herding to prevent the origin of incising or bare tracks.

The maintenance of sufficiently dense and high
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vegetation cover will normally imply an adjustment of grazing strategies (e.g. distribution of summer and winter pastures), a local and/or temporal reduction of animal numbers, or the use of the mires as hayfields for winter fodder instead of as rangeland.

In contrast to percolation mires, dams in ditches and gullies should be completely closed to force the water to flow diffusely over the surface and to prevent the origin of further preferential water pathways. To prevent the development of erosive flow paths next to the dam, overflow provisions (e.g. pipes or incisions) are often constructed in the middle of the dam/weir. Overflow provisions, however, have as a drawback that water flow is concentrated and that the drainage base remains too low to sufficiently rewet the adjacent peatland area.

3.6 Eroding peatlands

Increasing areas of peatland on the Ruoergai Plateau can not be considered ‘mire’ anymore because they have lost their capacity to accumulate peat. Such eroding peatlands suffer from:

- too little water: the water level is periodically too low to enable peat accumulation; instead peat oxidation occurs.
- too much water: the available water comes with too much force, washing the peat away and creating gullies.

These problems are interrelated because peat erosion and gully formation lead to rapid drainage and consequently periodically low water levels.

Even stronger than with surface-flow mires (see above) the problem can not only be solved by damming single ditches or gullies, because the abundant and concentrated water anyhow has to leave the peatland. When the gully is obstructed by a single dam, the water will find the next weak spot and erode the peat away there. Restoration of eroding peatlands therefore is not a matter of thinking in single dams, but of thinking in coherent hydrological systems in whole catchment areas. Even more than with percolation and surface-flow mires it is necessary to hold back the water starting from the highest part of the peatland and to disperse the water by guiding it over the largest possible area.

Restoration of eroding peatlands to peat accumulating systems (surface flow mires) can only be done by raising the water level above the peatland surface. This requires damming all drainage structures and allowing/stimulating a dense vegetation to develop. When degradation has progressed so far that it involves severe gully erosion, it is difficult to fully stop further erosion as the slopes of the gullies are too steep to allow for peat growth (Evans & Warburton, 2007). The primary aim will then be to limit further erosion, which next to hydrological measurements may also include active revegetation.

3.7 Perspectives

Whereas with respect to percolation mires and surface-flow mires, the objectives of restoration are clear and consistent (Table 2), it is more difficult to define achievable aims for eroding peatlands. This is not only attributable to the fact that the latter may comprise various stages of degradation (Table 1: stage ‘moderate’ to ‘maximal’) but first and for all to the difficulty to restore eroding peatlands to new peat accumulating mires.

Because restoration is extremely difficult to achieve, the highest priority is to prevent further degradation and to keep good things good. This implies:

- strict protection and where possible restoration of the rare and vulnerable percolation and spring mires,
- no further degradation of the ‘normal’ surface-flow (and similar water-rise) mires, and
- restoration of the heavily eroding peatlands at least to the extent that erosion is brought under control.

4. Peat Swamp Forests in Kalimantan

Peat swamp forests in south-east Asia are dome-shaped peatlands between lower-lying rivers (Fig. 4). Few people realize how special such peat domes are. The dome is able to shape the improbable paradox ‘high and wet.’ And this wetness has to be almost permanent, because the dome consists of organic material (peat) that rapidly breaks down when not saturated with water. This paradoxical situation is the result of close interactions between vegetation, peat, and water that lead to ‘self-regulation’-mechanisms that enable the continued existence of such peat domes under varying environmental conditions (Joosten, 1993).

![Fig. 4 Cross-section of peat domes in Borneo. (PS Konsultant, 1998)](image-url)
The condition of being at the same time ‘high’ and ‘permanently wet’ can only be achieved by continuous input of water from above. A close relationship exists between the height of the water bulge, the hydraulic conductivity of the soil, the amount of water input into the soil (rainfall), and the diameter of the dome, following the formula (for a circular peat dome):

\[
\frac{U}{k} = \frac{2h^2}{R^2 - r^2}
\]

in which

- \(U\) = the amount of water input into the dome (m)
- \(k\) = the conductivity of the peat (md\(^{-1}\))
- \(h\) = the height of the dome at point \(r\) (m)
- \(R\) = the radius of the dome
- \(r\) = the distance of any point to the dome centre (Bakker, 1992).

The formula shows that to keep a peat dome with a diameter of 6 km and a height of 5 m permanently wet, a water input of \(U = 5.6 \times 10^6\) k (md\(^{-1}\)) is required. When we apply a rather high conductivity value of 10 md\(^{-1}\) to our entire model dome, we find something astonishing: the dome only needs 5.6 \(10^{-6}\) md\(^{-1}\) of water input, or in more normal terms only 0.06 mm per day or 20 mm per year. Wider domes need even less water: a 5 m high dome with a radius of 6 km and a conductivity of 30 md\(^{-1}\), for example, only 15 mm per year. In a climate with several thousands of millimetres of annual precipitation, a peat dome thus needs only a miniscule fraction of that amount to maintain itself. One might wonder why peat domes are not much more common in the tropics.

The reason is simple: this small amount of – in our example – 20 mm per year must be absolutely evenly distributed over the year. Every moment that the peat dome is not fed with water, the water level will immediately drop below the surface because of continued gravity drainage. This leads to the surface peat layer becoming oxidized. If a constant supply of water of every day 0.06 mm or every minute 0.0004 mm is not guaranteed, the dome can not be maintained and will eventually disappear. This effect is aggravated by evapotranspiration, which may lead to additional water losses of several mm per day.

Even in the humid tropical climate of Southeast Asia, most of the time it is not raining. To persist, a peat dome thus needs a ‘device’ to guarantee the necessary, extremely small but constant water supply. It needs an AC/DC converter to transform the ‘alternating current’ of precipitation and evapotranspiration into a ‘direct current’ continuously feeding into the peat dome.

### 4.1 The AC/DC converter

The only way to guarantee a constant supply is by feeding the dome from some sort of water reservoir on top of the dome. Such ‘device’ must have the following properties:

1) It must – after rain showers – retain part of the water, that otherwise would flow away over the water-saturated surface. It must thus offer resistance against water flow, i.e. have a limited horizontal hydraulic conductivity.

2) It must have sufficient water in store to compensate – in times without precipitation – for all water losses from the dome by gravity drainage and evapotranspiration. It must thus have a large storage capacity.

3) It must supply the entire dome because water saturation is required for every part of the dome (Fig. 5).

Actually all material lying and standing on the dome will function as an AC/DC converter to some extent, as it will delay surface run-off and retain some water over some part of the dome surface for some time. Because the dome-inimical periods are frequent and prolonged, however, we need substantial material to create sufficient resistance and storage.

When this material is organic (and what else could it be?), the inevitable water level fluctuations will result in rapid aerobic decomposition. The proportion of coarse pores will decrease and that of small pores increase. This may look at first sight a positive development, because it might reduce lateral drainage by decreasing hydraulic conductivity. The collapse and the decreasing pore size, however, also imply a decrease in storage capacity (reservoir depth) and storage coefficient (storage per volume) and will, with the same volumes of water losses, lead to larger fluctuations of the water level. This enhances oxidation, a further collapse of the structure, and results in a positive feedback that will rapidly make the device useless (Couwenberg & Joosten, 1999). The only way to escape this dead-end development is the continuous renewal of the porous layers over our dome, i.e. by continuously adding new coarse plant material.

Such continual addition of new material to the surface leads to the development and maintenance of an explicit vertical gradient in hydraulic conductivity: a layer that is very coarse in pores in the uppermost part and that going downward becomes increasingly less porous. Such vertical gradient in pore space and hydraulic conductivity (cf. V-notch weir, Clymo, 1991) leads to more water flowing through the open structure of trunks, branches, and aerial roots at the surface in times of water surplus and high water levels. And it leads to less water flowing through the deeper, smaller pores of more decomposed material in times of low water levels and imminent water shortage (Bragg, 1997). Such structure
thus provides – by negative feedback – a self-regulation mechanism that reduces water level fluctuations under varying meteorological conditions.

The structure depicted here is the ‘active layer,’ as described by Ivanov (1953; 1981) and renamed ‘acrotelm’ by Ingram (1978). In tropical peat swamp forests, the vegetation constitutes an important part of the acrotelm. In fact, the sparsely available data indicate that in tropical swamps, in contrast to *Sphagnum* peatlands in the Northern Hemisphere, the effective V-notch structure is largely situated above the ground surface (Fig. 6) and encompasses also the litter layer and the vegetation mass up to the height that is reached by the highest annual water level. In the wet season the above ground material retards the run-off of water leading to a temporary storage of water over the surface, especially in the flatter centres of the dome (Hoekman, 2006).

This V-notch acrotelm structure of the lowermost vegetation layer was already exemplarily pictured in the first illustration of a tropical peat swamp, which the Dutch botanist Sijfert Koorders made during the Ijzerman expedition through Sumatra in 1891 (Ijzerman et al., 1895, Fig. 7).

### 4.2 Acrotelm building vegetation

In the temperate and boreal zones only five, six moss species of the genus *Sphagnum* are able to shape a continuously renewing acrotelm with the ‘critical compromise’ between a small hydraulic conductivity and a large storage coefficient (Joosten, 1993). The effectivity of these *Sphagnum* species is illustrated by the distribution of *Sphagnum* raised bogs over a very wide climatic range. The much richer diversity of species and life forms in tropical peat swamps and their different flora in different regions might suggest that species composition is not that critical for the maintenance of domed peatlands in the humid tropics and that the huge amounts of rainfall would enable the formation of peat domes with less regulation than in *Sphagnum* acrotelm bogs. However, ombrogenous domed peatlands have only a limited distribution in the tropics. Of the 12.5 million km² of humid tropics in the world (Schultz, 2005), less than an estimated 1% is covered by peat swamp domes. And although an estimated area of 150,000 km² of forested peatlands exists in tropical Africa and South-America, similar thick ombrogenous peat domes are not described from these continents (IMCG Global Peatland Database, cf. Sieffermann, 1988) in spite of seemingly suitable climatic, geologic, and geomorphic conditions.

These observations could indicate that in Southeast Asia special biogeographic conditions occur and that some species and life-forms are more important for bog dome formation and maintenance than others.

### 4.3 Forms of degradation

The challenges to restore severely disturbed peat swamp forest to living mire are enormous. Deforestation and fire not only destroy the vegetation, but with that also the major regulation device to maintain adequate hydrologic conditions for sustaining the peat body.

Drainage not only facilitates the discharge of surficial water needed to feed the peat body in the dry season. By subsidence it creates flatter domes and a more explicit microrelief (deep lying canals and ditches and adjacent deeply subsided areas). Whereas the former can make hydrologic regulation simpler, the latter leads to extra problems for restoration. The relief is furthermore being altered by deep fires that remove large parts of the peat body. As a consequence parts of the dome become too steep and too dry to support the ‘right’ vegetation, whereas in other areas the surplus of water and prolonged flooding in newly originated depressions hampers revegetation.

### 4.4 Minor degradation

Domes with ‘minor’ degradation (Table 1) include areas where the flora has been changed by selective forestry and that are not or only slightly drained by narrow and shallow logging extraction canals. Water outflow from the latter should be annulled or reduced. Change in species composition and the bottom-near vegetation

![Fig. 6](image1.png) Relation between ground water level (Wt, W.L.) and runoff (R, seepage rate) in a peat swamp forest in the upper catchment of the Sebangau River, Central Kalimantan during days without rainfall from March 1998 to February 1999 (left; Kayama et al., 2000) and in June - October 1997 and March - October 1998 (right; Takahashi et al., 2000).

![Fig. 7](image2.png) Vegetation types in the peatland near Biwak (Sumatra), as seen by Koorders during the 1891 Ijzerman expedition (Ijzerman et al., 1895; Potonié, 1907) with an explicit V-notch-structure over the surface.
structure by selective harvesting may change the quantity and quality of organic matter inputs that are relevant for peat accumulation. More importantly it may have made the hydraulic structure of the acrotelm more ‘open.’ Pioneer and secondary species may (temporarily) have less effect for hydrologic self-regulation than the original vegetation. Restoration of the latter by planting should focus on species that are indigenous to the spatially differentiated zones of the dome.

4.5 Moderate degradation

In the ‘moderate’ degradation stage, where the shape is still preserved, in any case anthropogenic drainage has to be stopped. Important in this respect is to think in coherent rewetting ‘systems’ and to work ‘with’ nature, not against her.

Firstly, one should keep in mind that enormous volumes of water ‘have’ to leave the bog, also in pristine conditions. Similar to the Tibetan percolation mires it thus makes no sense to try and make the dams fully impermeable and to dam up as much water as possible. The hydrologic restoration measures should be designed to allow the strongly varying surplus water to leave the bog without causing too much damage, but to retain a sufficient store for drier periods.

The main channels have to be blocked in such a way that the water is impounded above the surface of the peatland to rewat as much of the dome peat as possible. This will often mean constructing a dense network of dams cascading with little head differences (Ritzema & Wösten, 2006).

To disperse the water, damming should proceed centrifugally starting from the centre of the dome. By guiding the water over the largest possible area, flow velocity and erosive power are reduced. Preferential channelling around the dams can be restricted by allowing/stimulating a protective plant cover to re-establish before raising the water level. This may imply that continued peat oxidation is temporarily allowed to prevent later erosion.

When the vegetation and therewith the major natural hydrologic regulation device is largely removed, a kind of catch-22 situation exists. A water reservoir large (= deep) enough to keep the whole peat body wet in the dry season can only be realized when the vegetation effectively holds back the discharging water in the wet season. Pioneer species like ferns, however, do not sufficiently slow down water flow, whereas the species, that under natural conditions realize the AC/DC-converter, only germinate on raised hummocks and cannot survive the harsh, pioneer conditions after degradation and re-wetting. The result is that in the wet season the water drains away too quickly and that in the dry season the surface peat becomes too dry and oxidizes.

The solution to this dilemma could be applying a two step approach to restoration:

- first establish vegetation, that can hold back discharging water, can withstand rather high water levels, and – more importantly – can act as a facilitator for the necessary AC/DC-converter species and
- later, when the latter species have re-established, raise the wet season water level to the ‘natural’ level.

In developing such re-vegetation strategy, care has to be taken that planting ‘commercial’ species like rubber in the first phase may later result in conflicts when new or higher dams and further rising water levels will restrict access and annul investments.

4.6 Major degradation

In general peatland restoration should start with looking at peatland shape and relief, because these features determine the long-term perspectives of hydrologic restoration. When the peatland shape has substantially and irreversibly been changed (‘major’ degradation stage, Table 1) the prospects of full regeneration are extremely low. It will be impossible to recreate coherent hydrologic and vegetational conditions over the full dome and continued oxidation will progressively degrade the dome. Good three-dimensional elevation models must give insight in to what extent a balanced shape is still present, will spontaneously re-develop (by oxidation of too dry protuberances), or can easily be restored. When such shape is guaranteed, additional hydrologic and vegetational restoration measures (see above) may resurrect a living dome. If not, the area will spontaneously develop to the stage of ‘maximal’ degradation and solutions have to be found to limit the damage.

4.7 Maximal degradation

The maximal degradation stage involves areas that are intensively drained where the dome peat body is damaged or disrupted to such an extent that one or more (new) balanced peat domes (with the associated hydrologic and vegetational conditions) cannot be restored anymore. In some areas peat accumulating conditions might be restored locally but only through costly and complicated water control devices. In general, however, the focus has to be on restricting peat oxidation and peatland fires by re-wetting the area as far as possible.

The challenge for these areas is to develop and implement production techniques that combine economic benefits without impacting the environmental functions of peatlands: wet agriculture, wet forestry, or fishery (Wichtmann & Joosten, 2007).

4.8 Perspectives

As peat domes with limited damage (degradation stage ‘minimal’) are extremely rare in Southeast-Asia (if still existing) high priority must be given to conserving these areas, and to restore those domes that still have good perspectives for full restoration to self-regulating peat-accumulating entities (degradation stages ‘minor’ and ‘moderate’). It is of utmost importance that such areas are rapidly identified and adequately protected, restored, and managed.

Probably most of the intensively drained tropical peatland area is already in the stage of ‘major’ to
‘maximal’ degradation. The proposal of the recent Indonesian Presidential Instruction (No. 2/2007, 16 March 2007) to designate 62% of the 1.5 million ha large Central Kalimantan Peatlands Development Project (formerly Mega Rice Project) to ‘conservation’ seems therefore both too optimistic and not ambitious enough. In the ‘conservation’ area an artificial separation is made between conservation of ‘flora and fauna,’ ‘black water ecosystem,’ ‘hydrology,’ and ‘deep peat.’ The central characteristic of peatlands, however, is that these components are inextricably interwoven. Furthermore, it is doubtful whether self-regulating living mire conditions can be restored and maintained over the whole area in the long term.

On the other hand, to prevent further peat degradation and environmental damage the peat also has to be conserved in the agricultural and forestry areas. The challenge for the project will be to develop for areas that cannot be maintained or restored to living peat swamps a win-win situation between productive utilisation and environmental conservation by implementing wet agriculture and forestry.

5. Conclusions

Living peatlands are intricate systems with important self-regulation mechanisms to maintain the balance between ‘vegetation,’ ‘water’ and ‘peat.’ Self-regulation based on negative feedback is common in nature but often overlooked. The fact that both Tibetan percolation and surface-flow mires and tropical peat swamp forests have existed in a similar form for many thousands of years and over periods in which climatic conditions have changed substantially indicates that a wide spectrum of negative feedback mechanisms ‘must’ exist. An important part of this self-regulation is directly associated with vegetation, a component that – except for its water retention and storage – is generally ignored or insufficiently acknowledged in hydrological approaches to peatland restoration.

Both in Tibetan groundwater-fed surface-flow mires, where also the vegetation in the upland catchment is important, and in Kalimantan peat swamp forests which are solely fed by rainwater, the role of the vegetation in water retention and storage is indispensable to prevent erosion of the peat body.

Restoration research should therefore pay more attention to the interrelations between vegetation, water and peat as the basis of self-organisation and self-regulation. This is certainly opportune when planning and evaluating restoration measures.

As the vegetation in both peatland areas is the main object of human action, the restoration of peatlands is not only a matter of technical management, but has an important social dimension that needs to be acknowledged.

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