Water management for agriculture development in peatlands

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Abstract. Peatlands are very vulnerable, and their existence must be maintained as stores of water and carbon stocks. Moreover, due to improper management, peatlands in Indonesia have degraded, resulting in various environmental problems such as fire, flooding, and subsidence. Drainage on peatlands that is not carried out properly causes the peat to dry out and even become vulnerable or flammable. The peat becoming dry on a large scale has the potential to increase subsidence and greenhouse gas emissions (such as CO2), which can contribute to local and global climate change. The management of peatlands in the cultivation area must pay attention to the unity of the peat area (landscape), including the existence of peat domes. The main parameters that need to be taken into account in land and water management in peat land are (1) Drainability Limits, (2) Subsidence, (3) Land Useful Life, (4) Adjacent Ecosystem Linkages, (5) Peatland Externalities, and (6) Priorities and Prevention of Massive and Disastrous Damage. Water management is one of the most important aspects in peatland management, which needs to be performed by water regulation so that the peat soil surface remains wet, preventing it from drought in the dry season and causing fires, and at the same time preventing flood disasters during the rainy season. Efforts to utilize excess water during the rainy season to cover the water deficit in the dry season need to be endeavoured to minimize wasted water.

Keywords: Management, Water, Peatlands

1. Introduction

Along with the increase in population and the food needs of the people, in recent decades, peatlands have become the target of expanding agricultural and plantation areas, such as oil palm and industrial timber plantations. This is due to the limited amount of mineral land or other productive land in Indonesia [1].

Peatlands are very vulnerable and their existence must be maintained as stores of water and carbon stocks. However, due to inappropriate management, peatlands in Indonesia have experienced degradation, which has resulted in various environmental problems such as fire, flooding and subsidence. Excessive drainage can cause the peat to become dry and even vulnerable or flammable. In addition, the pyrite layers that are exposed can increase acidity, which will not only damage local lands but also associated bodies of water. To avoid degradation as mentioned above, it is necessary to regulate the water system in areas of development and conservation, in order to minimize the environmental impacts that will occur.

The government is very interested in the development of rice and food crops cultivation in peatlands, especially to improve food security as stated in the national development agenda. In peatlands, the management of water systems is necessary for the application of the principle of balance and
sustainability. To achieve success in the water management of peatlands within a cultivation area, the process must also follow the general development path, which involves assessment, planning, operation, supervision, monitoring, and evaluation. Furthermore, water management in peatlands within a cultivation area still needs to be further developed through various studies for the development of models that can be used as examples for stakeholders.

The purpose of this paper is to provide a guideline for water management in the development of agriculture on peatlands and tidal and non-tidal swamps for rice, horticultural, and secondary crop cultivation based on soil characteristics and hydrology in the development zone, established with regard to Peat Hydrological Unity and especially for crop cultivation in peatlands that have been licensed and cleared, or is currently being managed. This paper was prepared as a reference for policy makers, planners, managers, and technical implementers on the field.

2. Materials and Methods
In general, the method of this entire paper is the searching of information from literature. The theme of this study was chosen by considering the urgency for peatlands. The background and materials are based on information obtained from various journals, books, and the Internet from accountable sources, in order to understand the problem being investigated. Information about the concepts and practices of water management for agriculture development in peatlands in several places were extracted from previous studies and then reviewed.

2.1. Peat Ecosystem Environmental Conditions
Peat is unconsolidated surface deposits with high humus content on the surface of a wetland system [2]. Peatland ecosystems are the result of the interaction of three interrelated components: plants, water, and peat (Figure 1). This interconnection implies that when one of these components changes, the other components will also change. These changes are not necessarily all at once, but in the long run, changes will definitely occur [3].

![Figure 1. Interaction of 3 components of peatland ecosystems](image)

2.2. Peat Hydrological Unit
In Government Regulation Number 57 of 2016, it is stipulated that the hydrological unit of peat is a peat ecosystem located between two rivers, between rivers and a sea, and/or in swamps [4]. This definition states that the entire ecosystem within these limits is a unified governance. This Government Regulation also states that the peatland landscape within the peat hydrological unit is divided into functions of protection and cultivation.

To be able to use peatlands to provide sustainable benefits, an environmentally friendly land use option is needed by applying macro-zoning to the peat hydrological unit. Based on Water Management for Climate Change Mitigation and Adaptive Development in Lowlands, which is an effort for the sustainable management of lowlands, the concept of macro-zoning was established. The aim of macro-
zoning is to ensure that the activities that are carried out do not disturb the balance of the peat ecosystem. Macro-zoning is divided into two main zones: (1) Conservation zone (protection function) and (2) Development zone (cultivation function).

2.3. **Drainability**
Existing drainability and possible drainage schemes consist of the function of surface gradients and river/tidal water level fluctuations. Because of flooding and high groundwater tables, drainage is essential for development of the land. Areas close to tidal rivers can easily be drained by gravity during low tide, but drainage becomes increasingly difficult at greater distances from the rivers. Gravity drainage is also problematic for low areas along non-tidal river reaches. Drainability will likely become a major problem after a few decades of continued drainage and subsidence in peat areas as a result of subsidence of the peat [5].

2.4. **Irreversible Drying**
Peat in an irreversible drying condition generally has a layer of sand on the surface of peatland that is easily washed away by water [6]. Peat in this condition is highly flammable, no longer has the ability to absorb water and nutrients, and cannot easily decompose microbes.

According to Sabiham (2000), the decreased ability of peat to absorb water is related to the decrease in the availability of substances with carboxylic groups and OH-phenolics in peat material. Both of these organic components make up hydrophilic compounds, and thus if the moisture disappears, the originally hydrophilic peat turns hydrophobic [7].

2.5. **Subsidence**
The subsidence of the peat surface after reclamation is no doubt a major problem for the maintenance of agricultural activities. This is caused by changes in conditions due to drainage. Drainage that was initially thought to provide the greatest benefits for agricultural growth and plantations may contribute poorly to the environment, leading to subsidence, fires, CO₂ emissions, floods, loss of biodiversity, and changes in the physical and chemical characteristics of peat [8]. According to Agus F. (2011), after the drainage of peatlands, the rate of subsidence will occur faster in the first few years, but then the stability of surface subsidence will improve, approximately 2 cm/year. The fragile and irreversible drying nature of peatlands makes it difficult for peatlands to return or be restored to their original condition if they have been cleared and damaged [9].

Subsidence starts from the buoyancy and compaction of the organic material column underneath because of its own weight. Compaction results in changes in hydropedological parameters such as hydraulic conductivity, content weight, pore volume, and air content. The next dominant process that can take place over several periods is the oxidation and depreciation of peat. The level of subsidence can vary depending on the peat morphology profile, peat composition, peat depth, drainage depth, and land use [10].

2.6. **Water Management**
Water management is one of the main keys for peatland management. In its implementation, water management is carried out by ensuring that peat soil is kept moist. In addition to keeping the surface of the peat moist, an effort is made to prevent drought and fires in the dry season and floods in the rainy season. The water level standard in peatlands is stipulated in Government Regulations No. 71 of 2014 [11] and No. 57 of 2016 [4]. In these regulations, it is stipulated that the water level must be 40 cm below the surface of peatlands.

According to Hooijer *et al.* (2006), the principle of water management must pay attention to the impact on the rate of peat decomposition and the resulting emissions. Based on his research, there is a
linear correlation between the water level in drainage canals in peatlands and the level of greenhouse gas emissions, especially CO$_2$. Deeper water levels in the drainage canals lead to an increase in the rate of CO$_2$ emissions generated from peatlands [12].

2.7. Pyrite and Quartz Sand
Damage to peat ecosystems can occur in a) peat ecosystems with the protection function and (b) peat ecosystems with the cultivation function. Peat ecosystems with protection and cultivation functions are declared damaged if they exceed the criteria of damage standards, as the exposure of pyrite and/or quartz sediments below the peat layer (Government of the Republic of Indonesia Regulation No. 57, 2016).

3. Results and Discussion

3.1. Peat Hydrology
The water balance of peatlands is the main key that must be considered in the planning and implementation of peatland water systems. A good water system can avoid excessive deficits, which in the short term can cause land dryness, which facilitates fire and irreversible drying, and in the long term can cause excessive subsidence. The water balance of peatlands in Indonesia, in brief, consists of the parameters $\Delta S$, changes in aquifer storage (m); $P$, rainfall (m); $Q_{s,i}$, input from surface runoff (m); $Q_{g,i}$, input from ground water flow (m); $Q_{s,o}$, output in the form of subsurface flow (m); $Q_{g,o}$, output in the form of ground water flow (m); $ET$, evapotranspiration (m); and $I$, canopy interception (m), which are stated in the following equations:

$$\Delta S = P + Q_{s,i} + Q_{g,i} - Q_{s,o} - Q_{g,o} - ET - I$$  (1)

In an ombrogenous peatland water balance system, there is generally no input from the surrounding land [13], whether in the form of surface runoff or groundwater flow, or the quantity is not significant.

3.2. Water Management Zoning
Peatlands have a carrying capacity that can be utilized for the benefit of human life. In terms of geography and ease of management, peatlands are generally used for agricultural lands, plantations, settlements, and infrastructure development. However, in its use, the useful life and carrying capacity of peatlands are often ignored in consideration of the use and management of peatlands. The importance of obtaining short-term economic benefits is the reason why the useful life and carrying capacity of peatlands are often ignored. In order for peatlands to be used and provide sustainable benefits, environmentally-friendly land use options are needed by taking into account the suitability and carrying capacity of the land, as well as the application of management zoning in the area with the cultivation function. The carrying capacity of land is the ability of land to accommodate a number of individual plants per unit area and in providing productive results. The carrying capacity varies, based on the types of plants. Thus, the suitability of peatlands for different types of plants is not the same.

Indonesia's peatlands are generally ombrogenous and the position of the peak of the dome is always several meters higher than the dome foot. This topographic condition, together with nutrient poverty constraints leads to the need for zoning of water management based on land suitability. Zoning of peatland water management within the area with the cultivation function needs to be based on the peat hydrology unit. In accordance with the principle of balancing the functions of utilization and conservation, the use of peatlands should be arranged in a planned spatial zoning. As the nature of peatlands ecosystem is fragile, intact forests need to be prioritized to be sustained for the sustainability of their environmental functions. When land has been cleared in the utilization area, zoning of water management needs to be performed.
In principle, zoning for peatland water management requires a scientific study based on the following parameters: Drainability Limits, Subsidence, Land Useful Life, Adjacent Ecosystem Linkages, Peatland Externalities, and Priorities and Prevention of Massive and Disastrous Damage. Broadly speaking, the flowchart of zoning for water management for agricultural development on peatlands is presented in Figure 2.

![Flowchart of Zoning for Water Management](image)

**Figure 2.** Water management zoning flowchart

### 3.2.1. Drainability Limits
A drainability limit is a boundary condition where a land unit (peat) can no longer be drained by gravity due to climatic conditions and (changes in) local hydro-topography. There are three important aspects in the concept of drainability limits that need to be considered in peatland management:

1. **Drainability Elevation Limit (DEL)** is an elevation of a certain land unit on the surface of the earth, which marks the boundary where gravity drainage is no longer possible.
2. **Peat Depletion Time (PDT)** is the time it takes until the entirety of peat in a peatland unit has oxidized for a certain land use application, calculated from a certain time reference.
3. **Depletable Peat Thickness (DPT)** is the thickness of peat in a peatland unit that can be oxidized, or the total depth of the peat to the DEL limit.

The DEL of a land unit can be predicted by considering the hydro-topography and climatic conditions in the landscape where the land is located. The prediction involves the Drainability Elevation Limit, as the lowest elevation of the land as a limit of gravitational drainage; $H_{NWB}$, the average water level in the nearest natural water body; $C$, head loss slope constant = 0.0002; and $\Delta X$, the distance of a point observed from the nearest natural body of water. The following is the DEL calculation formula:

$$DEL = H_{NWB} + C \times \Delta X$$  \hspace{1cm} (2)

### 3.2.2. Subsidence
Subsidence is the sinking of the land surface. Subsidence is a form of peatland damage, and if it lasts for long periods, restoration may be difficult or impossible. Land subsidence occurs in two ways, without mass loss and with mass loss.

Because the basal contact of coastal peatlands in Indonesia is at very low elevations (generally at the same elevation as the sea level), subsidence that lasts for a long time can cause changes in local water balance patterns. To a certain extent, the land will sink in such a way that the input of water entering the
land can no longer be released through gravity, and will end up as permanent inundation, or inundation for long periods each year. If the peatlands are near the coast, the risk of saltwater intrusion will increase. Under the circumstances stated above, the land reaches the drainability limit. To be used further, mechanical drainage (by pumping) is required. When this is performed, subsidence will continue until all the peat has been oxidized, the basal contact is exposed to the surface, and the elevation of the land is lower than the surrounding water body. Peat subsidence has several serious consequences. Drainage must be regularly adjusted to new levels and conditions, or otherwise flooding will occur again.

Subsidence on peatlands can be correlated in direct proportion to the depth of the water table; a lower the ground water table will result in a higher rate of land subsidence [14]. The main factor causing the acceleration of peatland subsidence in Indonesia is the decrease in groundwater level, which causes consolidation (Sc) and shrinkage (Ss), which accelerate microbial decomposition (So) and threaten land fires (Sf). Thus, based on its components, the subsidence on peatlands (S) can be formulated as

$$S = S_c + S_s + S_o + S_f$$  \hspace{1cm} (3)

### 3.2.3. Land Useful Life

The land useful life is defined as the projection of the productive time of land or the time that land can provide benefits over the costs for each given land use option and the specific characteristics of the land. On peatlands, the useful life of the land is largely determined by the drainability limit. When the drainability limit is reached, the land can no longer be drained by gravity, thus requiring construction of polders and the application of pumps, as a consequence requiring large costs. Extremely high rainfall results in very high polder operational costs, which may not be possible to implement. Therefore, the useful life of peatlands needs to be one of the parameters considered in the zoning of peatland utilization; for example, lands that have a short life span need to be avoided.

As long as peatlands still provide benefits that exceed the costs required, the land can still be utilized. Conversely, if the costs exceed the benefits, the useful life of the peatlands has ended. Unsustainable use of peatlands can cause damage, especially with uses that involve drainage and deforestation. The land use life of peatlands can be represented with the following formulas:

If mechanical drainage is expected to be able to applied for future land use after the DEL has been reached, then the land useful life is

$$\text{LUL} = \frac{D}{S_{rate}}$$  \hspace{1cm} (4)

If mechanical drainage is not expected to be able to be applied after the DEL has been reached, the land useful life is

$$\text{LUL} = \frac{E-\text{DEL}}{S_{rate}}$$  \hspace{1cm} (5)

where LUL is land useful life (years), D is peat thickness (m), DEL is the Drainability Elevation Limit (m-msl), E is the peatland surface elevation (m-msl), and $S_{rate}$ is the subsidence rate (m year$^{-1}$). An example of a land useful life map is presented in Figure 3.
3.2.4. Adjacent Ecosystem Linkages

Peatland ecosystem has a very close relationship with the river ecosystem. Peatlands in several places also function as a hydrological buffer for the ecosystems in the upstream part of a river. The influence of this linkage needs to be considered in determining management options for a certain zone. One example of the aspect of adjacent ecosystem linkages can be seen if an area with a protection function is adjacent to a drained cultivation area. A decrease in groundwater level in drained cultivation (development) areas can result in a decrease in groundwater level and deterioration in protection function areas. The distance of this deterioration effect can be estimated by the Hoodhoudt equation:

\[
X = \frac{1}{5} \times \left( H \times \ln \frac{H_0 - H_x}{H - H_0} - (H_x - H_0) \right)
\]

where \( X \) is the distance between the upstream part and the drained area (m), \( S \) is the slope of the impermeable layer (in the case of peatlands = peat basal contact) (-), \( H \) is the groundwater level in the undrained area (m-msl), \( H_0 \) is the groundwater level in the drained area (m-msl), and \( H_X \) is the groundwater level at position \( X \) (m-msl).

Therefore, peatland management must pay attention to the principles of the peat hydrological unit, including water sharing if necessary.

3.2.5. Peatland Externalities

Each peat dome is occupied simultaneously by many catchment areas [15]. Because peatlands are fragile, easily oxidized, and subject to subsidence, any land management options that may result in subsidence can cause dome peaks to change and the composition of the catchment area to change as well. When the catchment area is reduced, there will be a decrease of the base flow in the dry season of the river. As a result, river navigability in the dry season is reduced, which is a detriment to fishermen. Whereas, if the catchment area increases, then an increase of peak discharge in the rainy season can occur. This will have an implications for the increased risk of flooding in the downstream part of the river. The possibility of the shifting of this catchment area will be even greater if drainage becomes closer to the peak position of the peat dome. Potential dome shifts can be predicted through spatial-dynamic subsidence modelling.
3.2.6. Priority and Prevention of Massive and Disastrous Damage

According to Government Regulation No. 57 of 2016, stipulations and provisions regarding the exposure of pyrite sediments and/or quartz sand under peat layers have been established. The peatland area that is known to store pyrite or quartz sand is prioritized as a protection zone. If an area with the cultivation function is adjacent to a zone containing pyrite or quartz sand, or if land drainage measures in the cultivation zone have the potential to cause the release of pyrite or quartz sand in the conservation zone, then the development zone needs to be managed in such a way to prevent or delay the impact of pyrite or quartz sand being released. The same principle applies to damage from other forms of disaster such as floods and droughts.

4. Conclusion

Water management is one of the most important aspects in peatland management. Water management needs to be performed by maintaining moisture in peat soils and preventing drought in the dry season so that fires do not occur, while also preventing floods in the rainy season. Water level standards in peatlands have been stipulated by Government Regulation No. 71 of 2014, wherein it is stated that the water level must be 40 cm below the surface of peatlands.

However, even with the best water management, subsidence cannot be stopped. Therefore, sustainable use of peatlands for agricultural development needs to be aimed at extending the life of peatland productivity, in relation to its ability to be drained with proper water management. Efforts must be made to slow down the process of subsidence for as long as possible until the drainability elevation limit is reached, thereby maximizing land use life.

A good water system must be able to utilize rainfall input in such a way that the excess input that occurs during the rainy season can be removed without causing damage. Meanwhile, deficits that occur in the dry season can be minimized through water control management. In addition, efforts to utilize excess water in the rainy season to cover the water deficit in the dry season need to be pursued in order to minimize waste of water. Peatland management must pay attention to the principles of the peat hydrological unit, including water sharing if necessary.

Subsidence can cause dome peaks to change and the composition of catchment areas to change as well. The possibility of catchment area shifting will be even greater if the drainage is close to the peak position of the peat dome. Therefore, the principles of the peat hydrological unit needs to be considered in seriousness.

Peat ecosystems with protection and cultivation functions are declared damaged if pyrite and/or quartz sediments below the peat layer are exposed. Therefore, areas of thin peatland containing pyrite and/or quartz sand in the lower layers need to be closely maintained.

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