Polder system water management on non-tidal swamp area based on water balance analysis

B Kartiwa¹, N Sutrisno¹, A Hamdani¹, W T Nugroho¹, I Muhardiono¹, Harmanto¹, I Yani², R Roland² and I Ismail²

¹ Indonesian Agroclimate and Hydrology Research Institute, Bogor, Indonesia
² Water Management Division PT. Astra Agro Lestari

E-mail: budi.kartiwa@gmail.com

Abstract. Polder system is the key to manage floods in agricultural non-tidal swamp land. Infrastructures to support polder system integrated management include: regional drainage systems, retention ponds, dikes, pumps and/or gates. Pump requirement in an optimally managed polder system is influenced by the polder area, rainfall, soil, and hydrological characteristic. This article presents water balance models application in determining the number and operational duration of pumps to achieve effective and optimal polder function in controlling floods and inundation during the rainy season. This study was conducted in a palm-oil plantation located in lebak swamp area in Pawalutan, Banjang, Hulu Sungai Utara, during September 2016 to September 2017. Pump units and operation durations were calculated based on estimated inundation volumes depending on the water inlet and water balance. Seepage discharge was estimated using Darcy equation. Result of the recovery test measurements showed hydraulic conductivity value of \(4.1 \times 10^{-5}\) ms\(^{-1}\), while the estimated seepage discharge was \(8.6 \text{ m}^3\text{ hr}^{-1}\text{ km}^{-1}\). The pump requirement analysis indicated the need of 55 pump units with \(2,500 \text{ m}^3\text{ hr}^{-1}\) pumping capacity to overcome inundation in the study site with 1,417 ha inundated area. These pumps were distributed into 9 zones, each with 4 to 10 units.

1. Introduction

A polder is a low-lying tract of land that forms an artificial hydrological entity, enclosed by embankments known as dikes. There are three types of polder, one of them is flood plains separated from the river by a dike [1].

The ground level in drained marshes subsides over time. All polders will eventually be below the surrounding water level some or all of the time. Water enters the low-lying polder through infiltration and water pressure of groundwater, or rainfall, or transport of water by rivers and canals. This usually means that the polder has an excess of water, which is pumped out or drained by opening sluices at low tide. Care must be taken not to set the internal water level too low. Polder land made up of peat will sink in relation to its previous level, because of peat decomposition when exposed to oxygen from the air.

Polders are at risk from flooding at all times, and care must be taken to protect the surrounding dikes. Dikes are typically built with locally available materials, and each material has its own risks: sand is prone to collapse owing to saturation by water; dry peat is lighter than water and potentially unable to retain water in very dry seasons [1].
Polder system is the key to manage floods in agricultural non-tidal swamp land [1]. Infrastructures to support polder integrated management system include: regional drainage systems, retention ponds, dikes, pumps and/or gates [2]. Pump requirement in an optimally managed polder system is influenced by the polder area, rainfall, soil, and hydrological characteristic. This article presented water balance models application in determining the number and operational duration of pumps to achieve effective and optimal polder function in controlling floods and inundation during the rainy season.

2. Methods
This study was conducted in a palm-oil plantation located in lebak swamp area in Pawalutan, Banjang, Hulu Sungai Utara, during September 2016 to September 2017. To cope with flooding, the palm oil plantation in the study locations had been protected by the polder system, namely embankments surrounding the garden boundary with inundated areas and some pumps were also installed.

Optimization of pump number and operating duration to manage the flooding inside of polder was analysed based on Water Balance Analysis. The estimation of flooding volume is calculated through the equation [3]:

\[ S = CH - ETP + R - P \]  
\[ G = 0 \text{ if } S < K \]  
\[ G = S - K \]

where,

- \( S \): Water Storage
- \( CH \): Rainfall
- \( ETP \): Evapotranspiration
- \( R \): Seepage
- \( P \): Infiltration
- \( G \): Volume of water should be evacuated from polder
- \( K \): Stock capacity of canal

We consider that the infiltration zone related to the non-compacted peat layer. The path flow of seepage under dikes has the ellipsoidal form. We applied Darcy equation for estimated seepage path flow under dikes [4].

\[ L_i = \pi \left[ 3(a+b) - \sqrt{(a+b)(a+3b)} \right] = \pi (a+b) \left[ 3 - \sqrt{4 - h_i} \right] \]  
\[ h_i = \left( \frac{a-b}{a+b} \right)^2 \]  
\[ q_i = K \left( \frac{PT-Pa}{10} \right) \left( \frac{H}{(a+b)} \right) \]  
\[ Q = \sum_{i=1}^{10} q_i \]

where,

- \( L_i \): length of path flows (m)
- \( h_i \): width of path flows (m)
- \( a \): abscissa of point the path flow of seepage (m)
- \( b \): ordinate of point the path flow of seepage (m)
- \( PT \): peat depth (m)
The variable data for the water balance model and the seepage model were obtained from secondary data from observations of a period of 5 years, while the values of the fixed variables and the coefficients model were measured in the field.

The hydraulic conductivity measurement was carried out on borehole with a dimension of 6 inches in diameter and 2 m in depth. The measurement of hydraulic conductivity was carried out using the recovery test method.

The process of measuring the rate of water level rise required equipment consisting of water level depth measuring and time measuring devices and writing instruments. In measuring the hydraulic conductivity, a contact gauge being a water level measuring instrument with manual reading was used. Apart from the contact gauge, a water level logger device capable of measuring and recording changes in groundwater level automatically was also used.

The data from the measurement of groundwater level rise are then presented in a graph showing the correlation between groundwater level depth and time. Furthermore, the correlation parameter between the depth of the groundwater level and the time presented in the semi-logarithmic graph was analyzed using the Darcy equation to obtain the hydraulic conductivity value.

3. Results and discussion

3.1. Site characteristic
The study location was in a low swamp area influenced by the hydrological characteristics of the Batu Mandi and Japang watersheds (figure 1). The Batu Mandi watershed has an area of 133.42 km$^2$ with a perimeter of the watershed reaching 78.77 km. Meanwhile, the Japang watershed has an area of 107.97 km$^2$ with a watershed circumference of 66.48 km.

![Figure 1. Batu Mandi and Japang Watershed.](image-url)

The soil in the study location was dominated by peat soils with varying thickness levels, ranging from shallow (50-100 cm), medium (100-200 cm), slightly deep (200-300 cm), deep (300-500 cm) and very deep (>500 cm).
In general, the maturity level of the peat soil in the research location is in the mature category (sapric). In several zones of limited area, medium maturity (hemic) were found at a depth of more than 150 cm.

3.2. Hydraulic conductivity

Figure 2 shows a graph of the relationship between log water table depth and time. Data obtained from the implementation of recovery tests on borehole at the research study.

![Graph of Log water table depth and time](image)

Note: Value of a = 0.0011.

Figure 2. Relationship between Log water table depth and time from the recovery test at Pawalutan site research.

According to figure 2, the values of the slope of the linear function Log (H(t)) versus time (t) (a) are -0.0011. Considering that diameter of borehole (r) is 0.075 m and the hydraulic conductivity value (K) is $4.13 \times 10^{-5} \text{ m s}^{-1}$ ($K = a.r/2$). This value indicates that the water movement speed in the ground was 14.8 cm hour$^{-1}$. This value is not much different from the results of measurements made by other researchers at different locations [5-7].

3.3. Seepage simulation model

The seepage discharge calculation model is presented in figure 3. The input data value as listed in table 1. The flow of seepage from the inundated area into the polder is assumed to be in the form of an ellipsoid which is divided into 4 layers. Seepage discharge decreases with increasing depth, so that the discharge in the upper layer is higher than that of the lower layer.

The model estimated the seepage discharge under dikes value was about 8.62 m³ hour$^{-1}$ km$^{-1}$. These results indicate that the seepage that enters the polder during a flood is very significant, which is equivalent to a water volume of 1,000 m³ day$^{-1}$ for a 5 km long dike.

Research results in other locations indicate that the seepage flow that occurs under the embankments in peatlands is relatively high and is strongly influenced by rainfall intensity.

It can be concluded that downward and lateral losses are highest in periods with high rainfall. In these periods with high water levels some unmeasured superficial runoff (leakage) may occur and lateral flow through the upper slightly humified peat layers may be substantial. The average downward seepage is estimated at 1.0 to 1.4 mm day$^{-1}$ [8].
3.4. Optimizing pump analysis
The main infrastructure designed to solve the problem of flooding in the study area is a dike around area and pumps installation. Water management currently applied was a zone system for flood management, divided into 9 zones and equipped with pumps according to their needs. The nine zones built were scattered around the site and concentrated along the north and west sides of the study area, and the middle part of the site (figure 4).

The nine pump zones in the study area were currently not optimal in controlling flooding and inundation, therefore a water balance-based approach was necessary to determine the optimal number and duration of pump operations in controlling flooding. The approach taken had considered the inflow into the polder, namely rainfall and seepage discharge, as well as the outflow in the form of evapotranspiration and pumped discharge, and also considered the characteristics of the surface storage in the polder (primary, secondary, and tertiary canals).
Figure 4. Characteristic of nine pump zones of the polder system in the study area.

The results of the daily dynamic analysis of the inundation volume to be pumped in zone 1 are presented in figure 5. Optimization of the pump duration to remove the inundation in zone 1 is presented in figure 6, while the recapitulation of its results is presented in table 2.

Figure 5. Daily dynamics of inundation volume to be pumped in zone 1.
Figure 6. Duration of pump operation to remove inundation volume in zone 1.

Table 2. Optimization of the pump number to handle flooding and inundation at the study area.

| Pump zone | Area (ha) | Storage capacity (m$^3$) | Wet area of canal (m$^2$) | Length of dikes (km) | Discharge of seepage (m$^3$ day$^{-1}$) | Actual pump number (unit) | Optimal pump number (unit) |
|-----------|-----------|--------------------------|---------------------------|---------------------|----------------------------------------|---------------------------|---------------------------|
| 1         | 177       | 109,150                  | 89,621                    | 1.9                 | 3,747                                  | 5                         | 6                         |
| 2         | 172       | 106,067                  | 87,089                    | 1.8                 | 3,549                                  | 4                         | 6                         |
| 3         | 172       | 106,067                  | 87,089                    | 2.9                 | 5,718                                  | 5                         | 7                         |
| 4         | 130       | 80,167                   | 65,823                    | 3.2                 | 6,310                                  | 3                         | 7                         |
| 5         | 123       | 75,850                   | 62,279                    | 3.0                 | 5,916                                  | 3                         | 6                         |
| 6         | 144       | 88,800                   | 72,912                    | 2.7                 | 5,324                                  | 4                         | 6                         |
| 7         | 89        | 54,883                   | 45,064                    | 1.0                 | 1,972                                  | 2                         | 3                         |
| 8         | 282       | 173,900                  | 142,786                   | 4.4                 | 8,676                                  | 8                         | 10                        |
| 9         | 128       | 78,933                   | 64,811                    | 1.2                 | 2,366                                  | 3                         | 4                         |

4. Conclusions
The recovery test measurements and Darcy Equation application showed that the hydraulic conductivity value at study area was $4.13 \times 10^{-05}$ m s$^{-1}$. The seepage discharge under the embankment was estimated to have a significant magnitude about $8.62$ m$^3$ hr$^{-1}$ km$^{-1}$ so that it greatly affected the inundation volume at the study area. The pump requirement analysis indicated the need of 55 units of pump with $2,500$ m$^3$ hr$^{-1}$ pumping capacity to overcome inundation in the study site with 1,417 ha inundated area. These 55 pump units were distributed into 9 zones, each with 4 to 10 pumps. The implementation of this recommendation will have implications for controlling flooding and inundation in the oil palm plantation area so that plant productivity will not decrease.

Acknowledgments
BK, NS, AH, WN, IM, H, IY, RR and II were main contributors of this article. All authors actively involved in data preparation and analysis, drafting and revising the manuscripts, and approved the final to be published version of the article.
References

[1] Segeren W A 1983 Introduction to polders of the worlds *Keynote paper in: Final Report Polders of the world International Symposium* Lelystad, The Netherlands

[2] Witteveen B 2008 Conceptual design report Development pilot polder Semarang and guidelines polder development Deventer the Netherlands

[3] Millar D J, Cooper D J and Ronayne M J 2018 Groundwater dynamics in mountain peatlands with contrasting climate, vegetation, and hydrogeological setting *J. Hydrol.* 561 908–917

[4] Bear J 2010 *Modelling Groundwater Flow and Contaminant Transport* Volume 23 London (New York: Springer Dordrecht Heidelberg)

[5] Lewis C, Albertson J, Xu X and Kiely G 2012 Spatial variability of hydraulic conductivity and bulk density along a blanket peatland hillslope *Hydrol. Processes* 26 1527–1537

[6] Morris P J, Baird A J and Belyea L R 2015 Bridging the gap between models and measurements of peat hydraulic conductivity *Water Resour. Res.* 51 5353–5364

[7] Prabir K K 2007 Hydraulic Conductivity of Tropical Peat Soil *Sarawak Conference: The 1st International Conference of European Asian Civil Engineering Forum (EACE)* Jakarta Indonesia

[8] Reeve A S, Siegel D I and Glaser P H 2000 Simulating vertical flowing large peatlands *Journal of Hydrology* 277 207–207