THE IMPACT OF DIFFERENT CANAL CONFIGURATIONS ON THE DRAINAGE OF TROPICAL PEATLANDS

A geohydrological model to predict drying of sloping peat aquifers in Central Kalimantan, Indonesia

BACHELOR THESIS

E. Vonk

UNIVERSITY OF TWENTE.

Bachelor Thesis

The Impact of Different Canal Configurations on the Drainage of Tropical Peatlands

A geohydrological model to predict drying of sloping peat aquifers in Central Kalimantan, Indonesia

Erwin Vonk

August 30, 2011

Supervisors:
Prof. dr. E. (Brenny) van Groesen
Dr. ir. M.J. (Martijn) Booij

Enschede, University of Twente
Faculty of Engineering Technology
Civil Engineering

Foreword

In this Bachelor Thesis my findings of three months research are presented. The research project was conducted in Bandung, at LabMath-Indonesia. Here I developed a geohydrological model to predict groundwater flows in a sloping peat aquifer. The derived model was a continuation of the work of previous interns at LabMath and should ultimately lead to a complete data-extensive model for hydrological predictions in poorly gauged tropical peatlands. In this research the Ex-Mega Rice Project (Central Kalimantan) was taken as study area.

This Thesis is for obtaining my Bachelor's Degree in Civil Engineering at the University of Twente. For making the research internship possible and for the assistance during the entire period I want to thank several people. First of all I want to mention Ellen van Oosterzee and thank her for her superb assistance in finding an internship and her advice on arranging all practical matters. Secondly I want to thank Brenny van Groesen as my direct supervisor at LabMath-Indonesia. Together with Andonowati he made this project possible and his daily supervision was of great quality. I also want to mention Martijn Booij and thank him for his useful feedback on my reports. Finally there are also my colleagues, together with who I had a great time in Bandung. They helped me many times to find my way around, which really enabled me to make a kickstart in Indonesia.

Erwin Vonk
Bandung, 2011

Summary

Excessive drainage of tropical peatlands in the province Central Kalimantan is a major environmental problem of Indonesia. The intention was to transform tropical peat swamp forests into a food production and living area for the country's rapidly growing population. Most well known example of these development schemes is the so called Mega Rice Project. Initiated around 1996, tropical rainforest were logged and a dense network of drainage canals constructed to prepare the area. But the project failed as the soil appeared not to be suitable for the rice agriculture it was intended for. Furthermore the dense drainage network caused the groundwater level to drop rapidly during the dry season, a decline that does not stop until the wet season commences again. Nowadays the site has a disrupted hydrological cycle and suffers many problems like drought, greenhouse gas emissions, fires and land subsidence.

During this research project for LabMath-Indonesia a data-extensive geohydrological model was developed to predict the peatland drying process under various canal configurations. The model is specifically intended for predictions in poorly gauged basins. Key aspect is the distinguishing between different drying processes: diffusional flow, gravitational flow and evapotranspiration. Several canal configurations have been evaluated for their performance during relatively dry years. The first one is the current situation. Secondly, as a reference, the effects of a complete fill operation of all canals have been determined. Thirdly a hybrid solution has been studied, in which the so called contour canals are preserved and equipped with weirs at their intersections with remaining side slope canals.

Currently the peatland is intersected with canals that have a spacing of approximately 80 m. On an average peat dome with a slope angle of 0.1 degrees this results in full drainage of the top layer (0-1 m below surface) within 80 days. Model outcomes show that evapotranspiration is the dominant process, while also canal spacing has great influence on the outflow. Even though diffusion is a relatively slow process, it starts to contribute significantly to the outflow when the canal spacing is small. In a situation where all canals would be completely filled, the remaining drainable storage is still 10% after 100 days. This can be approximated by constructing weirs in the contour canals at their intersection with the side slope canals. With a weir height of 0.75 m the water retention in the peatland can be increased by 20%, extending the drainage time from 80 till 100 days (compared to the current situation). The strategy seems promising, since it not only increases the water retention, but also allows for drainage during the wet season.

Overall it can be concluded that the natural situation can be approximated by filling nearly all side slope canals, except an absolute minimum necessary for drainage during the wet season. It is recommended to construct weirs at the intersections between the remaining side slope canals and contour canals. The higher the weirs, the more effective the solution will be. However, the exact height is to be determined by also taking agricultural requirements into account.

Contents

Chapter 1

Introduction

1.1 Background

The Indonesian province Central Kalimantan, on the island Borneo, is known for its rich ecosystem and extensive tropical rainforests. But nowadays it is threatened by rapid deforestation, causing a collapse of its ecosystem, a disrupted hydrological cycle and enormous greenhouse gas emissions. It all started around 1990, when vast areas of peat swamp forest were developed for agriculture and settlement. The largest of these development schemes was the so called Mega Rice Project (MRP), which is located in the southern part of Central Kalimantan and covers an area of more than one million hectares (figure 1.1).

The intention was to transform tropical peat swamp forests into a food production and living area for Indonesia's rapidly growing population. After deforestation a network of drainage canals, with a total length of over 4500 km, was constructed in the thick peat domes in the MRP-area. But the project failed as the soil appeared not to be suitable for the rice agriculture it was intended for. Moreover, the dense drainage network caused the groundwater level to drop rapidly during the dry season. This decline does not stop until the wet season commences again.

Figure 1.1: Location of the EMRP-site.

As a result the area nowadays faces many problems, including land subsidence, drought and peat fires. They are often intertwined with local socio-economical problems. Because of its enormous scale and complexity LabMath-Indonesia contributes to the current research efforts, which intend to find a sustainable solution for the area. Since there is a lack of good understanding of the peatland's hydrology and scarce availability of data, LMI's research focuses on the development of data-extensive groundwater and drainage models that can be used for evaluating different preservation strategies.

1.2 Problem analysis

The Ex-Mega Rice Project was abandoned just three years after its initiation in 1996 (Wösten et al., 2010). Ever since the site suffers many environmental problems:

- Large-scale peat fires have occurred in the past and still occur frequently. Due to the dry soil (as a result of excessive drainage) such fires can ignite easily and spread quickly throughout the area. They are hard to control, since the fires also burn under the surface. Especially the fires of 1997 are regarded as an enormous ecological disaster, causing a total carbon emission of almost 0.9 Gigatonnes. In perspective: the annual global emission from burning fossil fuels is 5.4 Gigatonnes (Page et al., 2002). Other negative side effects of such fires are heavy air pollution (figure 1.2) and health problems for the local population.

- Continuous oxidation. Dry peat starts to oxidate, resulting in greenhouse gas emissions (methane and carbon dioxide). This contributes heavily to the total annual emissions of Indonesia, making it the third largest greenhouse gas emitter worldwide (Hooijer et al., 2006).

- Land subsidence due to the oxidation process. Lowering of the groundwater level proportionally increases the rate of land subsidence. As the surface level decreases the affected region becomes prone to flooding (Wösten et al., 2008).

The area contains a dense network of drainage canals. In order to regain control over the situation and slow down the rate of dewatering, numerous dams are currently being constructed in as many canals as possible. Usually cascades of closely spaced dams are built; an approach that has proven to be most effective in tropical peatlands (Ritzema et al., 1998). Such dams are typically constructed with natural and locally available materials.

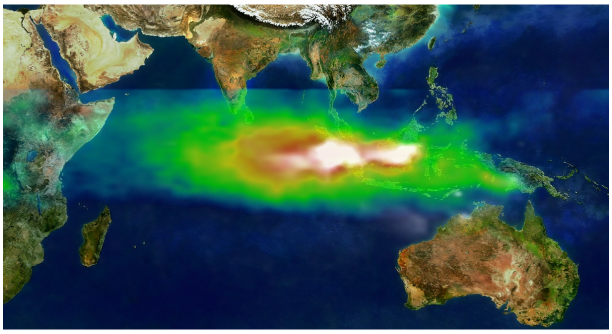

Figure 1.2: Smog caused by the peat fires of 1997. Image courtesy of NASA (2001)

The dams are often permeable and thus only create a small head difference, effectively tempering the rate of dewatering. Constructing fully impermeable dams would in itself be more effective, but lead to additional problems, like seepage and side erosion through the highly permeable soil around the structure (Wösten et al., 2010). As a result of the current dam-building approach the usual drop in groundwater level during the wet season is delayed. However, the dams cannot be regarded as a robust solution as they require frequent inspection and maintenance. They are also difficult to accept for local communities as the inhabitants nowadays use the canals for transportation and fishery (Rieley & Page, 2008)

Overall it can be concluded that the current dams are suitable to temporarily slow down the process, but they are not a sustainable solution to preserve the entire area. Therefore current literature points out that additional research is needed to develop solutions tailored to the local circumstances (Ritzema, 2007) and to evaluate the complex hydrological processes within the EMRP-area (Rieley & Page, 2008). However, accurate measurements of important parameters throughout the area are scarce, making it difficult to use sophisticated hydrological models. This creates a need for data-extensive models, a modelling approach which is in line with the scientific programme Predictions in Ungauged Basins (Sivapalan et al., 2003).

From a scientific perspective the ultimate solution would be to fill all drainage canals that have been dug in the past, thereby effectively restoring the natural situation again. But due to the costs and previously mentioned socio-economic reasons this solution can be regarded as impossible. A feasible alternative would however be to implement a strategy in which only a part of the canal system is filled. In this respect we can distinguish between so called contour canals (following the contour lines of the area) and side slope canals (normal to the peat dome contours). Due to their relatively large bottom slope, side slope canals typically have a high flow velocity and discharge rate.

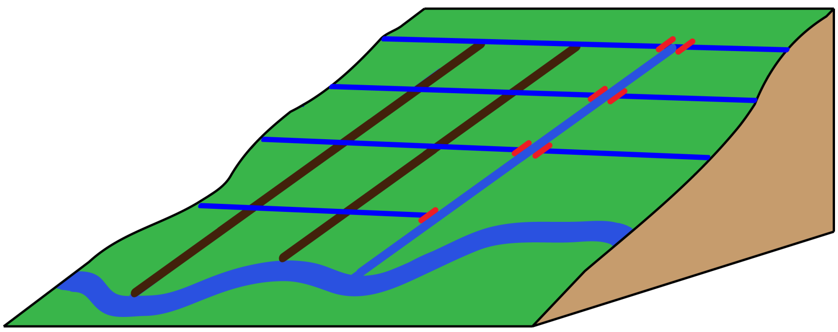

Figure 1.3: Impression of the suggested new canal system layout. Almost all side slope canals are filled in (brown), an absolute minimum is preserved to allow for drainage during the wet season. Water level in the contour canals is regulated with weirs (red) at the intersections with the few remaining side slope canals.

In this research project we investigated a proposed strategy in which a majority of the Side Slope Canals (SSCs) are filled and only the contour canals in a certain area are entirely preserved (figure 1.3). A minimum number of SSCs is maintained to provide for the necessary drainage during the wet season. The contour canals to which they connect can be equipped with weirs to regulate the outflow.

This hybrid solution is expected to lead to a significant reduction in discharge, allowing for economic land use while the costs are considered much less than a complete fill. Furthermore, navigation and fishery in the contour canals and remaining SSCs would still be possible. From a hydrological perspective, this strategy will more or less mimic the original natural situation, in which groundwater runoff played a dominant role in the drainage of the area. However, so far it is unknown which exact effect the contour canals will have on the hydrological processes.

1.3 Goal and research questions

The goal of this Bachelor Thesis is to evaluate the impact of different canal configurations on the drainage of tropical peatlands. The Ex-Mega Rice Project is taken as study case. The model required for evaluating the effects is intended to give a clear explanation of the hydrological processes in the area. Furthermore it is aimed to be data-extensive, making it suitable for predictions in poorly gauged basins.

Three questions are defined as a guideline for the research. These questions combined lead to the final conclusion about the effects of different drainage canal configurations:

1. What are the (geo-)hydrological characteristics of the EMRP-area?
2. Which model can be developed to predict drying of tropical peatland?
3. What are the effects of the new drainage canal configuration compared to the current and natural situation during the dry season?

1.4 Approach

As a first step the study area has been investigated by consulting existing literature. An assessment was made of the topography of the area, soil properties, local climate and drainage system layout. A comprehensive overview of the area characteristics is presented in chapter 2.

Based on this analysis a hydrological model was developed to predict the effects of the suggested alternative strategy. The model is specifically aimed not to require an extensive amount of data and its mathematical relations provide a logical description of the problem. Previous research at LabMath-Indonesia has already led to models that analytically describe the groundwater table in a horizontal aquifer (Noordermeer, 2010), and drainage flow through shallow canals (Meins, 2010). For this project several assumptions and functions of the existing models are used. The new model was developed by first taking a situation without any drainage canals. Secondly it was appended to cover interaction between the groundwater table and contour drainage canals. Derivation of the model is explained in chapters 3 and 4.

After deriving the mathematical relations, the model was implemented in MATLAB. Three different situations were evaluated: drainage of the aquifer under current circumstances, after a complete fill operation (equal to the natural situation) and a partial fill operation with preservation of the contour canals. In the last case the canals are equipped with weirs to control the water level. The model outcomes are discussed in chapter 5. Finally, the conclusions and recommendations can be found in chapter 6.

Chapter 2

Area characteristics

Following the first research question, this chapter gives an overview of the relevant characteristics of the Ex-Mega Rice Project. Since we intend to derive a model specifically tailored to this area, it is important to investigate where assumptions can be justified and which parameters are poorly estimated. Covered topics are the site and drainage system layout (section 2.1), local climate in the area (section 2.2), peat dome topography (section 2.3) and soil characteristics (section 2.4)

2.1 Site and drainage system layout

The most southern border of the EMRP-site is the Java Sea coast. From there it continues inland, up to 200 km in northern direction. The west side is bounded by the Sebangau River and the east side by the Barito River. Administratively the area has been divided into several sections: blocks A - E (figure 2.1). Because of the immense scale of the project most characteristics vary widely throughout the area.

Originally the whole area was covered by tropical peat swamp forest. But after the deforestation, canalization, peat fires, oxidation and subsidence the landscape changed tremendously. From table 2.1 it becomes clear that nowadays the predominant land cover is wet barren land. In the dry season the land is dry, while it partially inundates during the wet season. This type of land has become unsuitable for agriculture and is prone to peat fires in the dry season. Furthermore it can be concluded that from a preservation perspective the worst conditions are found in block A, which has the most dense drainage network.

Figure 2.1: The Ex-Mega Rice Project area and its internal block-division.

Table 2.1: General characterization of the EMRP-site. Data on land cover and drainage canal density were obtained from Jaya (2002) and Hoekman et al. (2007).

Block	**Area [×1000 ha]**	**Canal density [m/ha]**	**Predominant land cover**
A	268	5	Shrubland/wet barren land
B	175	0.8	Shrubland/wet barren land
C	441	0.8	Shrubland/wet barren land
D	137	2	Agriculture
E	Unknown	Very low	Peat swamp forest

Basically the drainage system consists of four different canal types, based on the average dimensions:

1. **Primary canals** are the largest canals found in the EMRP-area. They provide drainage where natural watercourses do not exist. The canals have a typical depth of 5 to 6 meters (Jaya, 2002) and span a total length of about 1000 km.

2. **Secondary canals** are the second largest canals. Their average depth is 3 meters (Jaya, 2002) and they span a total length of 900 km.

3. **Tertiary canals** are relatively small canals with a total length of 900 km. They are found in the following EMRP subdivision areas: Block A, Palingkau, Dadahup and Lumuti (Dohong, 2005).

4. **Quaternary canals**. The smallest canals in the area, with a total length of 1500 km (Dohong, 2005). In the past they have been dug with chainsaws and therefore their typical depth is 40 to 100 cm (Suryadiputra et al., 2005).

These canals either follow the contour lines of the sloping surface (contour canals), or run normal to contour lines (side slope canals). Depending on the amount of water they drain, they can differ in size from primary to quaternary.

2.2 Climate

Usually a dry and wet season can be distinguished in South Kalimantan. The average length of the dry season is 3 to 4 months (from August till October). Typical for the peatlands in the EMRP area is that they are only fed by precipitation (ombrogenous). As a result the groundwater level drops rapidly during the dry season. This decline does not stop until the next wet season commences again. The result is a large annual fluctuation in groundwater level, with drought during and shortly after the dry season and chance on flooding during the wet season. For the preservation of the peatlands in particular the dry season is of interest.

Precipitation, in the form of rainfall, is spread irregular through time. Accurate measurements are scarce. However, there is a meteorological station in Banjarmasin, on the southeastern border of the EMRP-area. The measurements from this station give a good indication of the precipitation and evapotranspiration patterns in the region (figure 2.2). It can be observed that evapotranspiration is relatively constant during the year, having a value of around 4 mm/d (Rieley & Page, 2008) (Wösten et al., 2008).

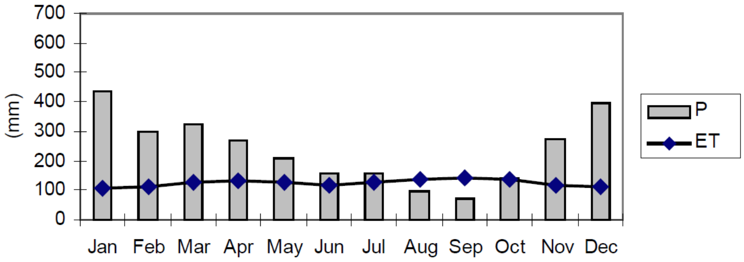

Figure 2.2: Precipitation (P) and evapotranspiration (ET) measured from Banjarmasin, on the southwest boundary of the EMRP-area. During the dry period, evapotranspiration exceeds the rainfall. Data obtained from Ritzema and Wösten (2002).

Extremely dry years have been reported, with almost no significant rainfall during the dry season. In extremely dry years (with an exceedance probability of 10%), the dry period be extended to seven months (Ritzema & Wösten, 2002). Most remarkable example is the El Ninõ event of 1997, which led to a dry season of 8 months and resulted in destruction of more than 20% of Central Kalimantan's peatlands. However, also 2002 and 2007 are known for their extreme drought. Such dry years are likely to occur more frequently in the nearby future, due to the effects of climate change. The annual surface temperature on Borneo is expected to increase with 1.05°C by 2020, and 3.3°C by 2080, while the precipitation during the dry season is expected to decrease even further (Rieley & Page, 2005).

2.3 Topography

The EMRP-site has a characteristic dome-shaped landscape. The oldest so called peat domes are found far inland and can reach up to a height of 30 m above Mean Sea Level (MSL), with a maximum slope of 24 m/km (Wösten et al., 2008). Younger domes are more commonly found. They are not higher than +4 m MSL, gently arising from the edges with slopes of 1 to 2 m/km. The peat domes are alternated with nearly flat central bog planes, with slopes of 0.5 m/km (Ritzema & Wösten, 2002).

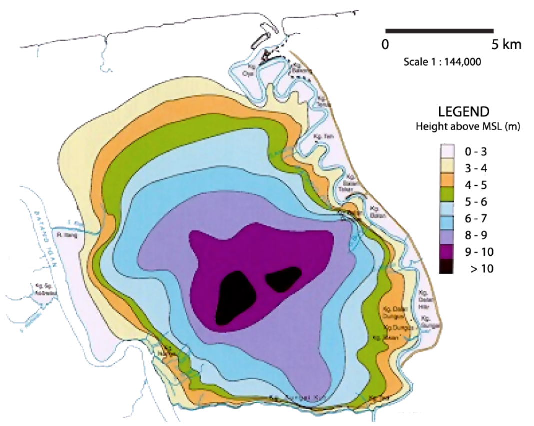

Figure 2.3: Typical topography of a peat dome (Ritzema & Wösten, 2002).

The peatlands are formed on a layer of marine clay and mud near to the coast, while inland they are underlain by sand, gravel and clay deposits of fluvial origin. In certain catchments the thickness of the peat layer can be over 10 m (Wösten et al., 2008). This maximum thickness is found in the center of the peat domes, while it is decreasing towards the natural watercourses. The peat domes do not correspond with elevation patterns of the underlaying clay layers, indicating that they in fact consist entirely of peat, as the name also suggests.

2.4 Soil

Several attempts have been done to obtain values for the saturated hydraulic conductivity of the peatland. An accurate value is however difficult to measure since it largely depends on the state of decomposition of the peat. This results in a relatively high conductivity near the surface, decreasing with the depth. As an approximation the peatland is often schematized in two layers. On top a thin layer (0-1 m below surface) of fibric to hemic peat with a relatively high saturated hydraulic conductivity (30 m/d) and underneath it sapric peat with a saturated hydraulic conductivity of 0.5 m/d (Wösten et al., 2008). The drainable porosity (specific yield) of the top layer is 0.45 and the total porosity 0.93 (Letts et al., 1999).

It is important to realize however that these values, in particular the hydraulic conductivity, can vary in a considerable range. Primarily this is caused by the fact that it is difficult to measure accurately for any type of soil. For peat the variation is even larger due to the dependency on peat humidification. Finally, for this specific case, it can be questioned if the relatively few measurements are representative for the EMRP-area as a whole.

Chapter 3

Aquifer without drainage canals

Deriving the geohydrological model takes place in two steps. First we consider an aquifer that is not intersected by contour drainage canals. Starting point for the model derivation is the conceptual model, described in section 3.1. After the schematization, the reasoning behind the model is explained (section 3.2). Special attention is paid to the explanation of diffusional and gravitational flow (section 3.3). In section 3.4 we zoom in on the diffusional flow throuth the unsaturated zone and determine the unsaturated hydraulic conductivity. Finally, in section 3.5, the governing equations of the model are presented.

3.1 Conceptual model

As displayed in figure 3.1, we consider a theoretical peat dome, which rises from the lowest point of its drainage basin to a height of about 10 meters over a horizontal distance of six kilometers (the average slope angle is thus 0.1 degrees; corresponding with 1.7 m/km). We assume that a natural watercourse flows through the drainage basin at the toe of the peat dome. Thus precipitation on the dome either runs off directly over the surface or infiltrates and then discharges as groundwater flow into the river. There is also percolation (in relatively small quantities) between the top layer and deeper, saturated peat. The peat dome is assumed to be perfectly symmetric. Therefore we only consider the left side in the model.

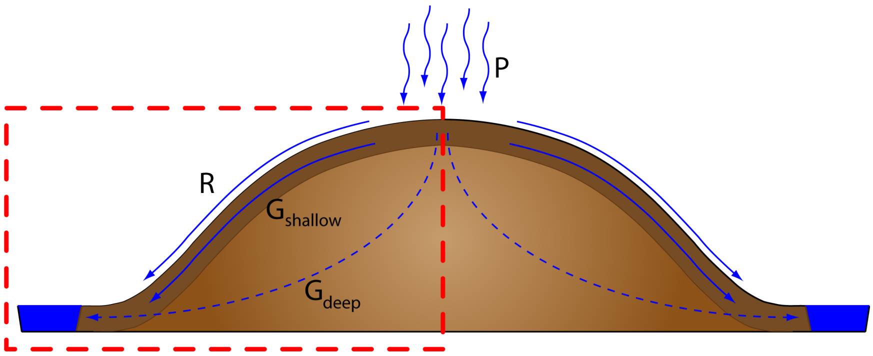

Figure 3.1: The theoretical peat dome considered. Precipitation (P) infiltrates in the highly-conductive top layer and discharges into the river as shallow groundwater flow ($G_{shallow}$) or runs off directly over the surface (R). Groundwater from the shallow aquifer can also percolate into the deep aquifer of low-conductive peat and then discharge into the river (G_{deep}). This is however considered a relatively slow process.

We schematize the situation into a model environment, using several assumptions:

1. The soil is fully saturated at the end of the wet season. Below groundwater level the soil is assumed saturated and in the unsaturated zone we assume the moisture content to be constant in time. Capillary effects are not taken into account and water in the unsaturated zone is assumed not to interact with the groundwater.

2. The slope of peat domes in reality is slightly curved and has an irregular steepness. In the model we treat it as a constant and straight slope.

3. Groundwater is treated as an incompressible fluid, moving with low speed (Reynolds number less than unity). Since we consider an unconfined aquifer, this also means that the hydraulic head of the fluid coincides with the height of the groundwater table.

4. The soil is schematized into two layers. According to Wösten et al. (2008), the top layer has a hydraulic conductivity that is sixty times higher than the peat in the bottom layer. Therefore it seems reasonable to suppose the lower peat to be impermeable compared to the upper layer. As a result the flow in the deep aquifer and interaction between the top layer and deeper soil layers can be neglected. The soil in the top layer is assumed to be both homogeneous and isotropic. This means that the same hydraulic conductivity and drainable porosity can be expected everywhere in the layer, with equal properties in all directions.

5. Following the Dupuit-Forchheimer approximation, the flow direction is assumed to be parallel to the resting bed of the sloping aquifer.

6. The natural watercourse at the toe of the peat dome is expected to be a relatively large river with infinite discharge capacity compared to the outflow of the peatland. The water level is constant through time.

7. We intend to simulate the drying of peatland during a relatively dry year, in which no significant precipitation occurs during the dry season. Therefore the only source flux is evapotranspiration.

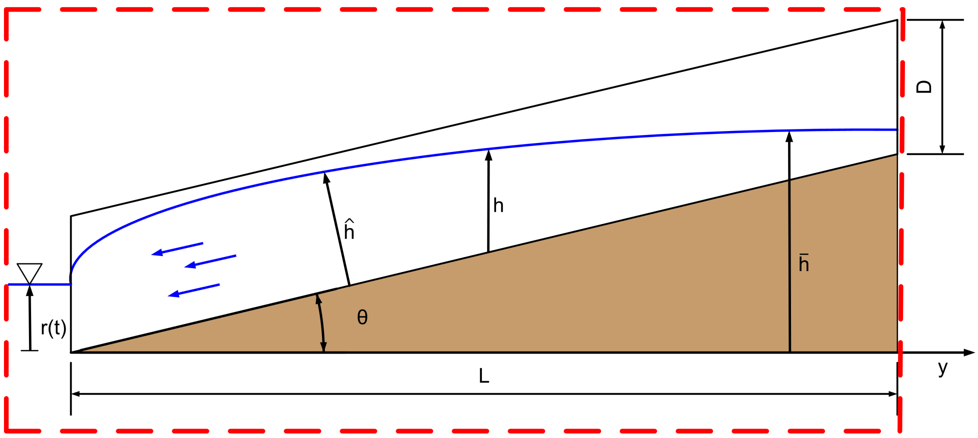

Figure 3.2: The schematized situation. Notice that the right side of the domain coincides with the top of the peat dome, meaning that no groundwater flow will occur there.

3.2 Theory

In itself, drainage of sloping unconfined aquifers is a common problem in geohydrology. Boussinesq already derived a partial differential equation for groundwater flow in horizontal aquifers in 1877. His equation was later modified for sloping aquifers by Childs (1971), which resulted in the following equation:

$$\frac{\partial \hat{h}}{\partial t} = \frac{k_s}{f}\left[cos\theta\frac{\partial}{\partial \bar{y}}(\hat{h}\frac{\partial \hat{h}}{\partial \bar{y}}) + sin\theta\frac{\partial \hat{h}}{\partial \bar{y}}\right] \tag{3.1}$$

in which $\hat{h}$ (m) is the height of the water table as measured from the impermeable bed, k_s is the saturated hydraulic conductivity (m/d), f the drainable porosity (-), θ the slope angle of the aquifer ($^\circ$) and $\bar{y}$ the distance from the watercourse measured along the impermeable bed.

Several analytical solutions have been proposed, generally based on two approaches. The kinematic wave approach is valid for highly conductive aquifers and steep slopes (Rupp & Selker, 2006). Under these circumstances it can be assumed that the hydraulic gradient equals the bed slope, resulting in loss of the second order (diffusional) term in equation 3.1. Alternatively, Brutsaert (1994) suggested to linearize $\hat{h}$ in the governing equation, thus obtaining a regular diffusion-advection equation. For most situations this approach gives satisfying results. However, the difference with numerical solutions is still relatively large.

For application to poorly gauged basins, like the EMRP-area, it can be argued that above solutions are not suitable. First of all they do not include interaction with canals in the system. Furthermore in some sense they create a misplaced feeling of accuracy when being applied to poorly gauged basins. Even though the models can produce an accurate result given the input, the input itself poses a huge inaccuracy to the simulations. Therefore the aim of this research is to derive a model that produces output with acceptable accuracy, but also increases the understanding of the actual processes that occur within the peatland.

3.3 Separating diffusional and gravitational flow

A sloping aquifer, not subjected to a constant recharge at $y = L$, will drain under unsteady flow conditions. Even though Darcy's law in itself is not valid for describing such a flow, most authors assume a so called semi-steady state condition. This justifies, to some extend, the use of Darcy's law for transient drainage. However, this approach also generalizes the processes that occur within the flow, which makes it difficult to interpret the flow's behaviour.

Example of such an interpretation problem is the linearization approach for equation 3.1, mentioned in the previous section. In this approach, $\hat{h}$ is linearized around a constant pD, in which D is the height of the aquifer and p a dimensionless constant (Brutsaert, 1994). Most authors suggest to obtain p by calibration, which usually results in a value of around 0.3 (Rupp & Selker, 2006). The linearized $\hat{h}$ term is then often somewhat arbitrarily referred to as the average fluid height. However, it can be argued that this linearized $\hat{h}$ can more correctly be explained as representing the diffusion height.

To explain this in more detail we start by considering two theoretical situations with unsteady flow conditions (figure 3.3). While for a steady flow the height of the flow zone will always coincide with total fluid height, in the unsteady condition this is no longer the case. Two separate processes occur simultaneously: gravity-driven flow, acting over the entire fluid height, and diffusional flow, only acting over a certain height h_d.

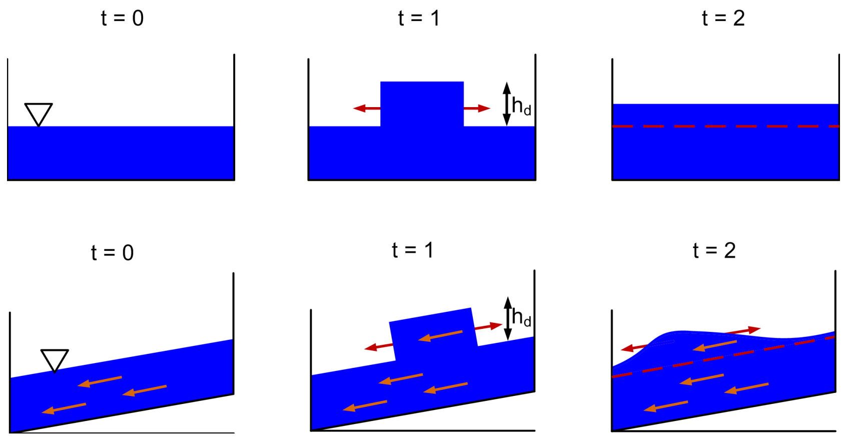

Figure 3.3: The different effects of diffusional and gravitational flow illustrated. In the upper situation logically no gravitational flow occurs. If at a certain time water is added to (or removed from) the system, there will only be (unsaturated) flow within a zone of height h_d. The same applies to a sloping aquifer. There the diffusion process tends to smoothen the water table over a height h_d, while gravity gives a constant forcing on the entire fluid. Notice that, as a result of the Dupuit-Forchheimer approximation, the flow direction is assumed to be parallel to the sloping bed.

In reality, the diffusion height varies both through time and space and is therefore rather difficult to obtain. However, in our situation the diffusion process is only induced by externally imposed variations on both ends of the spatial domain (evapotranspiration causes a uniform decrease in groundwater table and thus has no influence). Basically this comes down to the changing water level $r(t)$ at $y = 0$ and prescribed variations at $y = L$. Therefore we can approximate h_d by taking it as a constant, determined as the average of these imposed changes:

$$h_d \approx \frac{\text{change left} + \text{change right}}{2} \tag{3.2}$$

We assume that the gravitational flow causes a spatially uniform drawdown of the groundwater table. This seems justifiable, since it is known from observations that the water table depth near the edges of a peat dome is only slightly lower than in the center (Rieley & Page, 2005). It is most likely the diffusion process that causes the additional drawdown near the edges. As a result of the spatially uniform drawdown due to gravity, the diffusion height on the right side of the domain is the same as on the left side. And since the groundwater level on the left side will drop until it reaches the height of the natural watercourse, the diffusion height for this particular case is $D - r(t)$.

In the model to be derived the interaction between the sloping aquifer and intersecting watercourses plays a major role. Therefore we will explicitly take diffusional effects into account. In this approach we follow Rupp and Selker (2006). As a result we can identify in total three different processes that influence the storage within a sloping aquifer: gravitational flow, diffusional flow and recharge/evapotranspiration. These processes will first be treated separately and then combined afterwards.

3.4 The unsaturated zone

Water in a porous medium, only driven by diffusion, tends to spread from saturated into unsaturated areas. The flow zone, with height h_d, is just above the groundwater table. Even though the soil in the flow zone has a relatively high water content, it seems incorrect to use the saturated hydraulic conductivity. Therefore we determine the appropriate unsaturated hydraulic conductivity, which depends on the soil moisture.

As investigated in chapter 2, the total porosity ϕ_{total} of hemic peat is 0.95 and the drainable porosity f is 0.45. This means that the ineffective porosity is given by the difference (assuming that the drainable porosity is approximately equal to the effective porosity):

$$\phi_{ineffective} \approx \phi_{total} - f \tag{3.3}$$

We expect the soil to be fully saturated at the beginning of the dry season, meaning that all pores are filled. After gravitational drainage, the volumetric water content will ultimately decrease to a value equal to the ineffective porosity, which is 0.5. This is the same value as observed by Wösten et al. (2008), proving that our estimation of f and ϕ is rather accurate.

Typically the water content gradually increases from a value equal to the ineffective porosity nearby the land surface to a value equal to the total porosity in the saturated zone (below groundwater level). The effective saturation at any depth is given by Van Genuchten's equation (Da Silva et al., 1993):

$$\Theta = \frac{\theta_a - \theta_r}{\theta_s - \theta r} \tag{3.4}$$

In this equation Θ is the effective saturation (dimensionless) and θ_a, θ_r and θ_s are respectively the actual, residual and saturated volumetric water content(in m^3 m^{-3}). Letts et al. (1999) suggest that for the specific type of peat in the top layer of the EMRP-area θ_r can be neglected, as it is approximately zero. Furthermore, the saturated water content can be taken equal to the total porosity. The actual volumetric water content then varies from 0.5 at zero depth to 0.95 at groundwater level. As an approximation we take the average ($\theta_a = 0.73$ m^3 m^{-3}), yielding an effective saturation of 0.8 from equation 3.4. This value seems realistic, since the soil is subjected to a drying process (instead of wetting), meaning that the saturation just above groundwater level is still relatively high. Furthermore, typical water-retention curves from the EMRP-area indicate a similar water content in the zone above the groundwater table (Rieley & Page, 2005).

With the obtained effective saturation the unsaturated hydraulic conductivity can be determined, using Van Genuchten's method:

$$k_u(\Theta) = k_s \Theta^{\lambda}[1 - (1 - \Theta^{n/(n-1)})^{1-1/n}]^2 \tag{3.5}$$

In this equation k_s is the saturated hydraulic conductivity in m/d and λ a lumped parameter that accounts for pore connectivity, usually set to 0.5 (Schaap & Leij, 2000). Finally, n is a parameter representing the pore-size distribution. Based on the recommendations in Letts et al. (1999) and Seaman et al. (2009), this parameter was set to 2.3. Application of equation 3.5 for $k_s = 30$ m/d, $\Theta = 0.8$, $\lambda = 0.5$ and $n = 2.3$ leads to an unsaturated hydraulic conductivity k_u of 6 m/d.

3.5 Combining the processes

When considering all effects separately, we can derive water balance equations for each process. The full derivation for each process is given in Appendix B. For the gravitational flow the following relation is obtained:

$$(\frac{dS}{dt})_g = -\frac{k_s tan\theta}{fL} S(t) \tag{3.6}$$

From this ordinary differential equation it becomes clear that the change in drainable storage is determined by the saturated hydraulic conductivity k_s (m/d), the slope angle θ (^{0}), the drainable porosity f (dimensionless), the horizontal aquifer length L (m) and the drainable storage S (m^2). The change in drainable storage due to diffusional flow can be described as:

$$(\frac{dS}{dt})_d = -\frac{k_u h_d \pi^2}{4fL^2} S(t) \tag{3.7}$$

Notice that in this equation the unsaturated hydraulic conductivity k_u (m/d) is used. Diffusion acts over a certain height h_d (m). The equation shows a quadratic relation with L, indicating that the diffusion process will become more and more important with decreasing aquifer length. Finally the uniform drying due to evapotranspiration is modelled as follows:

$$(\frac{dS}{dt})_{ET} = -\bar{ET}L \tag{3.8}$$

In this equation $\bar{ET}$ is the actual evapotranspiration in m/d. This is assumed constant in time and space. In practice, all processes will occur simultaneously. The total change in drainable storage will then be given by the sum of the effects:

$$\frac{dS}{dt} = (\frac{dS}{dt})_g + (\frac{dS}{dt})_d + (\frac{dS}{dt})_{ET} \tag{3.9}$$

Substitution of 3.6, 3.7 and 3.8 after rewriting leads to an equation of the form:

$$\frac{dS}{dt} = -\delta S + \epsilon \tag{3.10}$$

This is the general form of a linear relaxation equation with δ as relaxation parameter (dimension d^{-1}) and ϵ as constant forcing term. In the initial situation $S(0)$ we expect the aquifer to be fully saturated. The solution for this problem can be found using 'variation of constants' (Roos, 2011):

$$S(t) = S(0)exp(-\delta t) + \frac{\epsilon}{\delta}[1 - exp(-\delta t)] \tag{3.11}$$

in which:

$$\delta = \frac{k_s tan\theta}{fL} + \frac{k_u h_d \pi^2}{4fL^2} \quad \text{and} \quad \epsilon = -\bar{ET}L$$

Above equation describes the drainable storage as function of time, draining under the influence of all three effects. The outcomes are presented in chapter 5.

Chapter 4

Aquifer with drainage canals

In this chapter a model is derived to describe the drainage of an aquifer intersected by contour canals. The same assumptions are used as in the previous chapter. Derivation starts with an overview of the canal layout and assumptions in section 4.1. All processes will again be reviewed separately: gravitational flow, diffusional flow and recharge are covered in sections 4.2 till 4.4, respectively.

4.1 Basic layout

We take a look at an identical aquifer as in chapter 3, which is now intersected with a variable amount of contour drainage canals (figure 4.1).

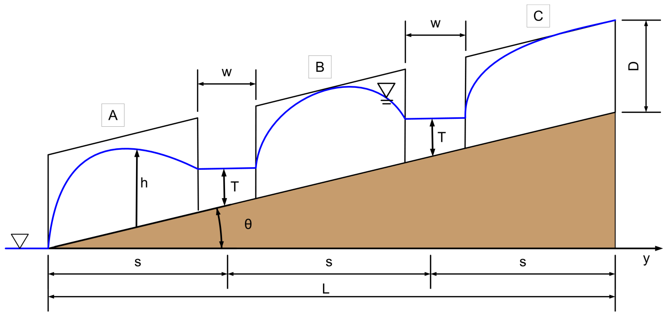

Figure 4.1: The same situation as in chapter 3, now with intersecting contour canals. Each canal is equipped with a weir of fixed height T.

All canals have equal spacing in between and are equipped with a weir of certain height (T in figure 4.1). For simplicity we take the weirs in all canals of equal height and assume the same hydraulic conductivity for each section. Water in the canal above weir height is expected to discharge through the canal system with infinite speed compared to the groundwater flow. We assume the weir to be fully impermeable and do not take seepage around it into account. At the start of the dry season we again assume the aquifer to be fully saturated, while the water level in the contour canal remains fixed at its weir height. Effectively the canals divide the peatland into several smaller aquifers. The number of sections can be expressed as:

$$n = \frac{L}{s} \tag{4.1}$$

with L being the total horizontal aquifer length in m and s the canal spacing (from center to center) in m. As a result the total amount of canals is given as $n - 1$.

4.2 Gravitational flow

If we only consider gravity as driving force, groundwater in section B will flow to the drainage canal on the left side. As long as the water level in this canal is still at weir height, all drained water will directly be discharged through the drainage system (Q_c). Meanwhile, sections A and B will also be subjected to a transient recharge induced by the canals. This recharge rate depends on the height of the water level in those canals.

First, let us consider a situation in which the weirs are set to the full height of the aquifer ($T = D$). In that case the situation is comparable with the aquifer without contour canals. Water draining from section B refills the canal and infiltrates with the same rate into section A. In other words: the aquifer does not feel the effect of intersecting canals.

In a second case we consider the weir height to be zero. In that case all water draining from section B will directly be discharged through the canal system. Effectively this leads to a situation in which the three different sections can be considered as disconnected aquifers, each draining at the same rate, but faster than in the original situation since the length is drastically reduced. The process is described by:

$$(\frac{dS}{dt})_g = -\frac{k_s tan\theta}{fl} S(t) \tag{4.2}$$

In this equation l is the length of the peatland section ($l = s - w$). If we let the weir height be somewhere between the aquifer bed and the surface, the situation will be a combination of previously considered cases in which the water level in the canal can be seen as a horizontal boundary. As long as the water level is at weir height, all water draining from sections B and C will directly be discharged through the adjacent canals. Same goes for section A, discharging in the natural water course. This process continues until the groundwater levels in A, B and C (simultaneously) reach weir height. From then on the situation will be as if it were a continuous aquifer without canals at all.

4.3 Diffusional flow

While gravitational flow occurs at the same rate in all sections, it can be observed that diffusion is subjected to different rates. The outflow rate depends on the water level in the adjacent canals of a particular section. Since the diffusion height in section A is relatively large, we can expect a relatively high outflow there. Section B is expected to have a slightly lower diffusional outflow, since the diffusion height is somewhat smaller than in A. In section C diffusional flow can be regarded small, since outflow only occurs on the left side.

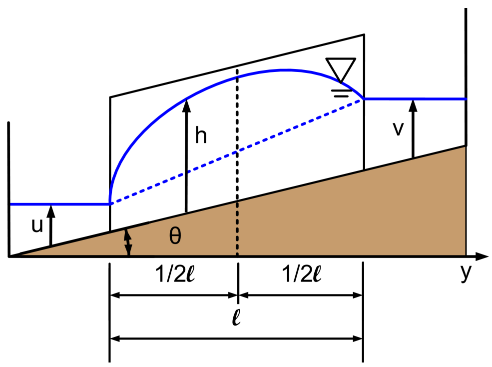

Figure 4.2: A peatland section with different water levels in the adjacent canals.

In appendix C an equation is derived to describe the diffusional outflow of a peatland section with different water levels in its adjacent canals. The following relation describes the change in drainable storage in such a section, with water level v in the left canal and u in the right canal:

$$(\frac{dS}{dt})_d = -k_u h_d \left[\frac{(8-\pi^2)(v-u)}{8l} - \frac{\pi^2 u}{2l} + \frac{\pi^2}{fl^2} S\right] \tag{4.3}$$

As an example the diffusional outflow of the three peatland sections is evaluated for an average water height in the contour canals (0.5 m). For the calculations the solution of equation 4.3 is applied (Appendix C), which yields the outflow as displayed in table 4.1. It can be observed that the averaged outflow of sections A and C is nearly equal to the outflow of section B. This averaging leads to a slight underestimation (10% at most) for higher water levels and an overestimation of equal magnitude for lower water levels. However, since we will consider aquifers intersected with a large number of intersecting canals ($n >> 3$), the relative contribution of sections A and C is small. Therefore it seems justifiable to evaluate the outflow of section B, and multiply it by the total amount of sections in the aquifer (thus assuming the averaged outflow of sections A and C to equal B).

Table 4.1: Difference in diffusion outflow between the three peatland sections. Remaining drainable water storage after 100 days of diffusion is given relative to the initial storage. For the drainable porosity and unsaturated hydraulic conductivity the following parameter values are used: $f = 0.45$ and $k_u = 6$ m/d.

Section	$\boldsymbol{u}$ [m]	$\boldsymbol{v}$ [m]	$\boldsymbol{l}$ [m]	$\boldsymbol{h_d}$ [m]	$\boldsymbol{S(100)}$ [%]
A	0	0.5	100	0.75	38
B	0.5	0.5	100	0.5	64
C	0.5	0.5	200	0.5	88
Average	-	-	-	-	63

4.4 Evapotranspiration

Since open water typically has higher evaporation rates than the land surface, it can be argued that the canal system increases the total evapotranspiration of the peatland. On the other hand, the canals under consideration have relatively small dimensions (about one meter width). Furthermore it can be argued that taking local evapotranspiration differences into account can create a misplaced sense of accuracy. Therefore it seems justifiable to treat evapotranspiration in a canal-intersected aquifer as if it were all land surface.

Chapter 5

Comparison of the effects

In this chapter the derived models from chapters 3 and 4 are used to evaluate the effects of several canal configurations. First the model constants are introduced in section 5.1. Then the model output for respectively the current situation, complete filling and weir construction is evaluated in sections 5.2 till 5.4.

5.1 Model constants

Based on the analysis of the area characteristics in chapter 2 and the simplifications introduced in the previous chapter, we can define the model constants. The unsaturated hydraulic conductivity has been determined in section 3.3. For each simulation the parameter values of table 5.1 are used, unless otherwise noted.

Table 5.1: The default simulation values used for the model.

Description	**Variable**	**Value**	**Unit**
Average slope angle	θ	0.1	degrees
Saturated hydraulic conductivity	k_s	30	m/day
Unsaturated hydraulic conductivity	k_u	6	m/day
Drainable porosity	f	0.45	-
Actual evapotranspiration	$\bar{ET}$	4	mm/day
Horizontal aquifer length	L	6000	m
Thickness of top layer	D	1	m
Length of dry season	T_{dry}	100	days

5.2 Current situation

Block A of the EMRP-area is currently drained by a dense network of canals. According to Noordermeer (2010), the contour canals have a spacing of approximately 80 m. The discharge through the canal system is not limited by any means. Therefore, from modelling perspective, the current situation is one with weirs of zero height.

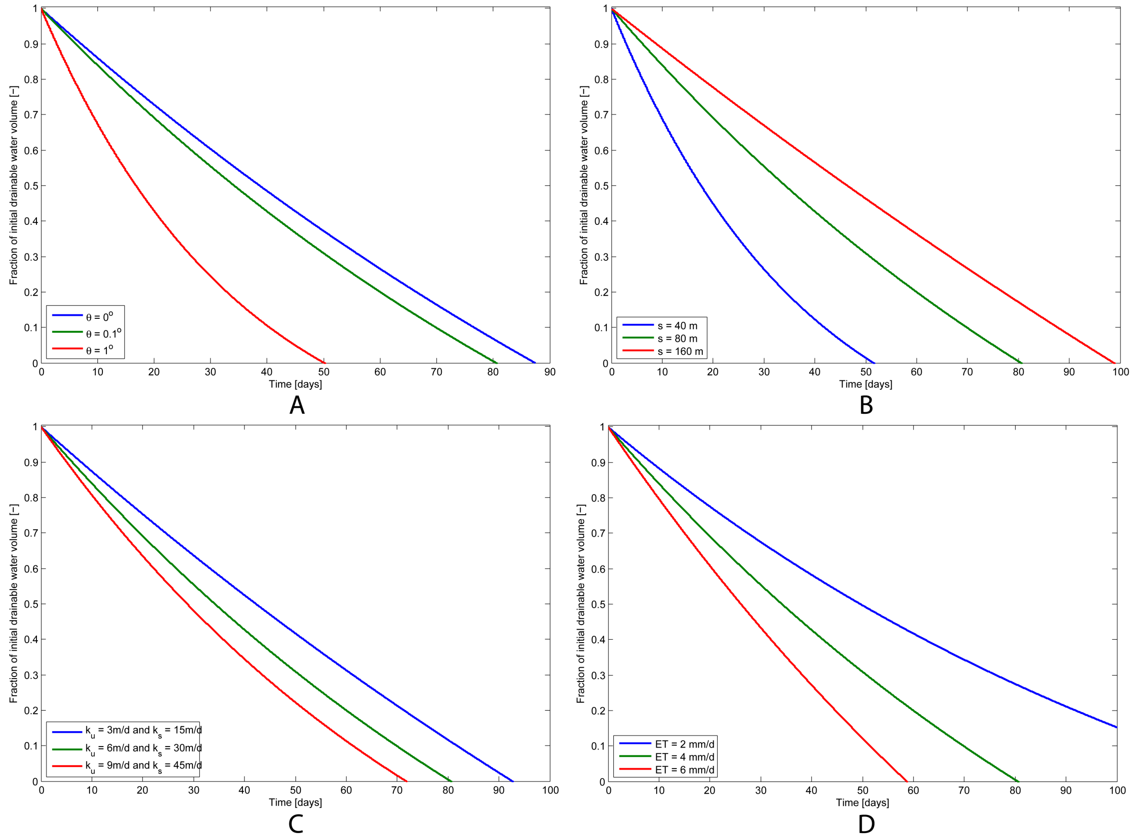

Figure 5.1: Drainage of a 6 km long aquifer. (A) indicates the influence of the slope angle on the drainage rate. For $\theta = 0$ drainage is solely driven by diffusion, combined with the effect of evapotranspiration. (B) shows the influence of canal spacing (in this simulation the slope angle was set to 0.1 degrees). (C) shows the influence of the hydraulic conductivity and (D) the influence of evapotranspiration. In nearly all cases the aquifer drains in less than 100 days. Plots with the default parameter values are displayed in green.

It can be observed from figure 5.1 that with a canal spacing of 80 m and an average slope of 0.1 degrees the aquifer drains in 80 days. This means that all water that can be drained by gravity has been drained. Approximately the groundwater table then drops till one meter below surface level. Rieley and Page (2005) confirm in their study that for relatively dry years the water table can indeed drop till lower than 1 m. Influence of the canal spacing is large, but evapotranspiration plays a predominant role. At a rate of 4 mm/day a total volume of 2700 m^3 per m^1 vanishes from the aquifer over a period of 100 days. Furthermore it can be observed that the hydraulic conductivity and slope angle are relatively insensitive parameters compared to the influence of canal spacing and evapotranspiration. It is remarkable that for the older peat domes, with a slope angle of 1 degree, full drainage of the top layer is achieved 30 days earlier than an average peat domes.

5.3 Complete fill

As a reference we evaluate the impact of a complete fill operation. It involves filling both the side slope canals and contour canals. As already mentioned in chapter 1, such a solution can be regarded unrealistic. However, it is interesting as a reference scenario. After the fill operation the drying process effectively equals the situation as it was before the initiation of the Ex-Mega Rice Project, in which no canals existed in the area. Without drainage canals the diffusion distance greatly increases, leading to a situation in which evapotranspiration predominantly contributes to the drying of the aquifer. After 100 days of drought with an evapotranspiration rate of 4 mm/day the aquifer still contains 10% of its original drainable water volume (figure 5.2).

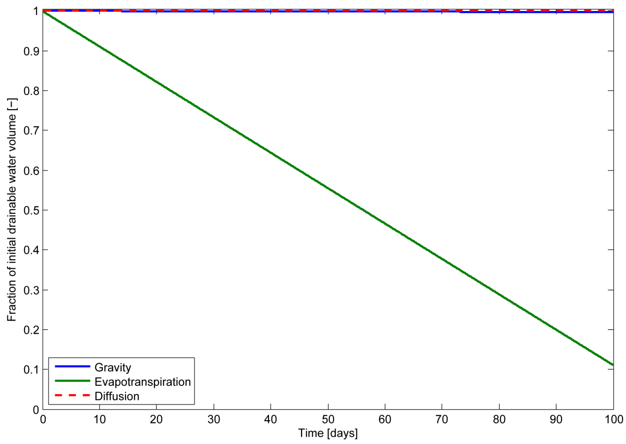

Figure 5.2: Contribution of the different processes to the total decrease in drainable aquifer storage. Evapotranspiration is the predominant process.

5.4 Contour canals with weirs

The last strategy to be evaluated is a partial filling of the side slope canals. In that case the contour canals are preserved and equipped with weirs at their intersections with the remaining side slope canals. This canal configuration provides for drainage during the wet season, when the water level will be above weir height. The water can then be discharged through the canal system. During the dry season the groundwater table will quickly adapt to weir height and from then on slowly drain as if it were one single aquifer.

During the wet season the water below weir height can be regarded as dead storage, acting as a buffer for the dry season. A weir height of one meter would mimic the reference scenario (complete fill). However, from agricultural perspective it might be preferable to use a different height, tailored to the intended land use. It has been calculated that a height of 0.75 meter would exactly bridge the dry season.

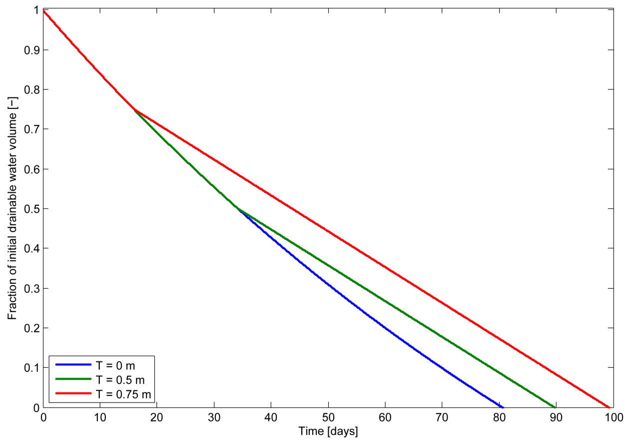

Figure 5.3: The effect of different weir heights on the total drainage time. Canal spacing is 80 m. The drainage curve for $T = 0$ is effectively equal to the current situation, in which all water can discharge with infinite speed. The typical shape of the curves clearly shows the point at which the water level in the peatland equals weir height. From then on evapotranspiration becomes dominant.

Chapter 6

Conclusions and recommendations

6.1 Conclusions

In the first chapter the goal of this research was formulated as:

To evaluate the impact of different canal configurations on the drainage of tropical peatlands.

The three formulated research questions can be seen as the red line towards this goal. In this chapter each question will be recapped and the major conclusions summarized.

The first question was answered in chapter 2, where the (geo-)hydrological characteristics of the EMRP-area have been identified. From this chapter it can be concluded that the EMRP-area in itself is extremely diverse, with a large spatial variation in characteristics. Block A is recommended as study area, since it has the highest canal density and most environmental problems. The canals that intersect the area can be categorized in both their size (primary to quaternary) and their trajectory (contour canals and side slope canals). From a preservation perspective, the dry season is critical for the peatland. During a period of approximately 100 days the peatland is exposed to a high evapotranspiration rate and low precipitation, resulting in fast drying. It has become clear that the average slope of peat domes is 0.1 degrees, which can be regarded small. An important weakness in hydrological models for the area is the poorly gauged saturated hydraulic conductivity parameter. This imposes a great inaccuracy to model predictions.

Based on the analysis of chapter 2 a data-extensive model was derived in chapters 3 and 4. It has been shown that it is possible to predict the peatland drying process with interpretable mathematical relations. Key aspect of the model is the distinguishing between different drying processes: diffusional flow, gravitational flow and evapotranspiration. By combining these processes the drainable storage within the aquifer can analytically be described as a function of time. The governing equations indicate that the slope angle and aquifer length are the major drivers of gravitational flow. Diffusional flow is independent of the slope angle, but is largely determined by the so called diffusion height. It also shows a quadratic relation with the aquifer length, indicating that the diffusion process will become more and more important with decreasing canal spacing.

The final research question, regarding the model predictions for different canal configurations, resulted in an evaluation of three scenarios. Currently the peatland is intersected with canals that have a spacing of approximately 80 m. On an average peat dome with a slope angle of 0.1 degrees this results in full drainage of the aquifer within 80 days. Approximately the groundwater table then drops till one meter below surface level. This is in line with observations of Rieley and Page (2005), who confirm that the groundwater table can drop till more than 1 meter below surface during relatively dry years. Model outcomes show that in particular evapotranspiration has a great influence on the drying of peatland. Even though diffusion is a relatively slow process, it starts to contribute significantly to the outflow when the canal spacing is small. In a situation where all canals would be completely filled, the remaining drainable storage is still 10% after 100 days. This can be approximated by constructing weirs in the contour canals at their intersection with the side slope canals. With a weir height of 0.75 m the water retention in the peatland can be increased by 20%, extending the drainage time from 80 till 100 days (compared to the current situation). This solution seems promising, since it also allows for drainage during the wet season.

Overall it can be concluded that the natural situation can be approximated by filling nearly all side slope canals, except a minimum number necessary for drainage during the wet season. It is recommended to construct weirs at the intersections between the remaining side slope canals and contour canals. The higher the weirs, the more effective the solution will be. However, the exact height is to be determined by the intended land use.

6.2 Recommendations

The recommended strategy (weir construction) has proven to be a suitable solution when it comes to water retention. However, it should also be reviewed in terms of social and economic feasibility. The weir height can be optimized by considering both the groundwater table requirements from agricultural perspective and the required minimum water retention from preservational perspective.

Additional research is needed to determine the required minimum amount of side slope canals necessary to provide for drainage in the wet season. Therefore a detailed simulation of the groundwater table throughout the entire year, in both x- and y-direction, is recommendable. An analytical approximation to simulate the groundwater table in a sloping aquifer as a function of place and time, based on Fourier series, has already been investigated in this research project. However, it led to several difficulties, making it advisable to use a numerical numerical approach for the groundwater table simulation in future research projects. Field measurements are necessary to validate the models and to obtain more accurate parameters, such as the saturated hydraulic conductivity, and to determine the spatial variation of these parameters.

References

Brutsaert, W. (1994). The unit response of groundwater outflow from a hillslope. *Water Resources Research*, *30*, 2759-2763.

Childs, E. C. (1971). Drainage of Groundwater Resting on a Sloping Bed. *Water Resources Research*, *7*, 1256-1263.

Da Silva, F., Wallach, R., & Chen, Y. (1993). Hydraulic properties of spagnum peat moss and tuff (scoria) and their potential effects on water availability. *Plant and Soil*, *154*, 119-126.

Dohong, A. (2005). *Implementation of canal blocking within Block A, Ex-Mega Rice Project.* Presented at International Symposium and Workshop on "Restoration and Wise Use of Tropical Peatland" on 21-24 September 2005.

Hoekman, D., Quinones, M., & Vissers, M. (2007). *K&C Science Report - Phase 1 Tropical Forest and Wetlands Mapping, Case Study Borneo.* Wageningen: Wageningen University.

Hooijer, A., Silvius, M., Wösten, H., & Page, S. (2006). *PEAT-CO2, Assessment of CO2 emissions from drained peatlands in SE Asia.* Delft: Delft Hydraulics.

Jaya, I. (2002). Study on spatial and temporal changes of forest cover due to canal establishment in peatland area, Central Kalimantan. *Jurnal Manajemen Hutan Tropika*, *8*, 27-45.

LabMath-Indonesia. (2011). *LabMath Indonesia - Laboratorium Matematika Indonesia.* Retrieved April 27, 2011, from `http://www.labmath-indonesia.org`.

Letts, M., Roulet, N., & Comer, N. (1999). Parameterization of Peatland Hydraulic Properties for the Canadian Land Surface Scheme. *Atmosphere-Ocean*, *38*, 141-160.

Meins, F. (2010). *Modelling drainage of tropical peatlands through a canal system* [Bachelor Thesis]. Enschede: University of Twente.

NASA. (2001). *NASA Satellite Tracks Hazardous Smoke and Smog Partnership.* Retrieved August 25, 2011, from `http://visibleearth.nasa.gov`.

Noordermeer, J. (2010). *Analytical water table height approximation* [Bachelor Thesis]. Enschede: University of Twente.

Page, S., Rieley, J., Bohm, H.-D., Siegert, F., & Muhamad, N. (2002). *Impact of the 1997 fires on the peatlands of Central Kalimantan, Indonesia.* Retrieved May 2, 2011, from `http://agris.fao.org`.

Rieley, J., & Page, S. (2005). *Wise Use of Tropical Peatlands: Focus on Southeast Asia.* Wageningen: Alterra.

Rieley, J., & Page, S. (2008). *Master Plan for the Rehabilitation and Revitalisation of the Ex-Mega Rice Project Area in Central Kalimantan, Technical Review Number 1.* Euroconsult Mott MacDonald / Deltares / Delft Hydraulics, in association with DHV, Wageningen UR, Witteveen+Bos, PT MLD and PT Indec. Retrieved May 4, 2011, from `http://www.geog.le.ac.uk/carbopeat/`.

Ritzema, H. (2007). The role of drainage in the wise use of tropical peatlands.

In *Proceedings of the International Symposium and Workshop on tropical Peatland, Yogyakarta, Indonesia on 27-29 August 2007.* Retrieved May 4, 2011, from `http://library.wur.nl/WebQuery/wurpubs/lang/375394`.

Ritzema, H., Mutalib Mat Hassan, A., & Moens, R. (1998). A new approach to water management of tropical peatlands: a case study from Malaysia. *Irrigation and Drainage Systems*, *12*, 123-139.

Ritzema, H., & Wösten, H. (2002). *Hydrology of Borneo's Peat Swamps.* Wageningen: Alterra.

Roos, P. (2011). *Mathematical Physics of Water Systems.* Enschede: University of Twente.

Rupp, D., & Selker, J. (2006). On the use of the Boussinesq equation for interpreting recession hydrographs from sloping aquifers. *Water Resources Research*, *42*, W12421.

Schaap, M., & Leij, F. (2000). Improved Prediction of Unsaturated Hydraulic Conductivity with the Mualem-van Genuchten Model. *Soil Science Society of America*, *64*, 843-851.

Seaman, J., Singer, J., & Aburime, S. (2009). Evaluating the relative importance of the Van Genuchten/Mualem parameters. In *Proceedings of the 2009 Georgia Water Resources Conference, University of Georgia, Atlanta, on 27-29 April 2009.* Retrieved August 28, 2011, from `http://www.gwri.gatech.edu/uploads/proceedings/2009`.

Sivapalan, M., Takeuchi, K., Franks, S., Gupta, V., Karambiri, H., Lakshmi, V., et al. (2003). IAHS Decade on Predictions in Ungauged Basins (PUB), 2003-2012: Shaping an Exciting Future for the Hydrological Sciences. *Hydrological Sciences Journal*, *48*, 857-880.

Suryadiputra, I., Dohong, A., Waspodo, R., Muslihat, L., Lubis, I., Hasudungan, F., et al. (2005). *A Guide to the Blocking of Canals and Ditches in Conjunction with the Community.* Bogor: Wetlands International - Indonesia Programme.

Wösten, H., Clymans, E., Page, S., Rieley, J., & Limin, S. (2008). Peat-water interrelationships in a tropical peatland ecosystem in Southeast Asia. *Catena*, *73*, 212 - 224.

Wösten, H., Ritzema, H., & Rieley, J. (2010). *Assessment of Risks and Vulnerabilities of Tropical Peatland Carbon Pools: Mitigation and Restoration Strategies.* Leicester: University of Leicester.

Appendix A

LabMath-Indonesia

This Bachelor Thesis project was conducted at Laboratorium Matematika Indonesia, more commonly known as LabMath-Indonesia (LMI). It is an independent and non-profit research institute, founded in 2005. LMI is located in the city Bandung, Indonesia (figure A.1). The institute performs its research activities under the umbrella of the Yayasan AB foundation.

Their research is focused on two subjects: coastal oceanography and environmental water. In both directions the effects from climate change play an important role. In detail, the current research portfolio includes topics like tsunami waveguiding, effects of climate change on waves, harbour waves, coastal morphology, hydrological modelling and the agricultural water footprint.

Problems are usually approached from a mathematical perspective. Besides the research objectives, LMI also aims to actively stimulate personal development of young researchers (LabMath-Indonesia, 2011). This Bachelor Thesis was conducted as part of the environmental water programme.

Figure A.1: Location of LabMath-Indonesia

Appendix B

Model derivation - aquifer without drainage canals

B.1 Gravitational flow

We start with the elementary consideration of a cross section of peatland (figure B.1), thereby defining the y-axis as horizontal datum, which intersects the sloping impermeable bed of the unconfined aquifer at $y = 0$. Following the Dupuit-Forchheimer approximation, water is expected to flow parallel to the sloping bed. Thereby we assume as an approximation that the water table will be subjected to a spatially uniform drawdown.

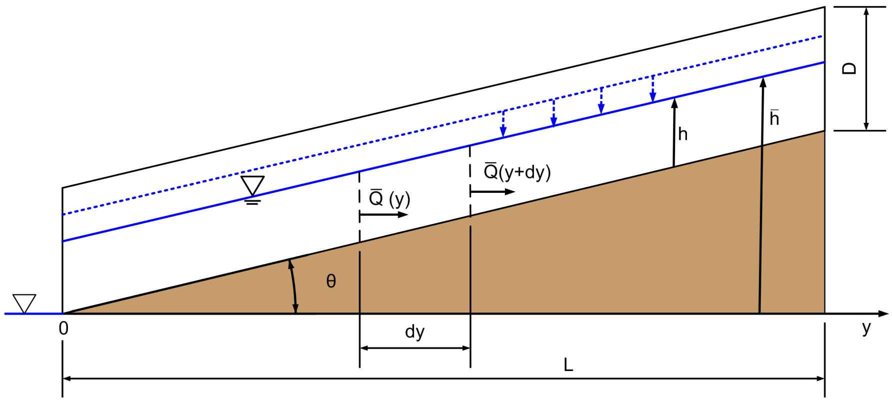

Figure B.1: Decreasing water table due to the gravitational flow. Since the right side of the domain coincides with the top of the peat dome, there is a no-flux boundary at $y = L$. Arrows indicate the positive direction of the fluxes.

In this section we only consider the gravity-induced groundwater flux, without taking the effects of unsteadiness and uniform recharge/evapotranspiration into account. The water balance equation for part dy can then be defined as follows:

$$\frac{dS_s}{dt} = \bar{Q}_g(y) - \bar{Q}_g(y + dy) \tag{B.1}$$

Since it is a twodimensional problem, the drainable storage for part dy, S_s, is given in m^2 and the horizontal component of the gravitational groundwater flux $\bar{Q}_g$ in m^2/d. Drainable storage is the volume of water that can be drained under the influence of gravity. It can be defined as the product of drainable porosity f (dimensionless) and total soil volume (hdy):

$$\frac{dS_s}{dt} = fdy\frac{dh}{dt} \tag{B.2}$$

Here h is the vertical water table height as measured from the aquifer bed. For $dy \to 0$ the following form is obtained, more generally known as the continuity equation:

$$f\frac{\partial h}{\partial t} = -\frac{\partial}{\partial y}\bar{Q}_g \tag{B.3}$$

We assume the water table to drop uniformly, so that h only depends on time (it follows the same shape as the impermeable bottom). We integrate over domain $[0, L]$ to eliminate $\frac{\partial}{\partial y}$ on the right side:

$$f\int_0^L \frac{\partial}{\partial t}h(t)dy = -\int_0^L \frac{\partial}{\partial y}\bar{Q}_g dy \tag{B.4}$$

which yields (since the flux on the right side of the domain, $y = L$, equals zero):

$$f\frac{\partial h}{\partial t}L = \bar{Q}_g(0, t) \tag{B.5}$$

We introduce Darcy's law to find an expression for the yet undefined groundwater discharge flux.

$$\bar{Q}_g = -k_s h\frac{\partial \bar{h}}{\partial y} \tag{B.6}$$

In this equation k_s is the saturated hydraulic conductivity in m/d and $\frac{\partial \bar{h}}{\partial y}$ the hydraulic gradient, with $\bar{h}$ measured from the horizontal datum level. Since the horizontal flow component is considered, we measure the hydraulic gradient along the y-axis. By applying Darcy's law we treat the flow as semi-steady. Later, in section B.2, we will introduce an additional term to account for the unsteadiness. We proceed by expressing $\bar{h}$ as:

$$\bar{h}(y, t) = tan\theta y + h(t) \tag{B.7}$$

Combining B.7 with B.6 yields, after differentiation :

$$\bar{Q}_g = -k_s htan\theta \tag{B.8}$$

By combining equation B.8 with B.5 we obtain our final expression for h:

$$\frac{\partial h}{\partial t} = -\frac{k_s tan\theta}{fL}h(t) \tag{B.9}$$

By substituting h in this equation with B.2, we obtain an identical statement for the drainable storage:

$$\frac{dS}{dt} = -\frac{k_s tan\theta}{fL}S(t) \tag{B.10}$$

This is a linear relaxation equation for which the solution can be written as:

$$S(t) = S(0)exp(-\frac{k_s tan\theta}{fL}t) \tag{B.11}$$

Since we assume the aquifer to be fully saturated at the end of the wet season, the initial condition $S(0)$ is a known parameter.

B.2 Diffusional flow

So far we have treated peatland drainage as a process solely driven by gravity. However, to account for the effects of local head differences, we distinguish an additional diffusional component. While gravity acts on the entire fluid height, the diffusional flow will only take place between locally occuring head differences. It can therefore be seen as an extra discharge flux, depending on the existence and magnitude of local head differences. The process is expected to be independent of the slope angle.

We will demonstrate this by considering the effects of only diffusion, starting with the continuity equation (B.3):

$$f\frac{\partial h}{\partial t} = -\frac{\partial}{\partial y}\bar{Q}_d \tag{B.12}$$

However, diffusion is expected to have a different influence on the shape of the water table than gravity driven flow. Therefore we define a function describing the water table as function of time and place:

$$h(y,t) = r(t) + \alpha(t)p(y) \tag{B.13}$$

In this equation $r(t)$ describes the water level of the natural watercourse at the toe of the peat dome. In this specific case we take $r(t)$ as a constant equal to zero, which further simplifies the formula. The amplitude of function $p(y)$ is determined by α and depends only on time. If the aquifer would have infinite time to drain, α is expected to reach zero, resulting in $h = 0$ for $r(t) = 0$. Substituting B.13 into B.12 and integrating over y leads to:

$$f\frac{\partial \alpha}{\partial t}\int_0^L p(y)dy = -\int_0^L \frac{\partial}{\partial y}\bar{Q}_d dy \tag{B.14}$$

The left side of the equation now states the water balance $\frac{dS}{dt}$ for the entire domain. Since the flux at $y = L$ is zero (no-flow boundary at the top of the peat dome), this can be rewritten to:

$$\frac{dS}{dt} = \bar{Q}_d(0,t) \tag{B.15}$$

Above equation shows that the entire diffusion process depends on the outflow at $y = 0$.

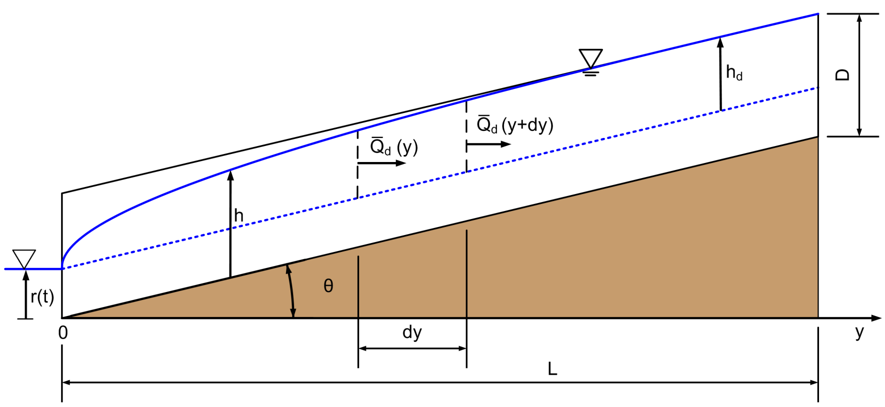

Figure B.2: Schematization of the diffusion process. Diffusion is driven by local head differences and will therefore only act over height h_d.

Again we use Darcy's law to define $\bar{Q}_d$. However, in this situation the hydraulic head needs to be measured with the semi-steady part of the flow as datum level. Reason is that we only consider diffusion, without the effects of gravitation (which are already accounted for in the previous section):

$$\bar{Q}_d = -k_u h_d \frac{\partial h_d}{\partial y} \tag{B.16}$$

The unsaturated hydraulic conductivity k_u is measured in m/d and h_d, the diffusion height, in m. Because in this situation we have taken the water level of the river $r(t)$ equal to zero, the diffusion height equals the total fluid height. Later we will demonstrate that in situations where $0 < r(t) < D$, the diffusion height is proportional to the water level in the river. Since the hydraulic gradient of the semi-steady flow follows the slope of the impermeable bed, $\frac{\partial h_d}{\partial y} = \frac{\partial h}{\partial y}$. We proceed by defining $p(y)$ and choose this function to be a sine on its interval from 0 to $\pi/2$, scaled to the domain $0 \leq y \leq L$. The cosine appearing in the denominator is a result of coordinate transformation:

$$p(y) = \frac{sin(\frac{\pi}{2L}y)}{cos\theta} \tag{B.17}$$

Combining B.17 with B.13 and substituting the result in B.16 leads to:

$$\bar{Q}_d = -k_u h_d \alpha(t) \frac{\partial}{\partial y}(\frac{sin(\frac{\pi}{2L}y)}{cos\theta}) \tag{B.18}$$

After differentiation over y and substituting in B.15 the following form is obtained:

$$\frac{dS}{dt} = -k_u h_d \alpha(t) \frac{\pi}{2Lcos\theta} \tag{B.19}$$

Now we need to find an expression for $\alpha(t)$. Therefore we recall (section B.1) that the drainable storage S can be expressed as:

$$S(t) = \int_0^L fhdy \tag{B.20}$$

Substituting h by B.13 and integrating $p(y)$ over y yields (notice that $r(t)$ is left out, since it equals zero):

$$S(t) = f\alpha(t) \int_0^L p(y)dy = f(\frac{2L}{\pi cos\theta}\alpha(t)) \tag{B.21}$$

This results in the following expression for α:

$$\alpha(t) = \frac{S}{f\frac{2L}{\pi cos\theta}} \tag{B.22}$$

We substitute B.22 into B.19:

$$\frac{dS}{dt} = -\frac{k_u h_d \pi^2}{4fL^2} S(t) \tag{B.23}$$

The general solution for this equation is:

$$S(t) = S(0)exp(-\frac{k_u h_d \pi^2}{4fL^2} t) \tag{B.24}$$

As we expected the decrease in storage due to diffusion is indeed independent on the slope angle. The outflow is predominantly determined by the aquifer length L.

B.3 Evapotranspiration

Apart from the gravitational outflow, we also need to consider the effects of evapotranspiration. It is assumed that the evapotranspiration flux is uniform over the spatial domain but varying through time. It will thus cause a spatially uniform drawdown of the water table.

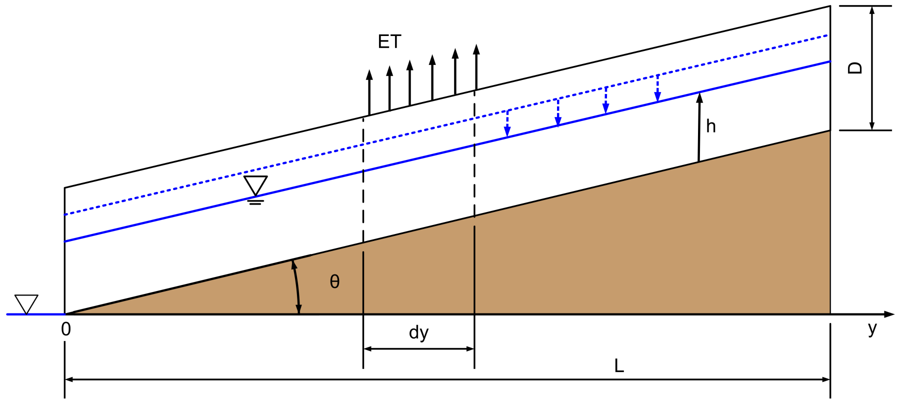

Figure B.3: Uniformly decreasing water table due to evapotranspiration.

Again we start with the water balance equation for an infinitesimal cross section of peatland dy, subjected only to spatially uniform evapotranspiration as displayed in figure B.3:

$$\frac{dS_s}{dt} = -ET(t)dy \tag{B.25}$$

Here ET is the actual evapotranspiration in m/d and S_s the drainable storage within a section dy. It is taken as a positive value for recharge. If we consider the entire aquifer (the domain from 0 to L) the equation becomes:

$$\frac{dS}{dt} = -ET(t)L \tag{B.26}$$

Integrating over t leads to the solution:

$$S(t) = S(0) - L\int_0^t ET(t)dt \tag{B.27}$$

However, if we take ET to be constant in time, the solution further simplifies to:

$$S(t) = S(0) + L\bar{ET}t \tag{B.28}$$

Appendix C

Model derivation - aquifer with drainage canals

In appendix B we derived a relation for the diffusional flow under the condition that the water level in the adjecent watercourse (r) is zero. However, in the new situation the water level in the canals is unequal to zero, and different water levels can exist on both sides of the peatland sections. Therefore we derive an equation for variable water levels. It will also be demonstrated that the original derivation is in fact a special case of the general formula derived in this appendix.

C.1 Situation

In the new situation we consider an unconfined sloping aquifer, which is intersected by a variable amount of contour drainage canals.

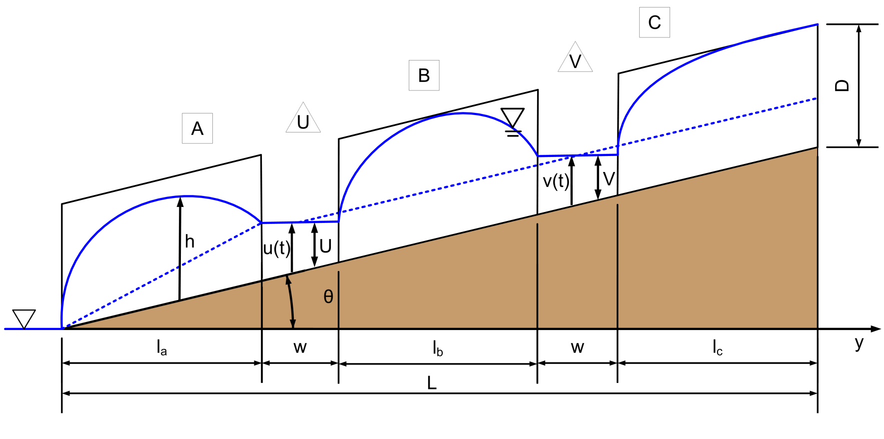

Figure C.1: Schematization of the diffusion process in case of two intersecting drainage canals. If the different sections have an equal length, the water table profiles can be shaped in three different ways.

For section A the water table starts at the water level of the natural watercourse, which is constant and equal to zero. On the right side of section A the profile ends at the water level in the adjecent contour canal. Section B has a water table that is on both sides connected to contour canals with equal weir height. This section can be duplicated in the model for as many canals as desired. Finally, the situation of section C will always appear on the right side of the domain.

C.2 Diffusional flow

Due to the water level differences the diffusion process will occur at a different rate in the sections. Therefore we take a generalized situation in which a sloping section of peatland, only subjected to diffusional outflow, has canals on both sides. The water level in these canals is taken constant in time. The sine-shaped water table profile needs to be superimposed on a line connecting the water levels of the adjecend canals. For the sake of consistency, we start again by considering the continuity equation as derived in B.3:

$$f\frac{\partial h}{\partial t} = -\frac{\partial}{\partial y}\bar{Q}_d \tag{C.1}$$

We integrate both sides over y to obtain the water balance equation for half of the peat section.

$$\frac{dS}{dt} = f\int_0^{1/2l}\frac{\partial h}{\partial t}dy = -\int_0^{1/2l}\frac{\partial}{\partial y}\bar{Q}_d dy \tag{C.2}$$

Thereby we assume symmetric outflow for each half length of the peat section, meaning that there is a no-flow boundary at the symmetry axis of the superimposed profile. Integration therefore yields:

$$\frac{dS}{dt} = \bar{Q}_d(0,t) \tag{C.3}$$

Again we apply Darcy's law in the same way as described in appendix B. We now define the following function to describe the water table as function of time and place:

$$h(y,t) = u + \frac{v-u}{l}y + \alpha(t)p(y) \tag{C.4}$$

$$\text{with } p(y) = \frac{sin(\frac{\pi}{l}y)}{cos\theta}$$

In which u is the water level in the left canal and v the water level in the right canal. Again, $\alpha(t)p(y)$ is the superimposed characteristic water table profile. Substituting C.4 in Darcy's equation (B.16) leads to:

$$\bar{Q}_d = -k_u h_d \frac{\partial}{\partial y}(u + \frac{v-u}{l}y + \alpha(t)\frac{sin(\frac{\pi}{l}y)}{cos\theta}) \tag{C.5}$$

After differentiation over y and substituting in C.3 the following form is obtained:

$$\frac{dS}{dt} = -k_u h_d(\frac{v-u}{l} + \frac{\pi}{cos\theta l}\alpha(t)) \tag{C.6}$$

Now we need to find an expression for $\alpha(t)$. Therefore we recall (section B.1) that the drainable storage S can be expressed as:

$$S(t) = f\int_0^{1/2l} hdy \tag{C.7}$$

Substituting h by C.4 and integrating over y yields:

$$S = f(\frac{ul}{2} + \frac{(v-u)l}{8} + \alpha(t)\frac{l}{\pi cos\theta}) \tag{C.8}$$

This results in the following expression for α:

$$\alpha(t) = \pi cos\theta(\frac{S}{fl} - \frac{u}{2} - \frac{v-u}{8}) \tag{C.9}$$

Substituting this result into equation C.6:

$$\frac{dS}{dt} = -k_u h_d [\frac{(8-\pi^2)(v-u)}{8l} - \frac{\pi^2 u}{2l} + \frac{\pi^2}{fl^2} S] \tag{C.10}$$

It can be observed that for $u = 0$ and $v = 0$ exactly the same form appears as in equation B.23 (taking into account that $l = 2L$). Above equation describes a linear relaxation process. It can be rewritten to the form:

$$\frac{dS}{dt} = -aS + b \tag{C.11}$$

For which the general solution is (Roos, 2011):

$$S(t) = S(0)exp(-at) + \frac{b}{a}[1 - exp(-at)] \tag{C.12}$$

in which:

$$a = \frac{k_u h_d \pi^2}{fl^2} \quad \text{and} \quad b = k_u h_d \left[\frac{\pi^2 u}{2l} - \frac{(8-\pi^2)(v-u)}{8l} \right]$$