# Analytical water table height approximation

.

Restoration of tropical peatland hydrology on Central Kalimantan

LabMath Indonesia, Bandung, Indonesia

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# Foreword

The report before you contains my findings during my civil engineering bachelor of science thesis project. The project was conducted at LabMath Indonesia in Bandung and concerned the mathematical modeling of the water table in peat soils. As part of the civil engineering bachelor of science program students are requested to perform their final project as an intern at a research facility, institution or company. This report is the final part of that internship and will bring closure to my studies for the BSc - Civil Engineering.

I would like to thank everyone for their tremendous support during this period. Firstly I would like to thank the supervisors at LabMath Indonesia, Brenny van Groesen and Andonowati for their tremendous help and for making it all possible. Additionally I would like to thank my supervisor from the University of Twente, Martijn Booij for his support before and during my internship at LabMath Indonesia. I would also like to thank Ellen van Oosterzee for her incredible effort organizing my departure and making sure that all tasks were completed on time. And last but not least i would like to thank Jeroen Bemelmans for taking the time to evaluate my research project.

*Joost Noordermeer*

# Contents

# Summary Report

One of the most important instigators of peatland deterioration is the over-drainage as a result of planned agricultural production. A large amount of tropical peatland has been converted for palm oil, rubber and rice production. The Ex- Mega Rice Project in Indonesia in the province of Central Kalimantan is a prime example of tropical peatland deterioration as a result of 'unwise' land-use. The drainage canals at that site greatly disturb the natural hydrological system. Low water tables result in oxidation and potential fires. Research shows that restoring the hydrological system of tropical peatlands is of primary importance to the restoration of the natural environments (Page et al., 2009).

This research project focuses on the possible routes to restoring tropical peatlands through partially or completely damping canals in order to influence the hydrological system so that it returns to its natural state. A model was constructed in assignment of LabMath Indonesia to simulate water table changes in ombrogenous (rain fed) tropical peatland bounded by canals during periods of drought as a result of damping. There are very few input variables for this model, which allows the model to be broadly applied to tropical peatlands even when data is not readily available. Complete and partial damping was investigated by scaling the distance between canals or influencing the canal depth during simulation.

From the various simulations it becomes apparant that completely or partially damping canals has a significant influence on the water retention capabilities of tropical peatland. This leads to a much slower water table drop thus slowing down the deterioration process. When one canal is damped in the tropical peatland analyzed a potential increase of water retention of 35% was achieved. When two more canals were damped this figure was increased to nearly 55%. Similarly, the water table height in the center of the peatland was investigated. By damping one canal the water table drop in the center of the peatland was reduced from 2.7 meters to 0.7 meters. Partial damping had a similar effect. By reducing the canal depth to half the original value, a 50% gain was achieved in the water table drop.

The model used for this research shows that partial or complete damping of canals can have a significant influence on the restoration of tropical peatlands on Central Kalimantan. This is an expected result as these measures return the peatland to its natural physical state where no canals are present. However, it has to be recommended that the hydrological model used in this research paper is developed further. Various groundwater and surface water flows have been ignored due to the fact that the model simulates the water table in only one horizontal direction. The validity of the model can be increased by expanding the model to a second horizontal direction.

# Chapter 1

# Introduction

Climate change has taken a central role in the media, politics and scientific research in the past decade. It is therefore not surprising that as time passes more knowledge about the causes of climate change and its influencing factors become known. In recent research an important link between peatlands and the global carbon cycle has been investigated. Peatlands, traditionally a carbon sink, are rapidly becoming carbon sources as a result of 'un-wise' land-use (Jaenicke et al., 2008). Knowledge regarding the relationships between peatfires, logging, drainage, climate change and carbon release is crucial when trying to influence this process. The hydrological system of a peatland takes a central role tying these factors together.

LabMath Indonesia (LMI) recognizes the severe consequences of peatland degradation on the local and global community. Through the oxidization and burning of peat a large amount of $CO_2$ is released into the atmosphere. Reducing these greenhouse gas emissions not only has a positive influence on the climate, it also allows Indonesia as a nation to promote its efforts to reduce the causes of global warming. One of the specializations of LabMath Indonesia is the mathematical modelling of environmental water. LMI wishes to apply its expertise to this issue because a clear relationship between peatland hydrology and its deterioration has become apparent. See appendix A for a concise description of LabMath Indonesia.

The research discussed in this paper aims to find methods to avert the damage done by the large scale and damaging land-use changes in the Ex-Mega Rice Project area on Central Kalimantan. Large drainage canal networks have dramatically disrupted the natural hydrological and ecological environment with many short and long term impacts. The solution to these problems will be sought in the complete and partial damping of the canals. In this introduction the problem at hand will be outlined. From this a research goal is formed that leads to three research questions that will guide this project. Each research question will be answered in a different chapter. Chapter 2 will outline the main problems facing tropical peatlands in general and give a detailed description of the study site, the EMRP area on Central Kalimantan. Chapter 3 describes the derivation of a model used in this research project to simulate ground water table changes at the research site. The relevant input data which has been used for model calculations is also discussed in this chapter. In chapter 4 the influence of complete or partial damping of canals on the water table will be analyzed using the previously constructed model. Finally conclusions and recommendations are discussed with regards to the above mentioned chapters.

## 1.1 Problem description

Drainage of the tropical peatlands in the former Ex-Mega Rice Project area has caused the peatland to suffer greatly from oxidation, subsidence and ongoing peatfires. The development and drainage of peatland in general, for various purposes, has a severe impact on its hydrological system. This leads to reduced carbon storage with the result that carbon enters the atmosphere in the form of the greenhouse gas $CO_2$ (Page et al., 2002). Additionally the (illegal) logging further reduces the water retention capacity of the peatlands and removes the only form of contribution to new peat formation from the area. Drainage and logging together form an serious threat for the ecology of tropical peatlands, in particular the hydrological functions are diminished (Wösten et al., 2008).

Under natural conditions peatlands are flooded or near flooded during the wet season and water levels drop between -20 and -40 cm in the dry season, but do not exceed -100 cm (Wösten et al., 2006). Peatland that has been drained drops to water tables lower than -40 cm frequently during the dry period. Research has illustrated that water tables lower than 40 cm under the peat surface pose a serious threat to peatland integrity because at this point the ground becomes dry enough for fires to ignite and penetrate into the peat soil (Usup et al., 2004). This makes them incredibly difficult to extinguish. Furthermore, the fires produce large gaps in the forests. In combination with the greater penetration of sunlight this increases the temperature of the region and lowers the soil moisture making it more susceptible to subsequent fires (Page et al., 2009).

When peatlands have degraded, as a result of drainage and peatfires, the only method of restoring the peatland is by negating the impact of the canalization and focusing on the recovery of the hydrological integrity (Page et al., 2009). In order to re-wet peat, methods need to be sought that counter the effectiveness of drainage canals. Partial or complete damping of the canals make it possible to significantly influence the water table in peatsoils. Small canals are slowly silting up, but the larger canals remain intact due to their relatively high flow-rates (Rieley and Page, 2005). Damping all the canals completely would require tremendous resources and is therefore not a feasible or realistic option. Furthermore, local communities use the canals as a transportation system and would therefore not concur with complete damping of the canals. Public support is very important in this matter as various attempts to build dams in the canals have been undone by local communities in the past (Page et al., 2009). This leads to the following research goal.

## 1.2 Research goal

The goal of this research is to reverse the degradation of tropical peatlands in Central Kalimantan by restoring the natural height of the ground water table through the investigation of ground water table dynamics of tropical peatlands in periods of drought with respect to the present drainage canalization.

## 1.3 Research questions

The following research questions have been formulated in order to reach the research goal:

1. What is the current consensus in literature regarding the causes, impacts and possible solutions for tropical peatland degradation with a focus on Central Kalimantan?

2. What model can be constructed to simulate the ground water table height in tropical ombrogenous peatlands bounded by drainage canalization?

3. How does the damping or partial damping of drainage canals influence the water retention and thus the ground water table height of tropical peatlands during periods of drought?

## 1.4 Research approach

This research will be conducted in three stages, each focusing on a different research question. The first research question will be answered through a literature study. The most recent developments with regards to tropical peatlands, and most notably the EMRP area, are investigated. The findings hereof are discussed in chapter 2. For the second question an analytical model will be constructed based on the water balance and a Fourier series expansion. The simplification, assumptions, calculations and finally the solution is presented chapter 3. This model will then be used to investigate the influence of partial and complete damping on the retention of ground water and the ground water table height in tropical peatlands in the EMRP area as stated in the third research question. The findings of the model calculations can be found in chapter 4.

# Chapter 2

# Tropical peatlands and degradation

In the introduction the causes and consequences of tropical peatland degradation have briefly been discussed. This chapter will focus on further exploring these topics in order to answer the first research question.

Research Question 1: *What is the current consensus in literature regarding the causes, impacts and possible solutions for tropical peatland degradation with a focus on Central Kalimantan?*

This research question will be answered over three different sections of this chapter. First a brief overview of tropical peatlands and all its functions will be discussed with an emphasis on the hydrological functions. After the importance of tropical peatlands in relation to their environment has been established the causes and impacts of its deterioration will be analyzed. The study site, the Ex- Mega Rice Project area on Central Kalimantan, will be discussed in the final section of this chapter in order to determine the primary causes of the peatland degradation at that particular site.

## 2.1 Tropical peatlands: a brief orientation

Peatlands haven been studied in great detail on the northern hemisphere (Fraser et al., 2001; Evans et al., 1999). Only recently has scientific research been performed in the peatlands around the equatorial zone. Many aspects of these peatlands are therefore unknown. Knowledge transfer from the temperate peat is not always appropriate as a result of the differences in climate and peatforming vegetation (Page et al., 2009). Due to the immense size of tropical peatlands it has not yet succesfully been determined how much is present. Differences in definition and survey techniques are a primary reason for discussion (Rieley and Page, 2005). The estimates about the area of tropical peatlands in Southeast Asia varies from 20 to 33 million hectares (Rieley and Page, 2005), which are based largely on aerial photography due to the sheer size of each peatland. This peatland serves many functions such as an ecological function, socio-economical function, hydrological function and a carbon storage function. These are described below.

### Hydrological functions

The hydrological functions that peatlands in their natural state perform are vast. Not only is it a fresh water supply for the region, it also regulates the water and stabilizes the water level. Drainage to facilitate agriculture has largely influenced these functions, not only in the drained region, but also in the adjacent peatlands (Rieley and Page, 2005). Water outflow is accelerated causing the water table to drop much more rapidly. A result of this, the total amount of water stored in a region is decreased significantly. The peatlands on Kalimantan are almost all completely rain-fed (ombrogenous), almost no water runs into the peatlands from external sources. This means that the water balance for these peatlands can be described as:

$$P = E + Q + \Delta S$$

where $P$ is the precipitation, $E$ is the evapotranspiration, $Q$ is the outflow of the region and $\Delta S$ is the change in the water storage of the region. Under natural conditions, over large periods of time the evapotranspiration and outflow can be considered constant and the change in water storage is negligible. Therefore the only big influence on the hydrological system is the precipitation.

Drainage causes much of the water systems storage function to be destroyed. Water will be transported to the rivers much quicker and therefore be transported out of the local water system. The sponge effect of peatsoils is destroyed by drainage eventually and as a result many hydrological functions disappear leading to the lowering of the ground water level and subsequent fires (Wösten et al., 2008). Logging adds to this effect due to the fact that the roots of the trees decrease water flow through the soil.

### Carbon storage function

Peatlands consist of largely organic matter that has been built up over long periods of time from the flora growing on it in waterlogged environments that lack oxygen (Jaenicke et al., 2008). The tropical peatlands play an important role in the carbon flux between the ground and the atmosphere. Through continued drainage much of the carbon sequestering function has been destroyed all over the world, causing peat oxidation and consequent $CO_2$ emission. Logging removes the biomass that is the sole contributer to the peat accumulation (Page et al., 2009) and subsequently has a tremendous impact on the hydrological system. Drainage and logging therefore not only have a short term impact on the carbon storage function of peatsoils, but in the long run also cripple future peat accumulation and increases the rate at which it enters the atmosphere. The restoration of tropical peatlands is therefore crucial to reduce the speed of the climate change.

When peatland deteriorates the carbon stored in it is released into the atmosphere in the form of greenhouse gases. With an estimated carbon storage of $55 \pm 10$ Gt in Indonesia (Jaenicke et al., 2008) and the ongoing 'unwise' use of the peatlands, the potential greenhouse gas emission is enormous. 7.2 Gt of $CO_2$ is released annually by fossil fuels equating the carbon store in Indonesian peatlands to approximately 8 years of fossil fuel emissions.

### Ecology

Tropical peatlands have a large biodiversity, however due to climatic and anthropogenic influences the flora and fauna on and in peatlands is under great pressure. Additionally, the species found within the ombrotrophic tropical lowland peatswamps are unique to the environment and cannot survive in adjacent rainforest (Page et al., 2009). When peatland is deteriorated much of the nutrition and sheltering functions of the habitat are destroyed causing the flora and fauna to disappear. (Illegal) Logging is another prime reason that many animals (especially birds and mammals) are forced to leave their territory as the trees serve as shelter for them. The orang utan population is often used as an example to illustrate this process (see figure 2.1). The orang utan population is steadily decreasing as a direct result of fire, transmigration settlements, encroachment and illegal logging (Rieley and Page, 2005).

Figure 2.1: *Orang utan in its natural habitat on central Kalimantan.* Source: (CareTourism, 2009)

**Socio-economic functions**

Generations of indigenous people have lived in harmony with the natural state of the tropical peatlands, but have since large scale land-use changes been forced to adapt to other forms of income. Historically they depended on the natural resources from the peatlands, but with deforestation and drainage many of these resources have become unavailable (Rieley and Page, 2005). This forces many to find other sources of income that often do not benefit the state of the ecological region. The various land-uses often require both migrant and indigenous communities as the labor force. When natural resources diminish within a region, more pressure is placed upon the resources in the adjacent regions (Page et al., 2009). Additionally, if people can benefit from timber, involvement in (illegal) logging is often a result. This rapid exploitation of the natural resources increases the deterioration of the tropical peatlands at an accelerated pace.

## 2.2 Causes and impacts of peatland degradation

Climate change is taking a public interest. As governments struggle to minimalize the usage of fossil fuels, other sources of greenhouse gases naturally need to follow. Environmental $CO_2$ emissions are being investigated worldwide. Tropical peatlands have shown to be an important carbon sink, but deteriorated peatlands contribute greatly to the carbon release to the atmosphere (Jaenicke et al., 2008). As a result of poor land-use policies the tropical peatlands are in poor condition. A result of this is increased peat subsidence, the lack of new peat formation and ongoing (and returning) peat fires.

Globally it has been observed that the sea level is rising, precipitation is increasing, temperature is increasing and extreme weather conditions occur with a higher frequency (IPCC, 2007). Greenhouse gasses are one of the primary drivers for the change of climate on earth according to the Intergovernmental Panel on Climate Change (IPCC) Synthesis Report. In recent research (Rieley and Page, 2005; Wösten et al., 2008; Hadi et al., 2000) it is described how peatlands contribute to the greenhouse gas release globally and how government policy, especially regarding land-use, has impacted its atmospheric dispersion.

Cultivation of peatlands, for the production of products such as palm oil and rice to support the growing population, has been very rapid in the past decades. The most notorious of these projects has been the Ex-Mega Rice Project in Central Kalimantan where one million hectares of land were converted for the production of rice. This site will be discussed to greater detail in section 2.3.2. Large networks of canals have been established on peatlands for drainage and much of the forest cover has been removed in order to facilitate crop production. As mentioned in previous sections, these actions have a tremendous impact on the natural peatland environment. Destruction of ecology, hydrology and carbon sequestering functions lead to drought, rapid peat subsidence and consequential peat fires (Hadi et al., 2000).

As soon as peatlands become drained for agricultural purposes, peat subsidence occurs. The only method of influencing the subsidence rate is by increasing the water level in the soil. On average 60% of peat subsidence is caused by oxidation and the remainder by irreversible drying or shrinkage of peat (Wösten et al., 1997). Peatland subsidence is positively related to drainage and therefore, with different land-uses, leads to substantial carbon emissions (Wösten and Ritzema, 2001).

In most cases peat shrinks when dried and expands when rewetted except for the cases when irreversible drying occurs. In the case of irreversible drying the top layer of the peatsoil becomes very susceptible to fire (Hooijer et al., 2006). In combination with the $CO_2$ emissions from peatsoils, as a result of oxidation, the greenhouse gas emissions have a significant influence on a global scale. Fires are often induced while preparing areas for agricultural purposes and have long lasting devastating effects for the environment both locally and globally. Repeat fires at the same locations further damage the peatland eventually leading to flooding in the wet season and increased susceptibility to fire in the dry season (Wösten et al., 2008).

Figure 2.2: *A peatfire by night on Kalimantan.* Source: (Siegert, 2009)

## 2.3 Study site

For this research the location of the former Ex- Mega Rice Project area will be used to investigate the influence of partial or complete damping of canals on the water table fluctuations in peatlands. The land layout and evapotranspiration will be used to simulate these measures applied to the drainage canals constructed for rice production. In this section the focus will narrow from peatlands in Indonesia as a whole to the Ex-Mega Rice project. Of this area some of the most problematic properties will be discussed.

### 2.3.1 Tropical peatlands in Indonesia

Indonesia has the 4$^{th}$ largest amount of peat on the earth, only preceded by the USA, Russia and Canada (Rieley and Page, 2005) making it the country with the most tropical peat. The amount of tropical peat in Indonesia is estimated to be anywhere between 17.8 and 20.0 million hectares (RePPProT, 1990). This peat is made of organic, partially decomposed material that due to the lack of oxygen maintains its present partially decomposed state. Kalimantan, Sumatra and Papua contain the largest peat storages in Indonesia, where Kalimantan holds an estimated 50.4% of Indonesian peat (Sukardi and Hidayat, 1988).

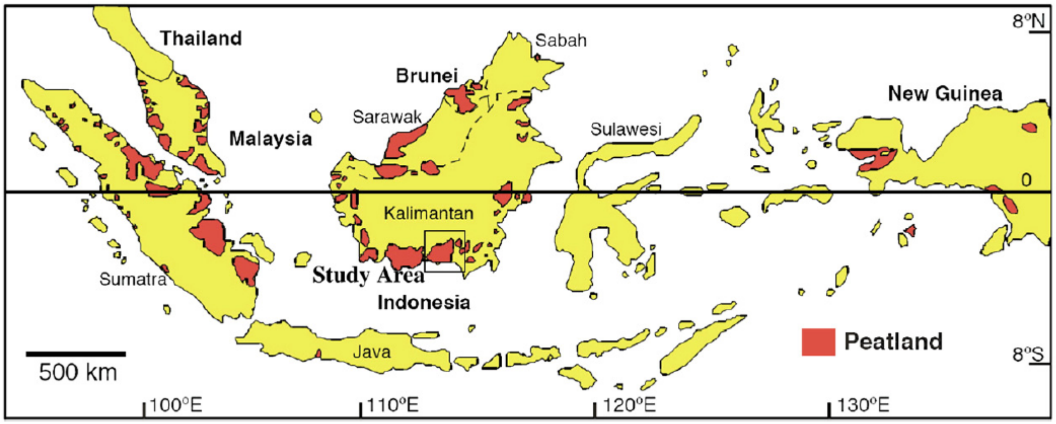


Figure 2.3: *Peatland distribution in Southeast Asia.* Source: (Wösten et al., 2008)

Almost all of the indonesian peatlands are of the ombrogenous type. By 1990, 531,000 hectares of tropical peat had been transformed for agricultural purposes. In the following years more peatland was converted for agriculture, but the extent of this was small compared to the Mega Rice Project set into motion by president Suharto in 1996 (Rieley and Page, 2005).

### 2.3.2 Ex- Mega Rice Project (EMRP)

The Mega Rice Project was initiated by presidential decree in 1996. The total area originally planned for development spanned over more than 1 million hectares of peatland in the eastern part of Central Kalimantan; see Fig: 2.4. It is bounded by the Sebangau River on the west side, the Barito River on the east side, the Java Sea on the south side and roughly by the Palangka Raya - Buntok road on the north side. The area was originally divided into 5 sections: Block A - E.

The aim of the project was to make Indonesian rice production self-sufficient. Over one million hectares of peatland were to be prepared for rice production. The result was a large drainage canal network with a total canal length of over 4000 kilometers and the intended transmigration of 50,000 migrant workers (Muhamad and Rieley, 2002). In 1999 the project was shut down because rice crops would not grow in the peatlands as expected. The peatlands were cultivated like any other type of soil while in fact many of its characteristics do not coincide (Rieley and Page, 2005). The extensive canalization caused the area to be overdrained, natural water reservoirs were destroyed and the irrigation required for the rice production could not be maintained.

As a result of the overdrainage the hydrological system within the area of the mega rice project became unbalanced. During the dry periods the canals would drain the area very rapidly and in the wet season flooding occurred as a result of the peat subsidence. This is the point at which peat soil becomes more compact and loses its water holding capacity (Rieley and Page, 2005). This further upset the possibility of crop production in the area. In the natural state almost the entire EMRP area was covered by natural lowland peatswamp forest. However, as a result of canalization, (illegal) logging and agriculture only 38% of this forest cover remains. The rest of the area is now covered by heavily degraded forest (14%), grass- & shrublands (37%) and agriculture (12%) (The Master Plan Team, 2008).

Fire, as a direct result of overdrainage and peatland subsidence is the most important cause for the forest and peatland degradation in the Ex-Mega Rice Project area

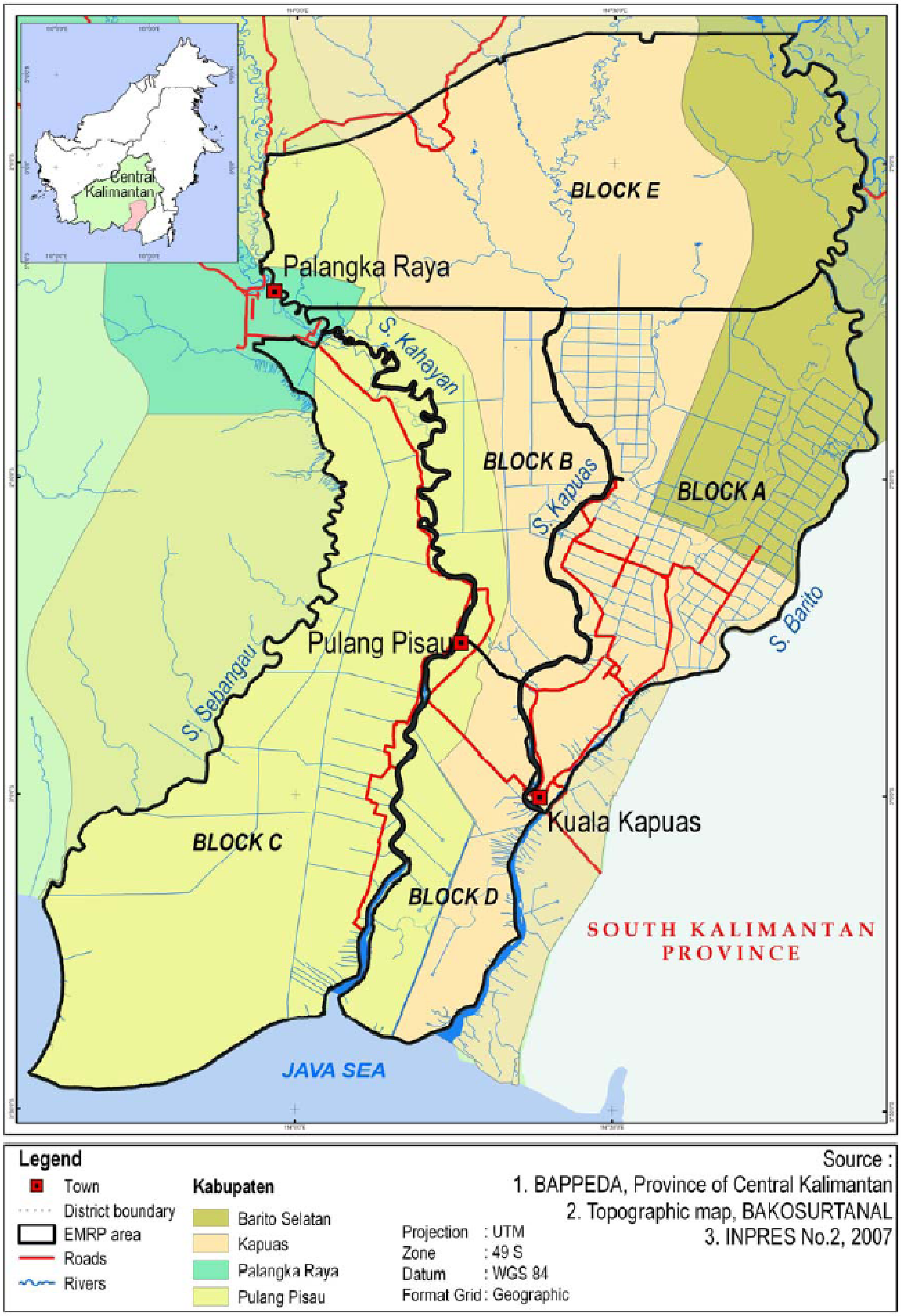


Figure 2.4: *This image shows a site overview of the ex-Mega Rice Project, Central Kalimantan, Indonesia. The image displays the extremely extensive drainage canalization that was introduced to make the area fit for rice production.* Source: (The Master Plan Team, 2008)

(The Master Plan Team, 2008). Nearly 80% of the EMRP area was severely damaged by fires in the very dry year 1997/1998, coinciding with the El Niño event. It is estimated that the MRP area was responsible alone for emitting between 0.12 and 0.15 Gt of carbon to the atmosphere in that year as well as contributing to the dense smog that covered a large part of Southeast Asia (Page et al., 2009). The annual *global* carbon release of fossil fuels constitutes of 7.2 Gt (IPCC, 2007), putting the amount released due to the peatfires into perspective.

After the Mega Rice Project was terminated in 1999 most of the migrant workers abandoned the region due to the lack of future prospect. They left behind a severely deteriorated and unproductive peatland with malfunctioning canals, rapid oxidation, frequent peatfires and a devastated ecological system (Page et al., 2009).

In conclusion, and in response to research question 1, it can be stated that it is of vital importance to restore the peatlands in the EMRP area in central Kalimantan in order for the natural functions of the tropical peatland to remain intact. Without these functions the peatland rapidly degrades and causes a large number of worsening impacts on the local, but also global, environment. The drainage canalization for agriculture is the direct result of 'unwise' use of peatland in the EMRP area. Peatfires, subsidence, oxidation and consequent $CO_2$ emissions are a direct result of the over-drainage in periods of drought and must be averted.

# Chapter 3

# Model derivation

In the previous chapter the challenges facing the tropical peatlands have been reviewed. One of the most pressing issues regarding tropical peatland degradation is the over-drainage and drought. This research aims to reduce the peatland degradation by impacting the drainage system in a way that the water table drops less during periods of drought. In order to address these issues a model has been derived that can interpret the impact of various (partial) damping practices of the canals. This chapter focuses on answering the second research question:

Research Question 2: *What model can be constructed to simulate the ground water table height in tropical ombrogenous peatlands bounded by drainage canalization?*

In this chapter the research question is answered through various steps. First the real scenario in the EMRP area will be simplified to a more general form in order for calculations to be made possible. After this various assumptions will be formulated. Finally the model will be found using mathematics. The most important steps in the calculation process and the solution in the form of a dynamic function will be presented in this chapter.

## 3.1 The simplified scenario

In order to create a generic model to calculate the water table height in tropical peatlands some simplification of the actual situation is necessary. In figure 3.1 the simplification steps are shown through a flowchart. The overhead photo shows how the drainage canals are laid out throughout the EMRP area. The picture next to it shows how the deforested and drained peatland canals are in the actual case. Notice how the land surface is very rough and inconsistent. In order for the model to be broadly applicable this inconsistency will be removed from the tropical peatlands surface; instead a mean surface height will be used. This generalization of the land surface is possible due to the relatively small height fluctuations in relation to the length of the cross-section of the peatlands.

For this research only one horizontal direction will be considered, which also comprises the final part in the simplification. The consequences of this simplification are outlined to greater detail in section 3.2. Notice how in this final step the slope of the embankment is made vertical. This allows for a constant length ($L$) during the calculations. This is assumed to be possible due to the relatively small change in $L$ compared to the full length of the cross-section.

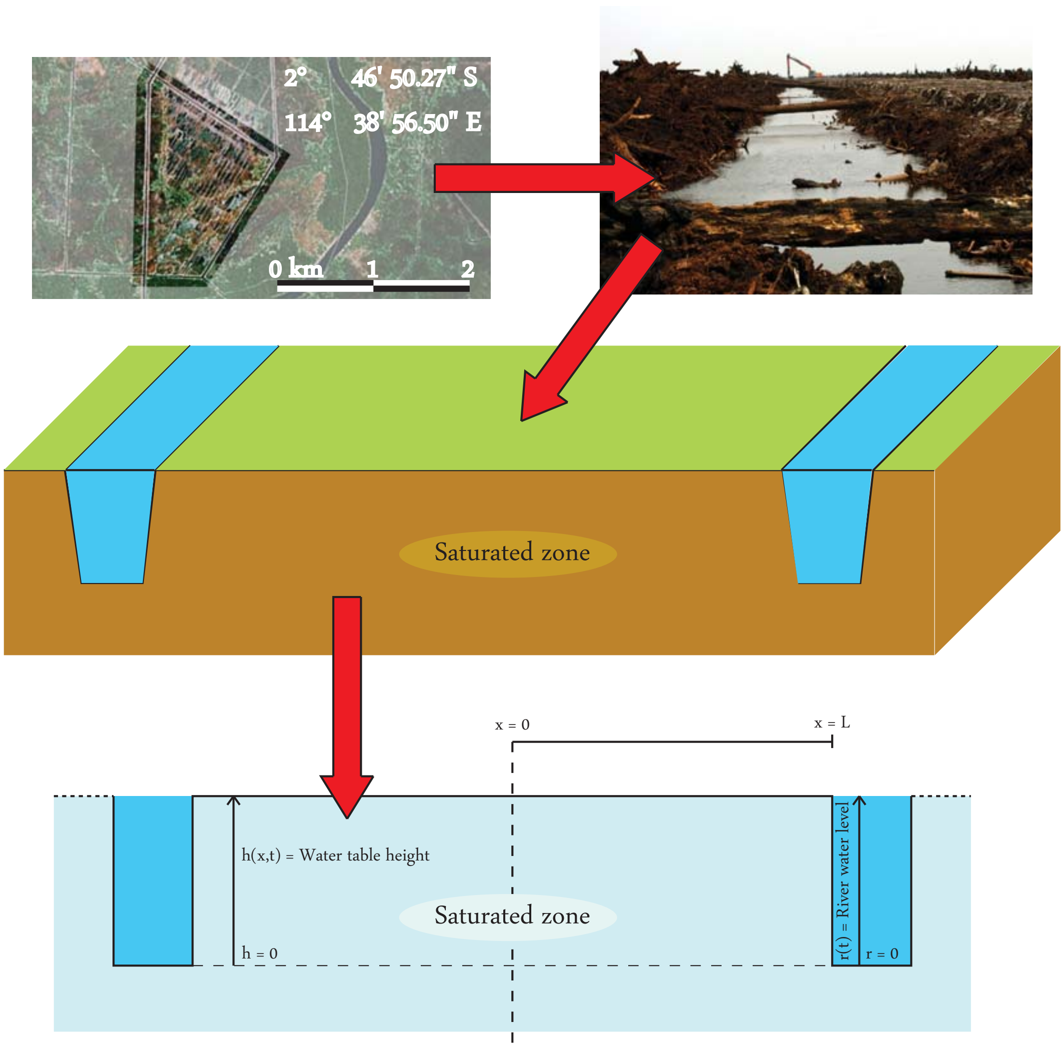


Figure 3.1: *Illustration of the simplification of the scenario. The overhead photograph(Google, 2010) gives a clear view of the canal layout throughout the EMRP area.*

## 3.2 Assumptions

Various assumptions have been made to simplify the situation and allow the derivation of the model. These are listed below:

- The water table is calculated in one horizontal direction. The horizontal direction focused on is the cross-section of the peatland between two drainage canals (see Figure 3.1). As a result all water flows that do not run along the axis of this direction are ignored. This means that the drainage through the canals has not been incorporated into this model and that there is no ground water flow in any direction other than towards or from the canals.

- It is assumed that the land area is uniform meaning that the water conductivity coefficient $\kappa$ is constant throughout the entire area and that the surface of the peat dome is horizontal and smooth.

- The canal embankment is assumed to be vertical instead of sloped. This allows for a constant $L$ to be used in the model.
- In this model infiltration of water through the unsaturated zone to the aquifer has been ignored. It has been assumed that the effective precipitation enters the aquifer immediately thus directly influencing the water table height.
- Capillary rise, where water rises upwards and leaves the aquifer through small pores in the soil, has also been ignored in this model.
- It is assumed that the water table in the peatland is symmetrical. This additionally means that the assumption has been made that the river water level $r(t)$ is the same on both sides of the peatland.
- The water table shape is assumed to react as displayed in figure 3.2. Near the canals the water table will drop much quicker than in the center of the peatland.
- All water that flows out of the peatlands is immediately drained by the canalization and therefore has no effect on the height of the water table once flown out.
- The tropical peatlands for which this model can be applied are ombrogenous. This means that the peatland is fully rain-fed with the result that the only flux of water into the system is precipitation. This assumption is realistic as most research points out that tropical peatlands in general are all completely ombrogenous (Rieley and Page, 2005).

## 3.3 The dynamic function in one horizontal direction

Partial differential equations are used to find a dynamic equation that describes the water table height. In general partial differential equations are used to described unknown functions of several independent variables and their partial derivatives with respect to those variables (Polkingn et al., 2006). The known properties of the system described in the previous sections will be used in order to solve for a dynamic equation for the water table height $h(x,t)$. Certain boundary conditions will be set that need to be satisfied that can be deducted from the assumptions made as visualized in figure 3.2. To solve for the dynamic equations certain initial equations will be used also based on the assumptions made and the known properties of the hydrological system in tropical peatlands. A solution will be presented in the form of a dynamic equation that approximates the water table in one horizontal direction. Finally the various input values that have been used in order to generate model output in order to answer the final research question will be provided. In this section the main equations, solutions and boundary conditions will be discussed that lead to the dynamic equation describing the water table in one horizontal direction using a mathematical approach. Please refer to appendix B for the complete derivation.

The solution of the water table is assumed symmetrical and is sought between two canals with the water level $r(t)$. The variable $x$ describes the location in the cross section of the peatland which can be anywhere between $-L$ and $L$. The middle of the water table, the axis of symmetry, is at location $x = 0$. The known influences on the height of the water table are defined to be the canal water level at a given time $r(t)$ and the effective precipitation $p_{eff}$ thus creating a general formula for: $r(t), p_{Eff}(x,t) \rightarrow h(x,t)$. Due to the assumed symmetry only $0 < x < L$ will be accounted for during the derivation.

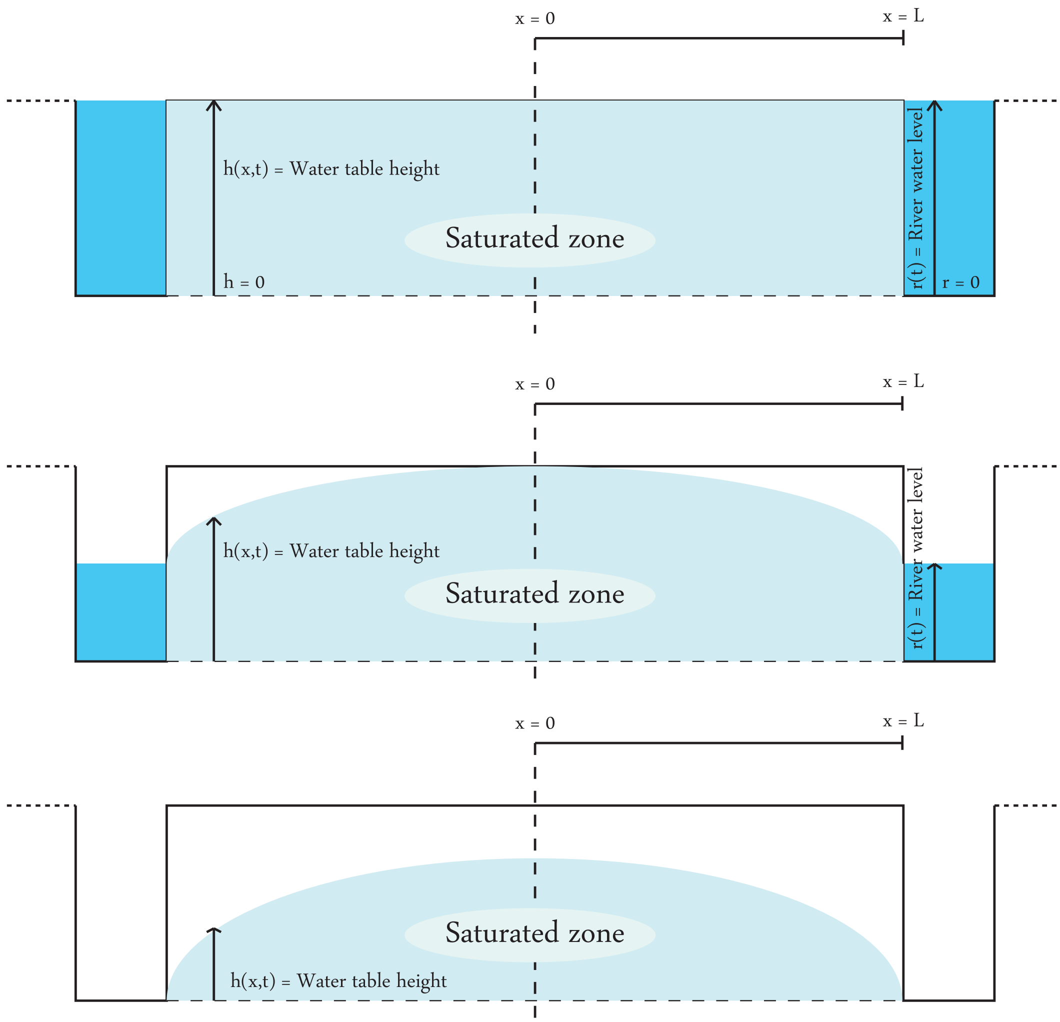


Figure 3.2: *Image displaying the assumed water table shape as $r(t)$ decreases. The centre of the water table will be much slower to react than the outer edges of the water table.*

### 3.3.1 Boundary conditions

The water table is assumed to react as displayed in figure 3.2. From this figure various boundary conditions can be defined that will need to be satisfied when defining the dynamic function.

- The water level in the peat at the canal, where $x = L$, is the same as the water level of the canal.

$$h(L, t) = r(t)$$

- The water level in the peat at $x = 0$ is horizontal as a result of the symmetry.

$$\partial_x h(0, t) = 0$$

- Lastly, the water level in the peat at the start of the simulation is the same as the water level in the bounding canals.

$$h(x, 0) = r(0)$$

### 3.3.2 Initial equations

In order to derive a dynamic function for the water table two initial equations were used. These are the water balance and an assumed shape of the water table height function $h(x, t)$. Both equations will be explained to greater detail below.

#### Water balance

The water balance equation for the ombrogenous tropical peatland to which this model can be applied is given by the equation:

$$\Delta S = \text{In} - \text{Out}$$

where $\Delta S$ is the change in storage of water volume inside the peatland, the outflow of water is defined by the diffuse flow of water as described by Darcy and the Inflow of water consists solely of the precipitation as the tropical peatlands for which this model can be used are ombrogenous. In essence this equation describes the conservation of mass. Because mass can be rewritten as the product of density and volume, and water can be considered and incompressible liquid therefore having a constant density, it becomes a conservation of volume formula. This can therefore be rewritten as a diffusion equation:

$$\frac{\partial h}{\partial t} = -\nabla \cdot q + p_{eff}$$

where $\partial_t h$ represents the change in storage, $p_{eff}$ represents the inflow of water and $-\nabla \cdot q$ represents the negative divergence of flux $q$ (Verruijt, 1970). The divergence of flux describes the net flux out of a volume through a closed surface as a result of the sum of the sources minus the sum of the sinks in that volume. The volume in this case refers to the aquifer where $h(x, t)$, the water table, is the closed surface. Darcy's law in vector form states that $q = -\kappa \nabla h$ (Zaradny, 1993) therefore the equation can be rewritten to be:

$$\begin{aligned} \partial_t h &= -\nabla \cdot (-\kappa \nabla h) + p_{eff} \\ \partial_t h &= \kappa \nabla^2 h + p_{eff} \\ \partial_t h &= \kappa \Delta h + p_{eff} \end{aligned}$$

where $\Delta$ is the laplacian operator. In this case, because we are only taking one horizontal direction into consideration, this becomes $\partial_{xx} h$. The diffusion equation used for this model therefore becomes:

$$\partial_t h - \kappa \partial_{xx} h = p_{eff} \tag{3.1}$$

Equation (3.1) describes the change in the water level as time passes $\partial_t h$ as the sum of the effective precipitation $p_{eff}$ and the water flux out of the land $\partial_{xx} h$ along only the $x$-axis. This last term ($\partial_{xx} h$) is influenced by the hydraulic conductivity of the soil $\kappa$. Because the land area is assumed uniform, $\kappa$ is a constant for the entire cross section. Notice that the water outflow is increased as the slope of the water table $\partial_x h$ is steeper. This means that when the river water level drops very rapidly, and the slope of the water table near $x = L$ is very steep as a result, the immediate outflow of water is very rapid.

#### Assumed form of the dynamic function

The second equation used to find a dynamic function describing the water table is the assumed form of the solution.

$$h(x,t) = r(t) + \sum_{n=0} a_n(t)\phi_n(x) \tag{3.2}$$

The canal water level was taken as a reference point and the shape of the water table is approximated using $n$ amount of terms of a Fourier expansion. In equation (3.2) the term $\phi_n$ is defined as follows:

$$\phi_n(x) = cos\lambda_n x$$

where $\lambda_n$ is:

$$\lambda_n = (1+2n)\left(\frac{\pi}{2L}\right)$$

Due to the fact that the function $h(x,t)$ is defined as a combination of functions depended on either only $t$ or only $x$, the solution will always be an approximation as the fourier expansion, a cosine function, can never describe a perfect horizontal funtion. As the amount of terms used is increased, the approximation will become more accurate. The actual amount of terms that needs to be used during calculations is greatly influenced by the distance $L$ over which the function is approximated.

### 3.3.3 The solution

Since $\phi_k$ is a known function, a solution needs to be found for the coefficient $a_k$. The solution is presented here, the full calculations to arrive at this solution are provided in appendix B.

$$a_n(t) = e^{-\kappa\lambda_n^2 t} C_n \int_0^t f(\tau) e^{\kappa\lambda_n^2\tau} d\tau \tag{3.3}$$

where $a_n(t)$ is the coefficient of any single term in the approximation function for the water table and $f(\tau)$ defines the source function. In this solution the variable $\tau$ is essentially the same variable as $t$ except for the fact that it limits itself to the point where the source term becomes zero. In other words, when there is no effective precipitation or change in the river water level. The constant coefficient $C_n$ is defined by the following function:

$$C_n = \begin{cases} \frac{4}{(1+2k)\pi} & \text{if } k \text{ is even,} \\ -\frac{4}{(1+2k)\pi} & \text{if } k \text{ is odd.} \end{cases} \tag{3.4}$$

and the function $f(\tau)$ is defined as:

$$f(\tau) = p_{eff}(\tau) - r'(\tau) \tag{3.5}$$

this function is the source function to this differential equation where $p_{eff}$ is the effect precipitation and $r'(t)$ is the change in the river water level.

### 3.3.4 The dynamic equation

The dynamic equation that approximates the water table height therefore becomes the substitution of (3.3), (3.4) and (3.5) into equation (3.2). This solution approximates the water table height using the Fourier expansion, therefore always being an approximation. In general a greater amount of terms increases the accuracy of the approximation. However it must be stated that every extra term added increases the accuracy less than the term before it. In appendix C the influence of the amount of terms has been visualized in figure C.3. This solution will be used to simulate and investigate the effects of (partial) damping on the water table height in the peatlands.

## 3.4 Simulation input values

In order to investigate the effects of partial or complete damping of the canals in the EMRP area, two input values where varied during the simulation. Partial damping was investigated by decreasing the river depth. Complete damping of the canals was simulated by increasing the distance $2L$ between canals. Figure 3.3 visualizes these geometric alterations. The distance is defined as $2L$ instead of $L$ due to the manner in which the model was derived. The variable $L$ was used for the distance over half the peatland due to the assumed symmetry. During model runs the entire distance needs to be accounted for and therefore the distance is increased to $2L$. The following input values where used during simulation:

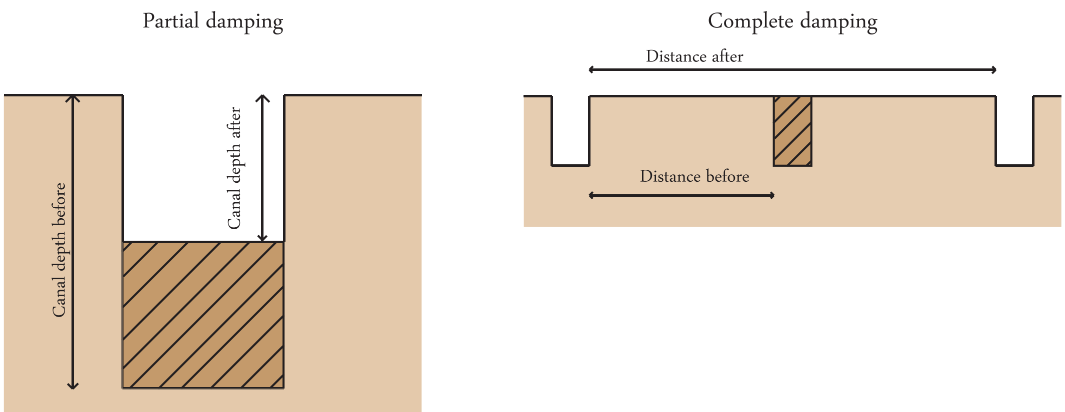


Figure 3.3: *This figure visualizes the partial and complete damping of canals. When canals are partially damped the canal depth is decreased and when they are completely damped the distance between canals increases.*

- The canal depth for the simulation were taken from the EMRP site geometry. Various articles state that the depth of the canals can be as deep as 4 meters (The Master Plan Team, 2008). To investigate the partial damping of the canals river depths of 4, 2 and 1 meter were used for simulation.
- For the distance between canals $2L$ the values of 80, 40 and 20 meters were used. These values were obtained approximately using Google Earth (Google, 2010).
- A value of 0.5 m/d was used for the hydraulic conductivity $\kappa$. This value has been used in other research concerning water table modeling in the EMRP area (Wösten et al., 2008). In this article a reference is made to Ong & Yogeswaran (1992) and Takahashi & Yonetani (1997) who used the pumping test method to acquire this value in the EMRP area.

- In a time of drought the effective precipitation $p_{eff}$ can be defined as only the evapotranspiration due to the absence of rain. The average evapotranspiration for the EMRP area has been measured to be between 3.8 and 4.5 mm/day (Wösten et al., 2008). The fluctuations on a yearly basis are so small that a constant evapotranspiration of 4 mm/day has been used for the entire period of drought. This makes the input value for the model, $p_{eff} = -4$ mm/day.

- The dry period for which the simulations were performed were 100 days long. This value is taken from the daily climate data provided by the National Climatic Data Center (NCDC) for the weather station located at the airport near the EMRP area: Pelangka Raya/Tjilik Riwut (NCDC, 2010).

- The river water level $r(t)$ was described by a cosine function that reaches 0 after a period of 10 days. The following function was used:

$$r(t) = \frac{\text{Canal depth}}{2} \cdot \left( cos\left(\frac{t\pi}{T_{dry}}\right) + 1 \right)$$

  where $T_{dry}$ is the time it takes for the river to dry up.

In this chapter research question 2 has been answered by finding a dynamic function that relates the ground water table in ombrogenous tropical peatlands to the effective precipitation and water levels in bounding canals in one horizontal direction. The input values for the model have been defined and these will be used in the following chapter to answer the final research question.

# Chapter 4

# Influence of damping canals

The final research question will be answered in this chapter using the model constructed in the previous chapter.

Research Question 3: *How does the damping or partial damping of drainage canals influence the water retention and thus the ground water table height of tropical peatlands during periods of drought?*

The dynamic equation was programmed into MATLAB in order to investigate the influence of complete or partial damping on the water retention and ground water table height in the tropical peatlands on Central Kalimantan. The full code can be found in appendix D. The various fixed values used in the simulation were provided in the previous chapter and are also summarised in table 4.1.

| Input value | |
|---|---|
| $p_{eff}$ $[mm/day]$ | -4 |
| Duration of drought$[days]$ | 100 |
| $\kappa$ $[m/day]$ | 0.5 |

Table 4.1: *These are the fixed input values that have been used for alle simulations.*

The canal depth and the distance between canals have been altered in order to investigate the influence of partial or complete damping. The different measurements used for the model calculations are summarized in table 4.2.

| Input value | | | |
|---|---|---|---|
| $L$ $[m]$ | 10 | 20 | 40 |
| Canal depth $[m]$ | 1 | 2 | 4 |

Table 4.2: *This table presents the values for the variables that have been changed during model calculations in order to investigate the complete or partial damping of the canals in the tropical peatlands of Central Kalimantan.*

## 4.1 Complete damping of the canals

By completely damping a canal the distance between canals essentially doubles as illustrated in the previous chapter in figure 3.3. The impact of damping canals will be analyzed in different ways in this section. First the cross section of the peatland will be displayed with the resulting water table after 100 days of drought,$h(x, 100)$, for different distances. Second the amount of water that flows out of the land will be displayed for the three distances. And third, the height of the water table at the center $h(0, t)$ will be presented for the varying distances.

### 4.1.1 Effect of $L$ on h(x,t) after 100 days of drought

Figure 4.1 shows the ground water table in the peatlands when the distance between canals is varied. Notice how the amount of peatland still saturated with water (area under the function $h(x, t)$) is a lot smaller when the distance between canals is less. The actual percentages of the ground water retention are discussed in the next section. Please note that the canals are located at different points in the figure for each different distance $L$. The canals for the different cross sections are located at the base of the ground water level curve.

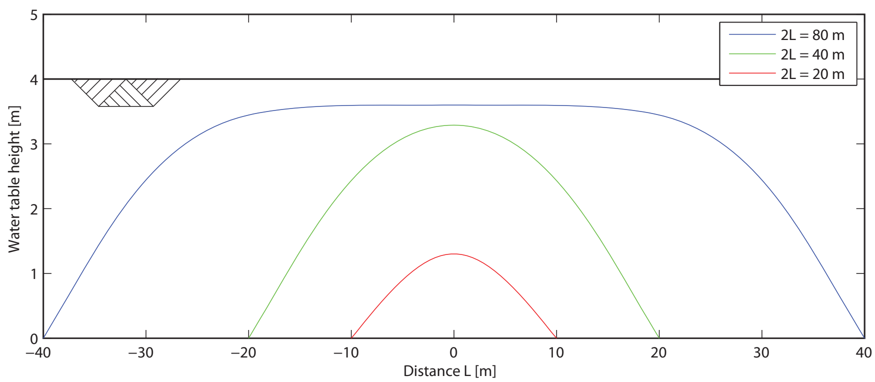


Figure 4.1: *Water table heights at the end of a 100 day simulation for different distances between canals. Three distances between the canals are displayed: 20m, 40m and 80m.*

This plot also very clearly shows how the function for the water table manages to approach the horizontal water table for the case where $2L = 80$ m. In this case 40 terms of the Fourier series were used in order to approximate the horizontal surface with the various cosine functions. Notice that the water table at $t = 100$ days has a maximum water table height of 3.60 meters as a result of the evapotranspiration. With and evapotranspiration of 4 mm/day for 100 days the water table drops 40 centimeters at the center. The horizontal outflow as a result of the water table change reduces as the distances between the canals is increased. This becomes especially clear in the next section.

### 4.1.2 Influence of $L$ on the volume outflow during 100 days of drought

It has become clear from the previous section that the distance between canals has a large influence on the height of the water table after 100 days of drought. In this section it is investigated how much of the ground water is conserved when this distance is increased.

When the width of the peatland is increased, or when canals are damped, the relative amount of water flowing out of the peatland decreases. Figure 4.2 shows how the saturation % of the peatlands' cross section changes when the width is increased. After a 100 day period the water content of the peatland drops by approximately 75% when the peatland is 20 m

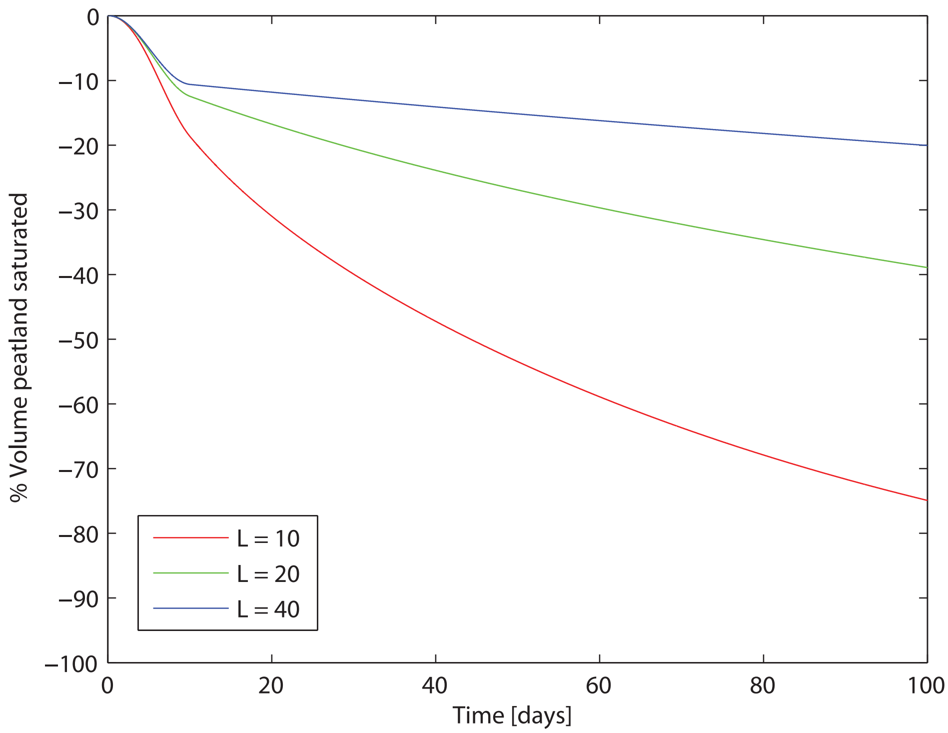


Figure 4.2: *Volume (in %) that has flown out of the peatland as a result of evapotranspiration and canal water level changes for different cross section sizes*

wide. When that width is doubled (or when a canal is damped) that percentage lowers to less than 40%. When more adjacent canals are damped, creating a peatland width of 80 meters, that percentage drops even further to approximately 20%. Notice how the damping of canals appears to have a significant influence on the water retention capabilities of the peatland. The speed at which water is flowing out of the area decreases significantly.

In the first few days the water content of the peat drops much faster than in the consecutive period. This is the result of the water level dropping very rapidly in the canal. Within 10 days the water level drops from 4 meters to 0. Recall that the outflow of the land was proportional to the steepness of the function $h(x,t)$. The ground water diffuse outflow, $\kappa\partial_{xx}h$, increases greatly when the steepness of the water table increases. Therefore, when the river level drops rapidly and the water table will adjust to the new river water level near the canal very rapidly, as a result water leaves the peatland at a greater speed. This means that when the peatlands width is increased, or when less canals are present in the peatland, the water table has to converge at less locations when the canal water level drops therefore allowing for more water to be retained in the peat as the outflow is decreased.

### 4.1.3 Influence of $L$ on the height of the water table at $x = 0$ during 100 days of drought

This last effect is presented more clearly when looking at the water table height at the center of the cross section. As the width of the peatland is increased, the water table drop at the center, where $x = 0$, is reduced. The following figure illustrates this clearly.

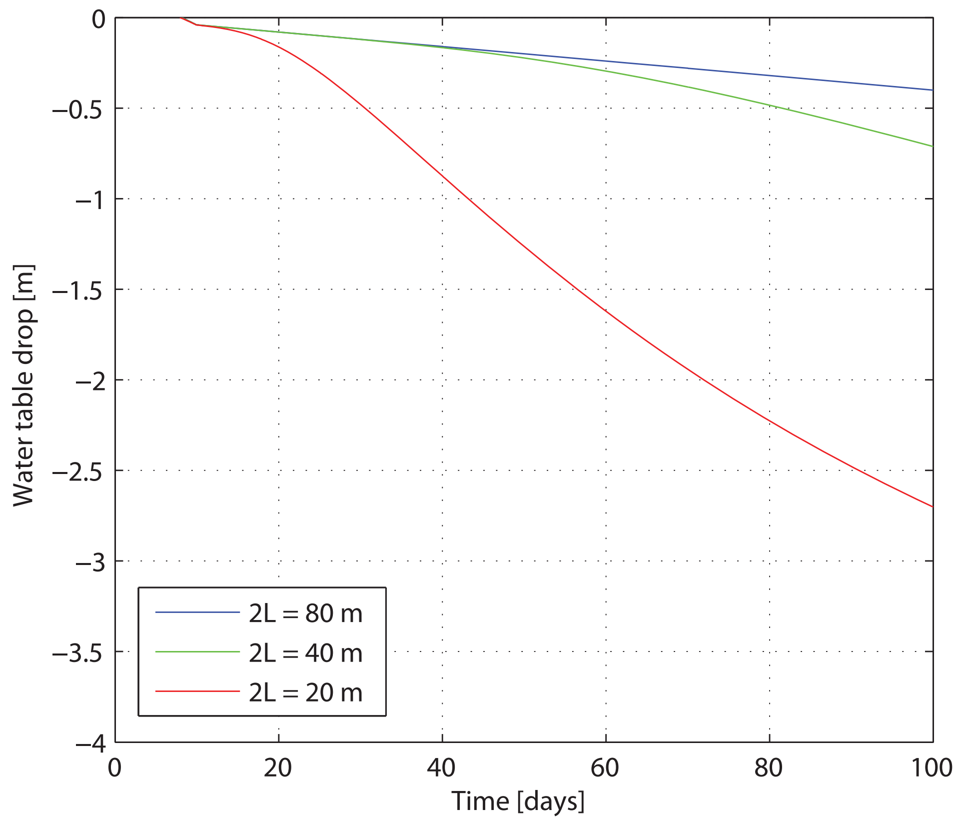


Figure 4.3: *Water table drop at the middle and highest point of the water table for different cross section sizes*

In the introduction it was introduced that peatlands naturally have a water table of -20 to -40 in the dry season. When peat is unhealthy and deteriorating the water table can drop much lower. Figure 4.3 shows how far the water table drops for different widths of peatland. When peatlands are fairly narrow, with a width of only 20 meters, the water table drops approximately 2.7 meters after 100 days at the center of the peatland. This greatly exceeds the 40 centimeters from which point on it is considered hazardous. When a canal is damped and therefore the peatland width is doubled the water table drops approximately 75 centimeters. When the peatland width is increased to 80 meters the water table at $x = 0$ only drops as a result of the evapotranspiration making the curve linear.

It can be stated that when the width of the peatland is greater that the aquifer notices the influence of a dried up drainage canal much later. This is a result of the tendency of the water table to maintain its horizontal linear shape around $x = 0$ for a much larger period of time. A very clear illustration of this effect can be observed around $t = 40$ days where $h(0,t)$ for $2L = 40$ splits from the linear function for $2L = 80$. When canals are damped a larger part of the peatlands' water table fluctuations depend solely on the evapotranspiration. Therefore it can be concluded that damping canals restores the natural hydrological system where the water table is dependent on evapotranspiration rather than canal water level fluctuation and drainage.

## 4.2 Partial damping

The canal depth has been varied in order to investigate the influence of partial damping on the water table height in tropical peatlands.

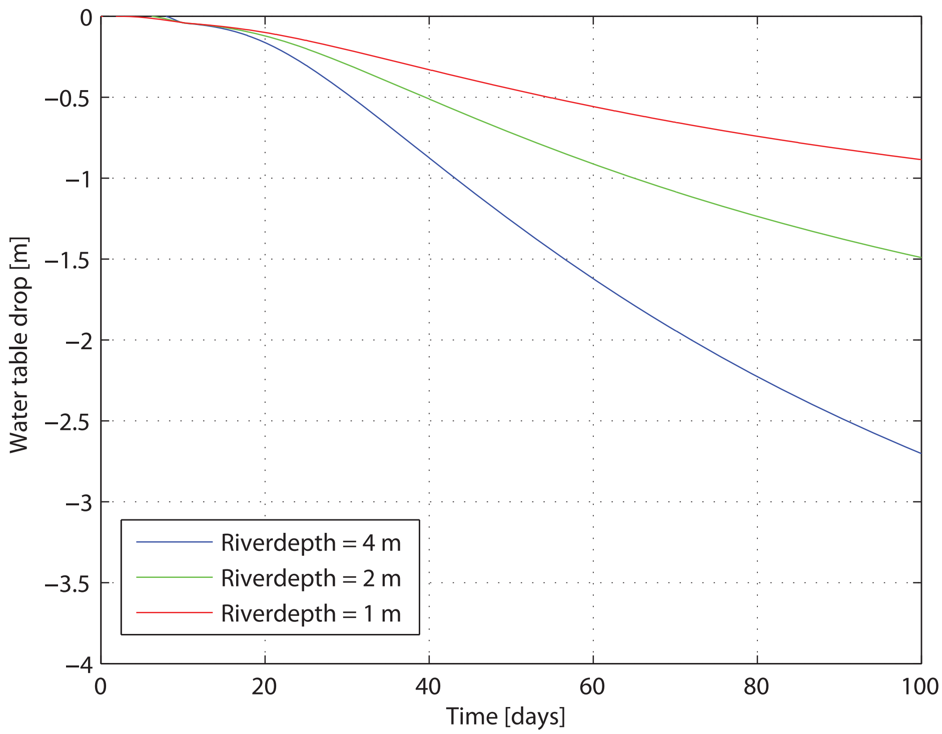


Figure 4.4: *Water table drop at the middle and highest point of the water table for different river depths*

The figure above illustrates how the partial damping of canals largely contributes to the water retention in tropical peatlands. In figure 4.4 the distance between the canals was only 20 meters. As seen in the previous sections, the peatland is highly fragile in this scenario. However, as the riverdepth is decreased from 4 meters to 2 meters and consequently to 1 m the influence of the riverdepth on the peatland water table becomes clearly visible. The water table change with varying river depths is directly proportional to that river depth. This image is only slightly distorted by the evapotranspiration that decreases the water table height in all three scenarios for the exact same amount.

In this chapter the third research question has been investigated. I can be stated that the partial and complete damping of peat soils has a beneficial effect on the ground water table drop and water retention capabilities during periods of drought. Especially on the smaller distances between peatsoils and the extremely deep canals can damping have a significant effect. By (partially) damping the canals the tropical peatlands physically come closer to their natural state. It is therefore not surprising that these effects are observed.

# Chapter 5

# Conclusion

The degradation of tropical peatlands is of local, regional and global importance as outlined in chapter 2. Peatfires, oxidation and subsidence are all primary causes of the ongoing deterioration of tropical peat. The construction of drainage canals, the practices of (illegal) logging and the preparation for agricultural development is detrimental to the tropical peatland integrity.

In the introduction the research goal was defined as:

*The goal of this research is to reverse the degradation of tropical peatlands in Central Kalimantan by restoring the natural height of the ground water table through the investigation of ground water table dynamics of tropical peatlands in periods of drought with respect to the present drainage canalization.*

Three research questions were formulated in order to achieve this goal. In summary they consisted of a literature study with regards to the primary causes and consequences of peatland degradation, the construction of a model to simulate ground water table height and the simulation of the influences of partial or complete damping on the aquifer. From the literature study it became clear that the hydrological system in Central Kalimantan has been severely damaged as a result of the over-drainage by the canals that were constructed for the Mega Rice Project. This over-drainage has a significant influence on the peatland integrity. Drainage in combination with periods of drought causes the peatlands to become susceptible to fires, oxidation and peatland subsidence.

The second research question was answered by constructing a mathematical model in the form of a dynamic equation that simulates the water table height in ombrogenous peatlands with drainage canals. This model accounts for one horizontal direction and gives a clear picture of the aquifer shrinkage in tropical peatlands during periods of drought. The effects of partial and complete damping on the ground water table were investigated using the model to answer the third research question. It was found that partial or complete damping of canals greatly increase the water retention capabilities of tropical peatlands, therefore reducing the lowering of the ground water table.

In conclusion it can be stated that the tropical peatland degradation on Central Kalimantan can be slowed down by damping the canals. The results found in this research conclusively show that the partial and complete damping of canals can increase the water retention capabilities of peatland. As a result the ground water table lowers much less during periods of drought. With reference to the natural state of tropical peatlands this research result can easily be explained.

Peatlands in their natural state undergo a water table drop of -20 to -40 centimeters during periods of drought (Wösten et al., 2006). This can primarily be attributed to the evapotranspiration. When damping or partially damping the canals in a drainage system, the natural state is approached physically. As a result the peatlands retain water on a much larger scale because there are less places for water to flow out. It can therefore be stated hypothetically that reversing the peatland degradation caused by the over-drainage as observed in the EMRP area in Central Kalimantan is best achieved by completely damping all the canals in the area. This is impossible to achieve due to the various secondary functions that the drainage canals have acquired, most notably a transportation function. Therefore it should be attempted to damp as much of the canals as is financially and socially possible.

## 5.1 Recommendations

It is recommended to expand the model derived in this research to two horizontal directions to further analyze the influence of damping canals on the height of the water table. By limiting the model to only one horizontal direction various water flows have been ignored with and over-simplified model as a result. Ground water flows in the second direction need to be accounted for as well as a realistic river discharge calculation. In the calculations water was assumed to instantaneously drain from the canals, therefore having no further influence on the water table dynamics. Linking the canal hydrodynamics to the model for the ground water table in two horizontal directions can greatly improve the validity of this model.

Alternatively it is recommended to investigate the geographical optimization for the damping of canals. Various social functions lead to the impracticality of completely damping all the canals. As a result it should be investigated what canals lead to the biggest gains when it comes to water retention. A similar optimization has already been researched concerning the placement of dams (Beekman, 2006) and may be of interest to investigate using this model with a focus on damping.

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# Appendix A

# LabMath Indonesia

This research project was conducted at LabMath Indonesia (LMI). LMI is a relatively young, non-profit research institute in Bandung, Indonesia. Their focus lies on research in the natural sciences with two primary research orientations: coastal oceanography and environmental water. In all research directions climate change plays an important role and is therefore accounted for in most research performed by LMI. Aside from focusing on research, LabMath Indonesia also wishes to provide opportunities for students and senior scientists to develop themselves. All of LMI's activities are performed under the foundation Yayasan AB, which is registered under the Indonesian Ministry of Justice (LabMath Indonesia, 2008).

Setting up a transfer function for water table variations during wetting and drying in peatland fits well under the environmental water research area at LabMath Indonesia. LMI investigates the ever growing consumption of water for human, agricultural and environmental needs. Hydrological modeling is used in order to develop and simulate well balanced water systems. Mathematical modeling using physical dynamic system approaches contributes to the understanding of the global water situation. The water table fluctuations in peatlands form an important part of the environmental water balance and the hydrological modeling done by LMI.

# Appendix B

# Full calculations

In this appendix the full calculations will be illustrated that have led to the 2-term approximation of $h(x,t)$. The initial equations provided by LabMath are illustrated below. With the general solution, the diffusion equation and the boundary conditions a solution will be sought.

## B.1 Initial equations and boundary conditions

An equation for the water table is sought for the domain in the horizontal direction $x \in [-L, L]$ of a uniform land area with a hydraulic conductivity of $\kappa$, enclosed by canals with the water heigh $r(t)$ and a given effective contribution of precipitation to the water table $p_{eff}(x,t)$ (where evapotranspiration and infiltration have already been subtracted from the precipitation data). Therefore the main research directive is to find the transfer function: $r, p_{eff} \to h(x,t)$. It is assumed that the water table is symmetric around $x = 0$. Therefore the boundary conditions become:

$$\begin{aligned} \partial_x h(0,t) &= 0 \\ h(L,t) &= r(t) \end{aligned}$$

In the boundary conditions above, the water table at the center of $x \in [-L, L]$ is horizontal as to be expected when assumed that $h(x,t)$ is symmetrical and the water table in the peatland at the canal, $x = L$, is the water table in the canal $r(t)$. The following diffusion equation describes the water balance in the peatland:

$$\partial_t h - \kappa \Delta h = p_{eff}(x,t)$$

Furthermore, the solution for $h(x,t)$ will be found in the form:

$$h(x,t) = r(t) + \sum_{k=0} a_k(t)\phi_k(x)$$

For the symmetric situation the base functions are chosen to be:

$$\begin{aligned} \phi_k(x) &= cos\lambda_k x \\ \lambda_k &= (1+2k) \cdot \frac{\pi}{2L} \end{aligned}$$

## B.2 Separation of variable

In order to find a dynamic solution to the equations described in the previous section the variables of the equation have to be separated. Due to the fast conversion of the second term (when $k = 1$) only 2 terms will be used for this approximation. The solution will then be of the form:

$$h(x, t) = r(t) + a_0(t)\phi_0(x) + a_1(t)\phi_1(x) \tag{B.1}$$

This equation will be modified to fit into the diffusion equation describing the groundwater level. Due to the fact that the solution for this case is to be found in 1 horizontal direction, the groundwater equation becomes:

$$\partial_t h - \kappa \partial_{xx} h = p_{eff}(x, t) \tag{B.2}$$

The function (B.1) will need to be differentiated with respect to $t$ once and with respect to $x$ twice.

$$\begin{aligned} \frac{\partial h}{\partial t} &= r'(t) + a_0'(t)\phi_0(x) + a_1'(t)\phi_1(x) \\ \frac{\partial^2 h}{\partial x^2} &= 0 - a_0(t)\lambda_0^2\phi_0(x) - a_1(t)\lambda_1^2\phi_1(x) \end{aligned} \tag{B.3}$$

Substituting (B.3) into (B.2) after rearranging the equation gives the following:

$$r'(t) + a_0'(t)\phi_0(x) + a_1'(t)\phi_1(x) = \kappa \left(-a_0(t)\lambda_1^2\phi_0(x) - a_1(t)\lambda_1^2\phi_0(x)\right) + p_{eff}(x, t)$$

The orthogonal properties of the functions $\phi_0$ and $\phi_1$ will be used to seperate the variable in the equation above. The calculations for the separation of variables will be presented for $a_0$, but the exact same steps apply for $a_1$. The function above will need to be multiplied by $\phi_0$ and consequently integrated over $x$. First the left hand side of the equation will be explored:

$$\begin{aligned} LHS &= \phi_0(x) \cdot \left(r'(t) + a_0'(t)\phi_0(x) + a_1'(t)\phi_1(x)\right) \\ &= \int_0^L \left(r'(t)\phi_0(x) + a_0'(t)\phi_0^2(x) + a_1'(t)\phi_0(x)\phi_1(x)\right) dx \end{aligned}$$

When integrated over $x$, the last term in the above equation is 0 due to the orthagonal properties of $\phi_0$ and $\phi_1$. Therefore the LHS becomes:

$$LHS = r'(t)\int_0^L \phi_0(x)dx + a_0'(t)\int_0^L \phi_0^2(x)dx$$

On the right hand side of the equation the same operations must be applied. First it will be multiplied by $\phi_0$ and then integrated over $x$.

$$\begin{aligned} RHS &= \phi_0(x) \cdot \left(\kappa\left(-a_0(t)\lambda_0^2\phi_0(x) - a_1(t)\lambda_1^2\phi_1(x)\right) + p_{eff}(x, t)\right) \\ &= \int_0^L \left(\kappa\left(-a_0(t)\lambda_0^2\phi_0^2(x) - a_1(t)\lambda_1^2\phi_0(x)\phi_1(x)\right) + \phi_0(x)p_{eff}(x, t)\right) dx \\ &= -\kappa a_0(t)\lambda_0^2\int_0^L \phi_0^2(x)dx + \int_0^L p_{eff}(x, t)\phi_0(x)dx \end{aligned}$$

The effective precipitation can be said to be independent of location $x$, and only dependent on time $t$ due to the small scale of the calculations. The distance between the canals $L$ will never become very large (greater than one kilometer) transforming $p_{eff}(x,t) \to p_{eff}(t)$.

Combining the LHS and the RHS:

$$r'(t) \int_0^L \phi_0(x)dx + a_0'(t) \int_0^L \phi_0^2(x)dx = -a_0(t)\kappa\lambda_0^2 \int_0^L \phi_0^2(x)dx + p_{eff}(t) \int_0^L \phi_0(x)dx$$

After rearranging and dividing the function by $\int_0^L \phi_0^2(x)dx$ the function becomes:

$$a_0'(t) = -a_0(t)\kappa\lambda_0^2 + \left(p_{eff}(t) - r'(t)\right) \left( \frac{\int_0^L \phi_0(x)dx}{\int_0^L \phi_0^2(x)dx} \right)$$

The separation of variables to find a ordinary differential equation for $a_1(t)$ is done using the exact same steps as above, with the small exception that each side of the equation is multiplied by $\phi_1(x)$ instead of $\phi_0(x)$.

$$a_1'(t) = -a_1(t)\kappa\lambda_1^2 + \left(p_{eff}(t) - r'(t)\right) \left( \frac{\int_0^L \phi_1(x)dx}{\int_1^L \phi_1^2(x)dx} \right)$$

Now the integrals are easily evaluated. The case of $a_0$ was used:

$$\begin{aligned}
\int_0^L cos\lambda_0 x dx &= \left| \frac{1}{\lambda_0} sin\lambda_0 x \right|_0^L \\
&= \left| \frac{1}{\frac{\pi}{2L}} sin\left(\frac{\pi x}{2L}\right) \right|_0^L \\
&= \left( \frac{2L}{\pi} sin\left(\frac{\pi(L)}{2L}\right)\right) - \left(\frac{2L}{\pi} sin\left(\frac{\pi(0)}{2L}\right)\right) \\
&= \frac{2L}{\pi} sin\left(\frac{\pi}{2}\right) \\
&= \frac{2L}{\pi}
\end{aligned}$$

For the integration of the term in the denominator a general formula will be used:

$$\begin{aligned}
\int_0^L cos^2\lambda_0 x dx &= \left| \frac{x}{2} + \frac{1}{2\lambda_0} sin\lambda_0 x cos\lambda_0 x \right|_0^L \\
&= \left| \frac{x}{2} + \frac{2L}{2\pi} sin\left(\frac{\pi x}{2L}\right) cos\left(\frac{\pi x}{2L}\right) \right|_0^L \\
&= \left( \frac{(L)}{2} + \frac{L}{\pi} sin\left(\frac{\pi(L)}{2L}\right) cos\left(\frac{\pi(L)}{2L}\right)\right) - \left(\frac{0}{2} + \frac{L}{\pi} sin\left(\frac{\pi(0)}{2L}\right) cos\left(\frac{\pi(0)}{2L}\right)\right) \\
&= \frac{L}{2}
\end{aligned}$$

When the integrals are placed back into their original context, the following constant arrives:

$$\begin{aligned}
\left( \frac{\int_0^L \phi_0(x)dx}{\int_0^L \phi_0^2(x)dx} \right) &= \frac{\left(\frac{2L}{\pi}\right)}{\left(\frac{L}{2}\right)} \\
&= \frac{4}{\pi}
\end{aligned}$$

For $a_1$ the same calculation can be made but with $\lambda_1$ instead of $\lambda_0$. Note that this does not change the denominator, however it has an influence on the numerator. This has to do with the fact that $sin\left(\frac{3\pi}{2}\right) = -1$. Therefore:

$$\left(\frac{\int_0^L \phi_1(x)dx}{\int_1^L \phi_1^2(x)dx}\right) = -\frac{4}{3\pi}$$

Separating the variables of the partial differential equation has lead to finding two ordinary differential equation that can easily be solved. The equations are:

$$a_0'(t) = -\kappa\lambda_0^2 a_0(t) + \left(\frac{4}{\pi}\right)\left(p_{eff}(t) - r'(t)\right) \tag{B.4}$$

$$a_1'(t) = -\kappa\lambda_1^2 a_1(t) + \left(-\frac{4}{3\pi}\right)\left(p_{eff}(t) - r'(t)\right) \tag{B.5}$$

## B.3 Solving the ordinary differential equations

Both (B.4) and (B.5) are first degree differential equations of the form:

$$y^{(n)} = \sum_{i=0}^{n-1} a_i(x)y^{(i)} + r(x)$$

where $r(x)$ is the source term. If $r(x) = 0$ the equation is homogeneous, and if $r(x) \neq 0$ then it is inhomogeneous. The differential equations above are homogeneous in the case that both $p_{eff}(t) = 0$ and $r'(t) = 0$, or in the case that $p_{eff}(t) = r'(t)$.

### B.3.1 Solution to the homogeneous equation

In the case that the equation is homogeneous, $r(x) = 0$ and therefore the equation becomes:

$$a_m'(t) + \kappa\lambda_m^2 a_m(t) = 0$$

For this exponential equation a general solution can be applied. The solution to the homogeneous equation above can therefore be written as:

$$a_m(t) = C_m e^{-\kappa\lambda_m^2 t}$$

where $C_m$ is a constant that can be solved for easily. Take the case where $t = 0$ in which case $e^{-\kappa\lambda_m^2(0)} = e^0 = 1$. Therefore the solution to the differential equation in the case that the source term is 0 becomes:

$$a_m(t) = a_m(0)e^{-\kappa\lambda_m^2 t}$$

This solution describes the response to the initial ground water profile when there is no rain, and no change in the river water level.

### B.3.2 Solution to the inhomogeneous equation

The homoegeneous solution described in the previous section has almost not practical application. The source term in the ordinary differential equations is nearly never 0, especially when considering longer periods of time. Therefore a solution needs to be found in which the source term is incorporated. To find this solution the source term is shortenen:$(p_{eff}(t)-r'(t)) \rightarrow f(t)$ and the constants $\frac{4}{\pi}$ and $-\frac{4}{3\pi}$ will be referred to as $C_m$.

To find the solution to the inhomogeneous first order differential equation is rewritten to be:

$$a'_m(t) - (-\kappa\lambda_m^2 a_m(t)) = C_m f(t) \tag{B.6}$$

In order to solve for the function $a_m$ the function needs to be multiplied both sides by a function that turns the left hand side of the equation into the derivative of a product. This function in general can be described by the function $u(t) = e^{-\int b(t)dt}$ where $b(t)$ is the coefficient of the function $a_m$ in (B.6). The integrating factor then becomes:

$$\begin{aligned} b(t) &= -\kappa\lambda_m^2 \\ u(t) &= e^{-\int b(t)dt} \\ &= e^{-(-\kappa\lambda_m^2)t} \\ &= e^{\kappa\lambda_m^2 t} \end{aligned}$$

When (B.6) is multiplied by this factor the equation becomes much easier to solve:

$$e^{\kappa\lambda_m^2 t}\left(a'_m(t) + \kappa\lambda_m^2 a_m(t)\right) = \frac{d}{dt}\left(a_m(t)e^{\kappa\lambda_m^2 t}\right) = C_m f(\tau)e^{\kappa\lambda_m^2 \tau}$$

Integrating both sides over $t$ leads to:

$$\begin{aligned} \int_0^t \frac{d}{dt}\left(a_m(t)e^{\kappa\lambda_m^2 t}\right)dt &= C_m \int_0^t f(\tau)e^{\kappa\lambda_m^2\tau}d\tau \\ a_m(t)e^{\kappa\lambda_m^2 t} &= C_m \int_0^t f(\tau)e^{\kappa\lambda_m^2\tau}d\tau \\ a_m(t) &= \frac{1}{e^{\kappa\lambda_m^2 t}} \cdot C_m \int_0^t f(\tau)e^{\kappa\lambda_m^2\tau}d\tau \\ &= e^{-\kappa\lambda_m^2 t} C_m \int_0^t f(\tau)e^{\kappa\lambda_m^2\tau}d\tau \end{aligned} \tag{B.7}$$

# Appendix C

# Additional graphs

This appendix contain some additional plots that aim to illustrate some of the approximation calculation.

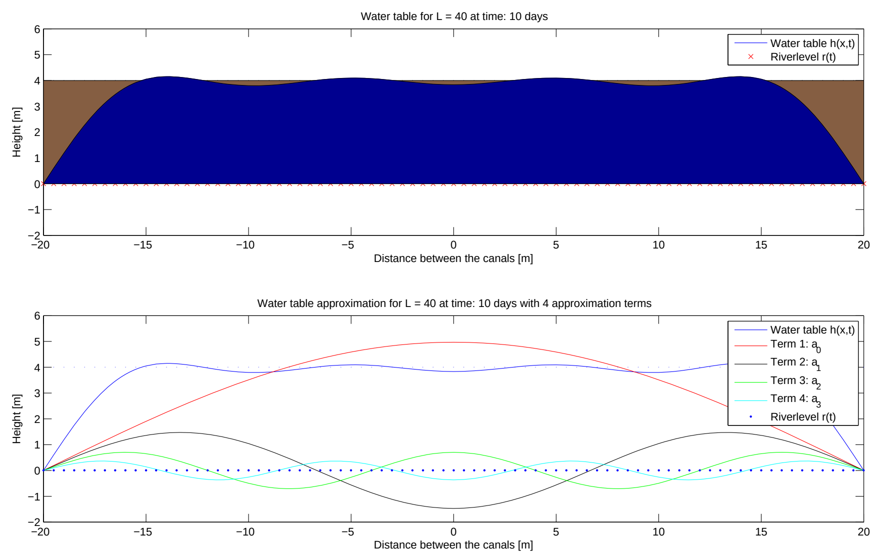


Figure C.1: *This figure shows the approximation of the water table at* $t = 10$ *days with four terms and how much these terms contribute.*

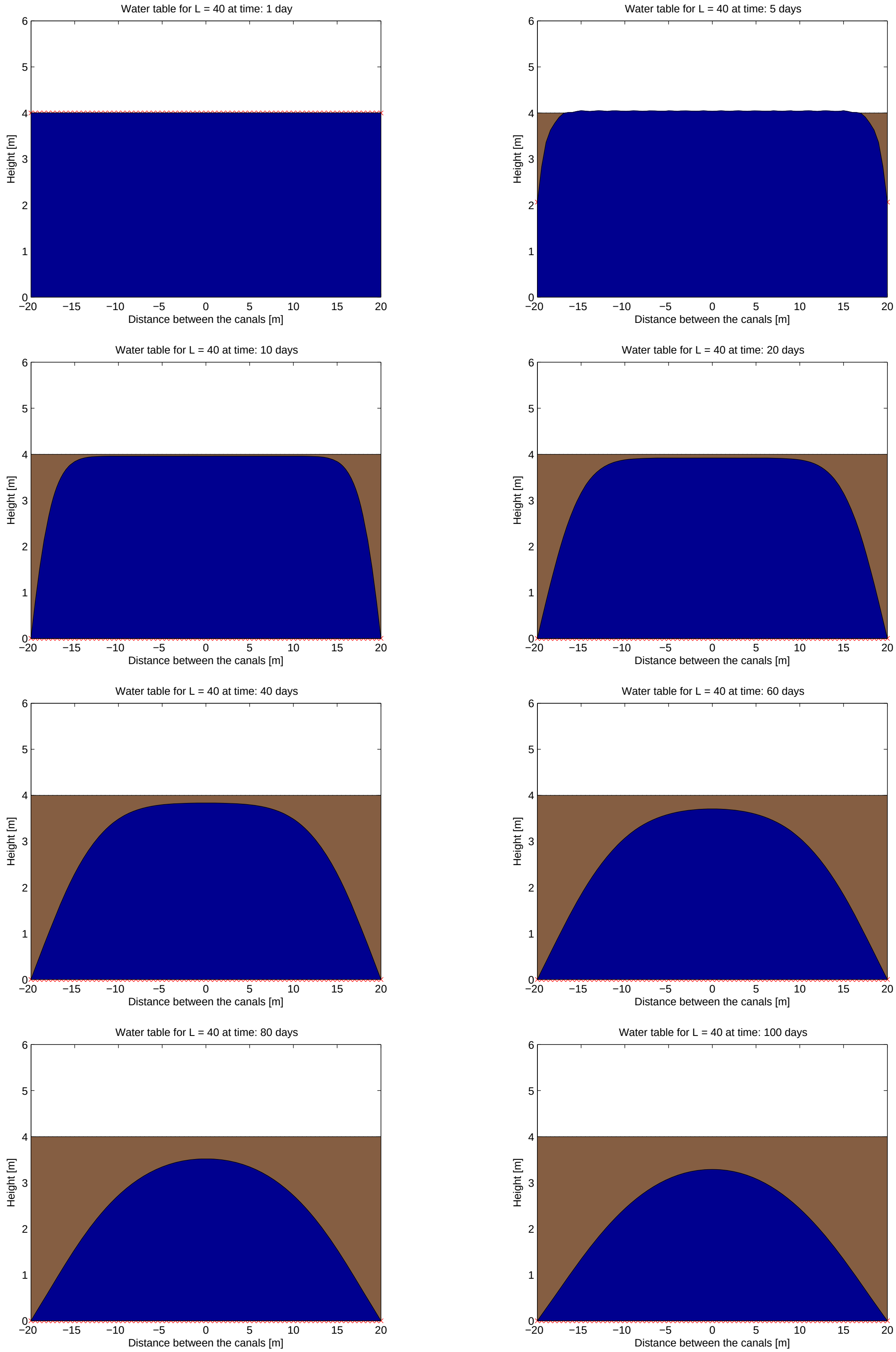


Figure C.2: *Frames for a 100 day simulation of the water table. Note that the first few frames are taken at a lower interval. Frame 2 shows the water table when the river has dropped half way and, and frame 3 shows the river water level when the river water level has just reached the bottom.*

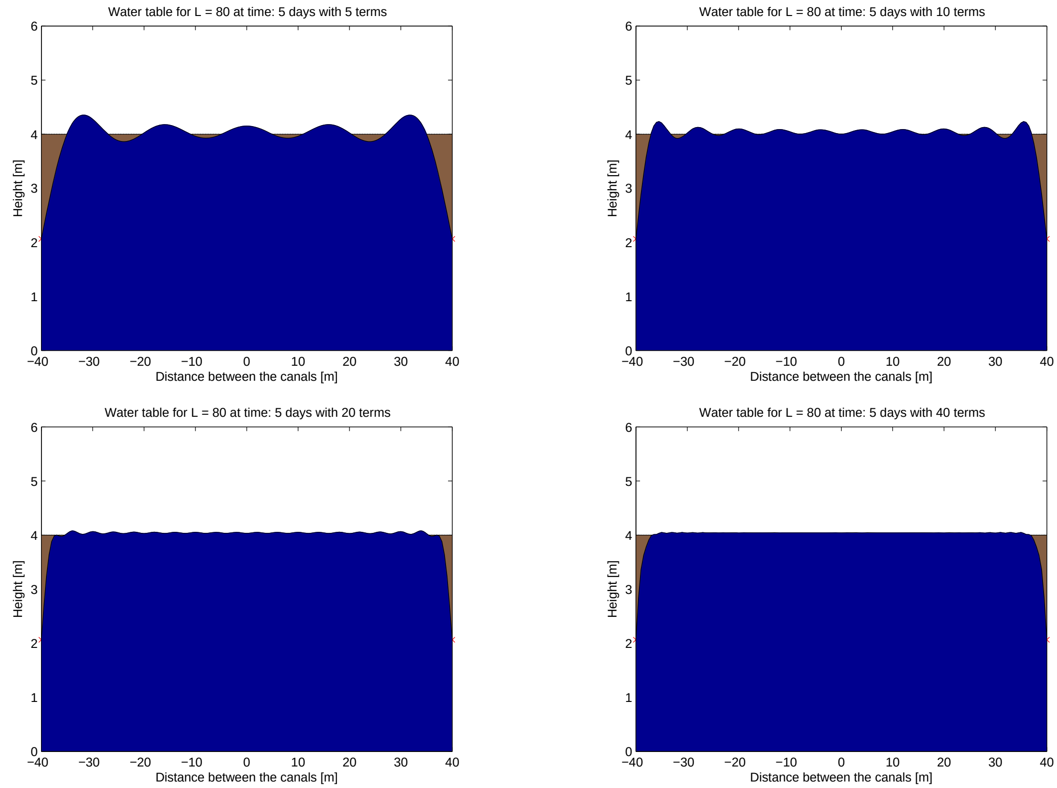


Figure C.3: *Figure displaying the water table approximation at $t = 5$ days for different amounts of terms. 5, 10, 20 and 40 terms were used for the figures above. Notice the Gibbs phenomena especially in the frame with 10 terms. Although this phenomena should be clearly visible in the higher term orders, it is not. This has to do with the grid size of $x$, which is set to 0.5 meters*

# Appendix D

# Matlab Code

The following text contains the MATLAB code used for the various simulations:

```
% Joost Noordermeer, LabMath Indonesia, UTwente, Civil Engineering
% BSc project: Water table approach in Peatlands

clear all
close all
clc

%=============================== INPUT VALUES ===============================
Tdry = 100;             % days      Period of drought
Riverdepth = 4;         % m
kappa = 0.5;            % m/day     Hydraulic conductivity
L = 40;                 % m         Distance between rivers / 2
%============================================================================

%============================ SIMULATION VALUES =============================
stepsizex = 0.5;          % m
stepsizet = 0.1;          % days
Triv = 10;                % days - Time it takes for r(t) to reach 0
rain = 0;                 % mm/day
k = 20;                   % Number of terms (INTEGER VALUE)
%============================================================================

%==================== DEFINITIONS x, t, r, devr ===========================
x=-L:stepsizex:L;

t=0:stepsizet:Tdry;

for i = 1:(Triv/stepsizet)
    r(i) = (Riverdepth/2)*(cos((t(i)/Triv)*(pi))+1);
end

for i = 1:length(t)
```

```
    peff(i) = (rain/1000)*stepsizet;
end

% The rest of the values for r are filled with 0. This has to be upto 1
% timestep later than Tdry due to the calculation of the derivative
r((Tdry/stepsizet)+2) = 0;

devr = diff(r);

%==========================================================================

%======================== lambda, phi and C ===============================
for n=0:(k-1)
    lambda(n+1) = ((1+2*n)*pi)/(2*L);

    if mod(n,2)~=0
        C(n+1) = -4/((1+2*n)*pi);
    elseif mod(n,2)==0
        C(n+1) = 4/((1+2*n)*pi);
    end

    for j = 1:length(x)
        phi((n+1),j) = cos(lambda(n+1)*x(j));
    end
end
%==========================================================================

%================================ h(x,t) ==================================
h = zeros(length(x),length(t));

for i = 1:length(t)
    for n = 1:(k)
        for tau = 1:i
            Integral(tau) = (peff(tau)-devr(tau))*exp(kappa*(lambda(n)^2)
                                                    *((tau)*stepsizet));
        end

        Source(n,i) = sum(Integral);
        a(n,i) = C(n)*Source(n,i)*exp(-kappa*(lambda(n)^2)*t(i));

        for j = 1:length(x)
            if n == 1
                h(j,i) = r(i) + a(n,i)*phi(n,j);
            else
                h(j,i) = h(j,i) + a(n,i)*phi(n,j);
            end
        end
```

```
    end
    if i/1000 == ceil(i/1000)
        i
    end
end
%===========================================================================

%============================== VOLUME =====================================
for i = 1:length(t)
    for j = 1:length(x)
        Volumetimestat(j) = h(j,i)*stepsizex;
    end
    Volume(i) = sum(Volumetimestat);
end
Volumepercent = (Volume-Volume(1))/Volume(1);
%===========================================================================

%================================ h(0,t) ===================================
% for i = 1:length(t)
%     h0t(i) = a0graph(1,i);
% end
% h0t = h0t/max(h0t)-1;
%===========================================================================

%============================ Graph & MOVIE ================================
% The following commands make the figure fill the screen from the start.
% This is especially useful when making the movie because it's impossible
% to interfere with the process. Note that making a figure fullscreen will
% also make the video of the same resolution. Files with a larger
% resolution can be difficult to play on a slower computer, it also makes
% the filesize significantly larger

f1 = figure(1);
% screen_size = get(0, 'ScreenSize');
% set(f1, 'Position', [0 0 screen_size(3) screen_size(4) ] );

j=0;         % a counter used for storing the frames of the movie per day
             % instead of per timestep

% aviobj = avifile('L80T100-Peff.avi');
% aviobj.quality = 100;
% aviobj.fps=10;

figure(1)
for i = 1:1/stepsizet:length(t)
    time = round(i*stepsizet);
    M=plot(x,h(:,i),'-b',x,r(i),'xr',x,Riverdepth,'-k');
```

```
    hold on
    area(x,(h(:,i)+(Riverdepth-h(:,i))),'FaceColor',[.52 .37 .26])
    area(x, h(:,i))
    hold off
    axis([-L L 0 6]);
    title(['Water table for L = ',num2str(2*L),' at time: ',num2str(time),' days'])
    xlabel('Distance between the canals [m]')
    ylabel('Height [m]')

    if i/stepsizet == ceil(i/stepsizet)
        j=j+1;
        F(j)=getframe(gcf);
    end
end
% aviobj = addframe(aviobj,F);
% close(f1)
% aviobj = close(aviobj);
%===========================================================================
```