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ASSESSING THE IMPACT OF CLIMATE CHANGE ON EXTREME HYDRAULIC HEAD LEVELS AND DRY-WET CYCLES OF DUTCH CANAL DIKES

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Canal dikes in low-lying polders worldwide are critical earth structures for flood protection. Historically, inner-slope instabilities have been triggered by extreme dry and wet subsurface water conditions. Additionally, cyclic wetting and drying affect the dikes' resistance through mechanisms such as swelling and shrinkage, shear-strength reduction and soil consolidation. To accurately estimate failure probabilities of canal dikes, quantifying extreme hydraulic head levels and the magnitude of dry-wet cycles is crucial. However, there is limited understanding of changes in extreme head levels and the dry-wet cycles under climate change. This study assessed the impact of climate change on extreme hydraulic head levels and dry-wet cycles of canal dikes and how it varies across different dikes. This is done by analyzing dry-wet cycles and extreme head levels at three canal dikes in the Netherlands using both observations and models. Head observations from three monitoring sites provided data for developing time series models. By forcing 30 years of precipitation and evaporation to these models, extreme head levels and dry-wet cycles were derived. This was done under different climate scenarios to quantify the impact of climate change. It was found that the impact of climate change has a more pronounced effect on extreme low head levels than on high ones for the dikes considered. By 2100, extreme low levels could decrease by up to half a meter in drying scenarios, potentially shifting events from a 100-year frequency to every 2 years. Climate change also amplifies dry-wet cycles in canal dikes, with increases of up to several decimeters. In general, dikes with higher peak head responses and longer response times are more affected by climate change, emphasizing the importance of considering site-specific factors when evaluating canal dike stability under future climate conditions.

Keywords: Dike safety, time series models,hydraulic heads, extreme loadings, droughts and floods, dry-wet cycles

1. Introduction

Many people live in low-lying polders around the world. These places are characterized by their unique water management, as they lie below sea or river levels and are separated from the surrounding hydrological regime by dikes. Due to this separation, the rainfall that falls in the polders has to be drained out to prevent flooding. This is done using inland drainage canals. Water levels in these canals are controlled and can rise above the polder elevation due to soil subsidence, causing earthen embankments to form along the canals. People in these polders live with a continuous threat, as the water levels in these canals can be several meters higher than their houses. In the event of a dike breach, their houses can be flooded. Therefore, the performance of these dikes and how they evolve over time is of key interest to society. Their performances are periodically assessed and if the dikes' performance does not meet the safety standard, they are reinforced. These reinforcements have to ensure reliable performance for the decades to come. But do these reinforcements account properly for the changes in strength and load that can be expected in the future?

Canal dikes often consist of organic materials, like clay and peat. These soils are continuously exposed to environmental interactions, especially to variations in atmospheric conditions. This resulted in several inner-slope instabilities over time, see for example Fig. 1. Relevant load variables for dike instabilities include the pore-water pressures, or head levels, within the dike body, as both extreme high and low head levels can lead to failure. Low head levels are accompanied by weight loss in the unsaturated zone, potentially causing deformations and uplift that may trigger failure. High head levels, on the other hand, reduce effective stresses and shear strength, resulting in reduced stability. Next to extremes, cyclic wetting and drying also affect the dikes' resistance. Soils may lose shear strength due to swelling and shrinkage (Stirling et al., 2021). Effects that improve the strength can also be expected, as saturated soils consolidate over time. This process can be amplified by climate change. Lower head levels increase effective stresses, potentially reaching levels higher than ever experienced. This, in turn, contributes to undrained shear strength (Ladd & Foott, 1974). Depending on the subsoil and site-specific conditions, changing extreme head levels and dry-wet cycling can improve or worsen dike stability. However, there is little known about how the dynamics of head levels might evolve in the future. This paper dives into the dry-wet cycles and extreme head levels at three canal dikes in the Netherlands and tries to answer the research question: What is the impact of climate change on extreme hydraulic head levels and dry-wet cycles of canal dikes and how it varies across different dikes?

Fig. 1.Left: The dike breach at Terbregge, The Netherlands, in 2003. Right: the dike breach at Reeuwijk, The Netherlands, in 2021. In both cases, the canal is on the left side and the polder is on the right side. The canals were rather shallow and up to about one meter deep, limiting the development of the breach and the water that could flow into the polder.

Answering this question involves analyzing dry-wet cycles and extreme head levels at three canal dikes in the Netherlands using both observations and models. Head observations from three monitoring sites provided data for developing time series models. These models aim to explain the observed heads by other observed variables, like precipitation and evaporation. By forcing 30 years of precipitation and evaporation to these models, extreme head levels and dry-wet cycles were derived. This was done under different climate scenarios to quantify the impact of climate change.

2. Monitoring sites

The Netherlands has around 10,000 km of canal dikes, of which the majorityof the dikes consistof soft organic soils, like peat and clay (Bezuijen et al., 2005). This study considered three dikes located at three different polders in the Western part of the Netherlands.Thesedikes are characterized by gentle slopes(1:10) and small head differences (2-4 meters), see Figure 2. At each dike, the phreatic head levels in the dike body are measured with five piezometers for over four years. Thehead level fluctuationsare mainly driven by precipitation and evaporation under both daily and extreme conditions, as the fluctuations in the canal water levels are small (see bottom of Fig. 2).

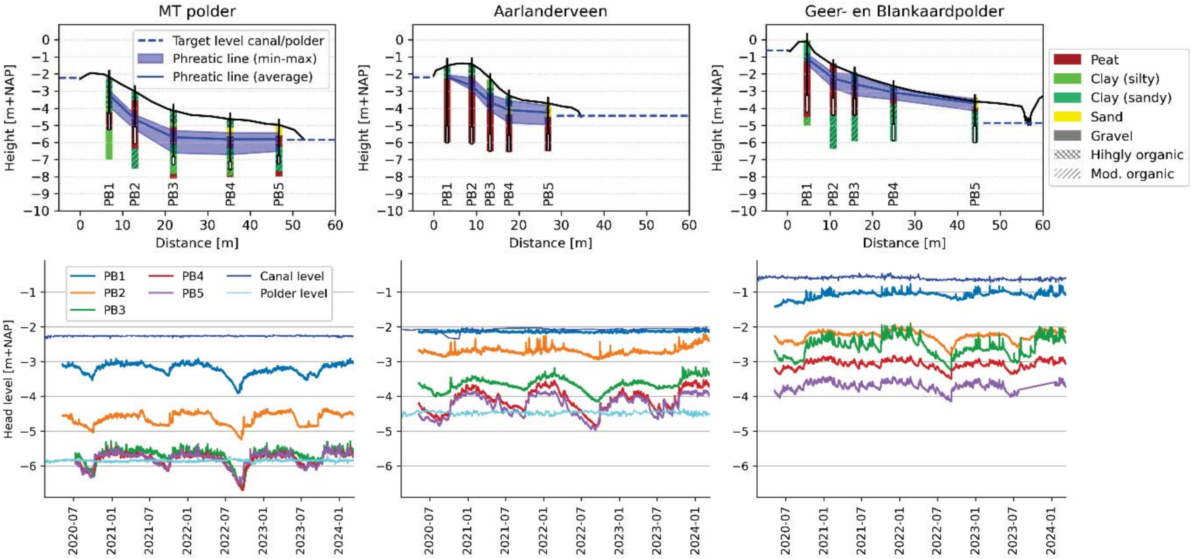

Fig. 2.Top: cross-sectional profile of the three canal dikes and the variation of the head levels. Bottom: evolution of the observed head levels and canal/polder water levels.

3. Methodology

3.1. Modelling head levels using time series modelling

To assess the impact of climate change, models are needed to analyze head responses in dikes under different scenarios. Numerical groundwater models are commonly used, but they struggle to reproduce observed head levels in dikes. This is due to uncertainties in subsurface conceptualization, spatial heterogeneity, and boundary conditions (Van Esch, 2012). Therefore, data-driven time series models have been used to model head dynamics (Bakker & Schaars, 2019). These models rely on multi-year head observations but do not require detailed subsurface information.

Although the physical processes are not represented, time series models, like the PIRFICT approach, can be insightful in understanding the head dynamics. This approach uses impulse response functions to represent the contributions of various drivers, such as precipitation and evaporation, to the head (Collenteur et al., 2019). Among the available model structures, the TARSO model was chosen (Knotters and Gooijer, 1999). This structure accounts for nonlinearity, with the head responding differently above or below a threshold. This nonlinearity can be found in the head observation, where head levels are capped, which can be caused by surface runoff or different soil properties at the top layer (Strijker & Kok, 2024). Furthermore, the only driver in this model is the net groundwater recharge, representing the combined effects of rainfall and evaporation. This factor is likely the most important because it explains the observed head series very well.To make the most of available data, a separate model was calibrated for each piezometer along the dike profile, using the entire set of observations.An example of one of these calibrated models is shown in Figure 3.

To understand why head levels vary as they do, two key characteristics of the response functions are useful. First, the peak of the block response (A) indicates the maximum effect of an impulse on the head level. Second, the response time (t_{95}) reflects how long it takes for the influence of the impulse to dissipate.These characteristics vary across dikes and can helpexplain why climate change affects head levels differently from one dike to another.

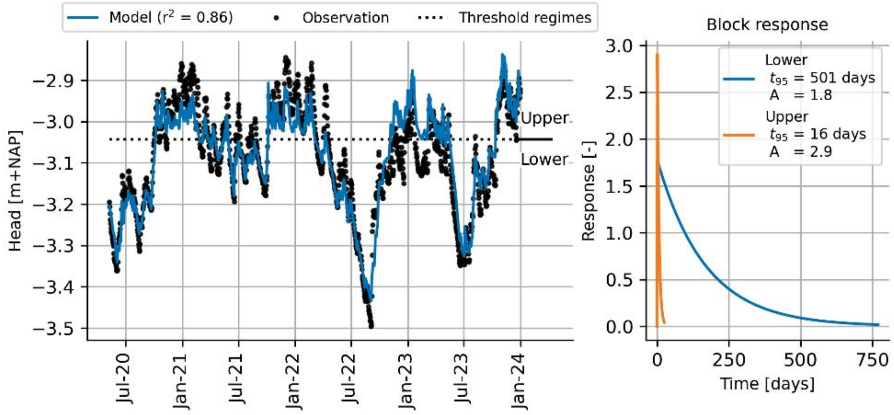

Fig. 3.A time series model that explainsthe observed head levels for PB4 at Geer- en Blankaardpolder, where the threshold level of the two regimes is indicated (left) with the corresponding response functions (right)

3.2. Quantifying the impact of climate change on head dynamics

Answering the research question requires head time series under different climate scenarios and time horizons. Therefore, these models were simulated using 30-year time series of precipitation and evaporation corresponding to different climate scenarios. These scenariosprovide plausibleand physically consistent storylines or pathways of climate change in the Netherlands, considering uncertainty for regional climate change and global temperature changes driving it. Note that these time series are a representation of the climate and not an estimate of the actual weather (Van Dorland et al., 2023). In total, nine different model simulations were used. One simulation for the current climate and eight for the future climate with combinations of different time horizons (2050 and 2100), emission scenarios (High SSP5-8.5 and Low SSP1-2.6) and regional climate response(wet and dry-trending). These simulations give a range of possible head time series that can be expected in the future, see Figure 4. This study does not account for changes in head responses caused by shifts in hydraulic conductivity and water retention capacity under the impact of climate change (Azizi et al., 2019).

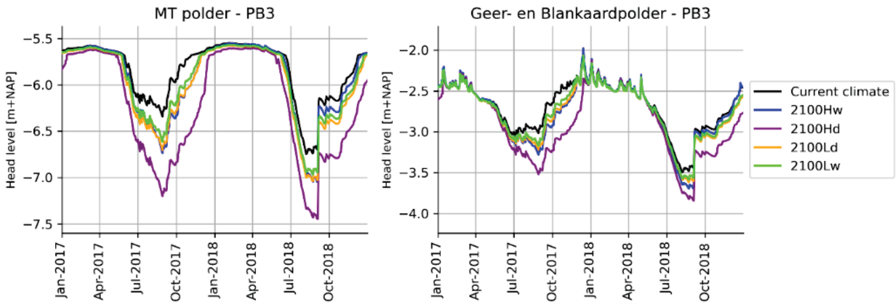

Fig. 4.Simulated head levels under different climate scenarios for two monitoring points at two different dikes

To address the research question, extreme hydraulic head levels and dry-wet cycles must be quantified. This involves analyzing extreme head values across the nine simulations. The extreme levels have two sides; highs and lows. Both were examined by separately fitting extreme value distributions (exponential distributions) to the minima and maxima. The minimum and maximum values were identified using the Peaks-Over-Threshold method, using a 90-day time window between adjacent values to ensure the independence of selected values. To accurately capture extreme values, a threshold was set to select only 15 peaks from the 30-year time series. The fitted extreme value distributions were used to estimate the head levels with a 100-year return period, aligning with required safety standards. Secondly, the extreme value distributions of the low head levels were used to calculate the size of wet-dry cycles. This cycle size is defined as the average distance between the surface level and the low head level occurring once every 10 years, representing the zone where the dry-wet cycle occurs and a decrease in shear strength is likely to occur.

4. Results: climate change effects on extreme heads and dry-wet cycles

The findings demonstrate the impact of climate change on canal dikes.This is done by first focusing on extreme hydraulic head levels (highs and lows), then on dry-wet cycles, and finally on the variability of both across different dike profiles.

First, the extreme head levels are discussed, where a clear pattern emerges: the impact of climate change is more pronounced for low levels than for high ones (see Tables 1 and 2). The extreme high head levels increase only slightly up to 2050, and in some cases, even decrease due to increasing drought affecting high levels during winter as well. By 2100, high head levels with a 100-year return period could rise by up to 7 cm in the Hw-scenario.Expressed in terms of changing frequencies, by 2100 and under the Hw-scenario, the extreme head level that now occurs once every 100 years could happen every 25 years, driven by wetter winters. For extreme low head levels, a drop of 8 to 23 cm is expected by 2050, with further decreases of up to nearly 50 cm possible by 2100. Extreme low head levels become far more frequent, as also expected by decreasing precipitation and increasing evaporation during summers. In 2050, head levels that currently occur once every 100 years might occur every 15-50 years and by 2100could occur on average every 2 years, in the Hd-scenario.

Table 1. Increase in the T=100 high head level for different climate scenarios (High/Low emissions; dry/wet regional climate response) in 2050 and 2100. Dash sign indicates no change.

	2050				2100			
	Hd	Hw	Ld	Lw	Hd	Hw	Ld	Lw
MT-polder	-1 cm	-	-1 cm	-1 cm	-1 cm	+3 cm	-1 cm	-1 cm
Aarlanderveen	+1 cm	+1 cm	+1 cm	+1 cm	+7 cm	+5 cm	+1 cm	+1 cm
Geer- en Blankaardpolder	-1 cm	+1 cm	-1 cm	-	-	+7 cm	-1 cm	-

Table 2. The change in the T=100 low head level for different climate scenarios (High/Low emissions; dry/wet regional climate response) in 2050 and 2100.

	2050				2100			
	Hd	Hw	Ld	Lw	Hd	Hw	Ld	Lw
MT-polder	-23cm	-13 cm	-18 cm	-14 cm	-48 cm	-26 cm	-18 cm	-14 cm
Aarlanderveen	-8 cm	-8 cm	-10 cm	-8 cm	-38 cm	-15 cm	-10 cm	-8 cm
Geer- en Blankaardpolder	-10 cm	-10 cm	-12 cm	-10 cm	-39 cm	-20 cm	-12 cm	-10 cm

Next, the impact of climate change on the dry-wet cycles is analysed.Under the current climate, these cycles already vary in size across the three dikes due to differences in horizontal groundwater flow, influenced by canal water intrusion and drainage capacities.At the MT polder, the cycles are the largest, reaching about 2 meters—twice the size of those at the Geer- and Blankaardpolder, see Figure 5. While the cycle sizes differ across locations, climate change causes a similar absolute increase in cycle size at all sites. By 2100, average cycles, based on different climate scenarios, could rise by 15 cm compared to current levels, with a maximum of up to 40 cm in the Hd-scenario at the MT polder. At Geer- and Blankaardpolder, cycle sizes could increase by just over 30 cm.

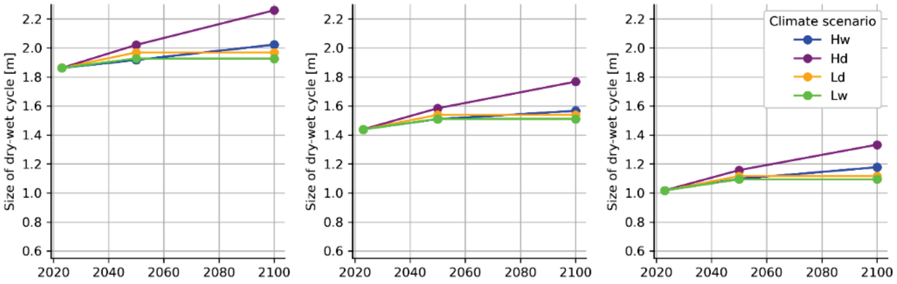

Fig. 5.Evolution of the dry-wet cycles under different climate scenarios

Lastly, differences between dikes are explained by considering the variations in response functions. For extreme high head levels, climate change has a greater impact when upper-regime head levels respond strongly toprecipitation. This is indicated by larger peak block responses and slower drainage, shown by longer 95% response times. Similarly, for extreme low head levels, higher peak block responses and longer response times in the lower regime amplify the impact.

5. Qualitative impacts and implications for dike safety

As shown, climate change is expected to result in more extreme high and low head levels, along with enlarged dry-wet cycles. How does this impact dike stability? This depends on the failure mechanism and site-specific characteristics being considered.Let’s consider the three canal dikes and instabilities triggered by extreme high pore pressures, as analyzed in the safety assessments of Dutch canal dikes.A first indication can be drawn by examining changes in effective stresses and shear strength along critical or representative slip planes.For the three canal dikes studied, the representative slip planes are mainlyseated below the phreatic linewith lengths from 15 to 60 meters. The total shear resistance is modest due to the presence of soft, lightweight soils. These light soils, in combination with gentle slopes, also keep the driving moments relatively low. The first effect considered is more extreme head levels, which lead to a decrease in effective stresses along the slip planes and, consequently, a reduction in stability. Secondly, the enlarged dry-wet cycle has two consequences.On one hand, it can induce deterioration processes, which decreases the shear strength of soils in the unsaturated zone.On the other hand, it can cause consolidation, which increases the shear strength of soils in the saturated zone. Whether the latter occurs, depends on the stress history of the soils, which is unknown for the considered locations.The impact of the shear strength reduction of the unsaturated zone, depends on the initial contribution of the shear strength from this zone.This initial contribution is small for the considered slip planes that run largely through the saturated zone where the majority of the resistance comes from. If the contribution of the unsaturated shear strength is larger, for example for shallower and smaller slip planes, the impact of soil deterioration can be expected to be higher. However, for dike safety, these slip planes are irrelevant, since they are unlikely to cause dike breaches. To summarize, while more extreme head levels and deterioration in the unsaturated zone can slightly reduce the dike stability, consolidation has the potential to counteract these effects.

6. Conclusions

This study examined the impact of climate change on 1) extreme hydraulic head levels, 2) the size of dry-wet cycles and 3) the variation of these effects across different canal dikes. Firstly, the findings indicate that climate change has a more pronounced effect on extreme low head levels than on high ones. By 2050, changes in extreme high heads will be modest, with some scenarios even showing decreases due to increasing droughts. Next to limited changes in extreme high head levels, extreme low levels may drop up to several decimeters, with highest drops in dry-trending scenarios. By 2100, the effect on extreme high heads is still moderate, while extreme low levels may decrease further: up to half a meter compared to the current climate in scenarios with a drying trend. Therefore, low levels are expected to occur far more frequently, with some scenarios indicating a shift from a 100-year event to occurrences as frequent as every 2 years.

Secondly, climate change amplifies the size of dry-wet cycles in canal dikes affecting the resistance in both positive and negative ways. These cycles vary in size across the studied dikes under the current climate. The MT polder exhibits the largest cycles, reaching about 2 meters. This is twice the size of the cycles observed at the Geer- and Blankaardpolder. Despite these site-specific differences, climate change leads to a similar absolute increase in cycle sizes across all locations of about 15-20 cm by 2100, with maximum increases of up to 40 cm for the high emission scenario and dry-trending regional climate response.

Thirdly, the variation in how climate change impacts head dynamics across different dikes was analyzed. Dikes with head responses characterized by higher peak block responses and longer response times were found to be generally more susceptible to the effects of climate change.

The impact of changing head dynamics on stability was qualitatively assessed. It revealed that whilemore extreme head levels and deterioration in the unsaturated zone may slightly weaken dike stability, consolidation has the potential to mitigate these effects. These findings emphasize the need to consider site-specific characteristics when assessing the stability of canal dikes under future climate scenarios.

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