Coordinated management of reservoirs

Optimizing valve settings to mitigate flooding in Westland

S. A. (Sabine) van Esch

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by

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Preface

For my Environmental Engineering studies, I investigated the possibility to use automatic control within the Rainlevelr initiative. This initiative aims to prevent a polder from flooding by creating storage in reservoirs prior to a rain event. The research was carried out during my internship at the waterboard of Delfland. The waterboard of Delfland is one of the oldest institutions of the Netherlands, founded in 1289. This made this internship for me even more valuable. The Rainlevelr project started in 2015 and was initiated by the waterboard and greenhouse owners. Until now the Rainlevelr actions are carried out manually. Delfland initiated the search for a means of automation and my supervisor Ronald van Nooijen proposed to use Model Predictive Control for this. As I discovered the theory behind control systems I became interested and started this graduation project. I want to thank Ronald van Nooijen and Markus Hrachowitz of the TU Delft for supervising my work. I also want to thank my supervisors at Delfland: Saskia Jouwersma and Hugo Vreugdenhil for introducing me to Rainlevelr and guiding me during the process. Finally, I want to thank my family and friends for their support.

S. A. (Sabine) van Esch
Delft, 2025

Samenvatting

Omdat het grootste deel van het Westland wordt gebruikt voor glastuinbouw, infiltreert regenwater nauwelijks in de bodem waardoor wateroverlast kan ontstaan. Daarnaast worden regenbuien intensiever, variabeler en wordt neerslag moeilijker te voorspellen (Beersma et al., 2019). Door de tuinbouw is de ruimte beperkt om oplossingen te vinden waarmee wateroverlast kan worden verminderd.

Het Hoogheemraadschap van Delfland en de tuinders hebben een kleinschalige oplossing gevonden die Rainlevelr wordt genoemd. De oplossing richt zich op het lozen van bassin water voordat een zware regenbui plaatsvindt zodat de bassins regenwater kunnen bergen tijdens de regenbui. De tuinders doen op een vrijwillige basis mee aan Rainlevelr. Voorwaarde voor de tuinders is daarbij dat er voldoende water voor irrigatie overblijft. Als de voorspelde regen niet overeenkomt met de werkelijke neerslag, kan een verkeerde strategie voor het lozen van water alsnog leiden tot wateroverlast in de polder of het verspillen van bassinwater. De vraag is nu of het mogelijk is een algorithme te definieren voor het afwegen van de belangen van de verschillende stakeholders.

Met een numeriek model kunnen waterniveaus in de peilvakken en in de bassins worden voorspeld op basis van weersvoorspellingen. Een controller kan toegevoegd worden aan het model waarmee de hoeveelheid water die geloosd wordt kan worden geoptimaliseerd. Het doel van dit afstudeerwerk is het ontwikkelen van een Model Predictive Control (MPC) strategie voor een polder in Delfland waarmee klepstanden van Rainlevelr buizen worden geoptimaliseerd. Met de voorgestelde strategie kunnen de risico's worden gereduceerd. Polder secties falen als het waterniveau boven een drempelwaarde stijgt en reservoirs falen als de waterstand beneden een drempelwaarde zakt.

Het Python model POKKA is ontwikkeld om de effecten van de klepstanden op de waterniveaus voor zowel de bassins als de peilvakken te onderzoeken. De Kralingerpolder is als casestudy gebruikt.

Uit een POKKA simulatie van de polder waarbij MPC de klepstanden bepaalde bleek dat het aantal drempelwaarde overschrijdingen in de peilvakken kon worden verlaagd ten koste van het aantal overschrijdingen in de bassins. De controller was echter niet in staat om wateroverlast in de polder te voorkomen tijdens een zware regenbui aan het begin van november 2023. De controller selecteerde een optimale sequentie van klepstanden uit een verzameling van 100 realisaties. Het verhogen van het aantal realisaties naar 1000 gaf kleine verschillen in de voorspelde waterstanden. De rekentijd nam echter met een factor van tien toe. Een parallelle berekening over een periode van 1 jaar kostte ongeveer 2 uur voor 100 realisaties, daarom is ervoor gekozen om de berekeningen met 100 realisaties uit te voeren. De controller stelde de afwegingen tussen de peilvakken en de bassins vast met gewichten op de afwijkingen tussen de waterniveaus en de referentie peilen. Met een berekening is aangetoond dat minder peilvakken de drempelwaarde overschrijden als de gewichten voor de peilvakken worden verhoogd. De controller berekent de optimale klepstanden op basis van weersverwachtingen en presteert slechter als de weersverwachting minder nauwkeurig is. De functie van de controller verbetert als er een terugkoppelingsloop wordt toegevoegd waarin gemeten waterniveaus worden gebruikt om de modelvoorspellingen te corrigeren. Het verhogen van de Rainlevelr capaciteit heeft een effect op de Model Predictive Control prestatie. Een laatste berekening toonde aan dat de controller in staat was om wateroverlast in de polder sterker te verminderen als alle bassins in de Kralingerpolder aangesloten worden op Rainlevelr.

Abstract

Because most of the area in Westland is taken up by greenhouses, water hardly infiltrates into the ground which may result in flooding. Furthermore, rain showers are getting heavier, more variable and harder to predict due to climate change (Beersma et al., 2019). The space to find solutions for mitigating flooding is limited by the greenhouse area.

The waterboard of Delfland and the greenhouse horticulturists have found a small-scale solution that is called Rainlevelr. The solution focuses on releasing reservoir water before a predicted heavy rain event such that the reservoirs can capture precipitation during the actual event. The greenhouse horticulturists participate voluntarily in Rainlevelr. While both the horticulturists and the water board want to mitigate flooding, the greenhouse horticulturists also want to keep as much water as possible in their reservoirs for irrigation. When predicted rainfall differs from the actual rainfall, the resulting suboptimal strategy for releasing water from the reservoir can result in flooding the polder or wasting reservoir water. This raises the question of how to define an algorithm to assess trade-offs between the interests of different stakeholders.

A numerical model could predict polder water levels and reservoir water levels based on a weather forecast. A controller could then be added to the model to optimize the amount of water that should be released. The goal of this thesis is to design a Model Predictive Control (MPC) strategy for a polder system in Delfland by optimizing the valve setting of the Rainlevelr pipes in the reservoirs. With the proposed strategy the risks can be reduced, and possible trade-offs can be identified. Polder sections fail when the water level exceeds a threshold water level and reservoirs fail when their water level falls short.

The Python model POKKA was developed in order to study the effects of the valve settings on the water levels of both the reservoirs and the polder sections. The Kralingerpolder was used in a case study.

A MPC simulation showed that the controller was able to reduce the number of polder section threshold exceedances at the expense of reservoir threshold exceedances. However, the controller was not able to prevent flooding of the polder during the heavy rain event at the beginning of November 2023. The controller selected an optimal sequence of hourly valve settings out of a set of 100 realizations. Increasing this value to 1000 only leads to a small difference in predicted water levels whereas the computation time increased with a factor 10. A parallel computation over a period of a year took about 2 hours for 100 realizations. For this reason the remaining calculations were performed with 100 realizations. The controller implements the trade-offs by setting weights on the deviations of the polder water levels and the reservoir water levels from their reference level. A simulation showed that fewer polder sections fail if the weights favor of the polder sections. The controller computes the optimal valve settings based on weather predictions and its performance decreases with decreasing accuracy of the weather forecast. Its performance was improved by introducing a feedback loop where measured water levels were used to correct the model predictions. Increasing the Rainlevelr capacity has a large effect on the Model Predictive Control performance. The simulation showed that the controller came very close to completely preventing a level exceedance of the polder during the heavy rain event at the beginning of November if all reservoirs in the Kralingerpolder were part of the Rainlevelr initiative.

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A	Area	[m^2]
B	Width	[m]
C_w	Weir coefficient	[-]
D	Diameter	[m]
e	Vapor pressure	[kPa]
g	Gravity acceleration	[m/s^2] (≈ 9.81)
$J(\cdot)$	Objective function	[-]
$l(\cdot)$	Cost function	[-]
n	Amount of pumps	[-]
N_{hor}	Total time horizon	[d]
P	Daily precipitation amount	[mm]
Q	Discharge	[m^3/s]
R	Radiation	[J/m^{2}d]
t	Time	[s]
v	Valve opening	[-]
V	Volume	[m^3]
w	Weight factor	[-]
z	Crest level	[m or m NAP]
ζ	Water level	[m or m NAP]
η	Runoff coefficient	[-]
μ	Contraction coefficient	[-] ($\approx \frac{2}{3}$)
ξ	Entry or Exit loss coefficient	[-]
ρ	Density	[kg/m^3]

1
Introduction

1.1. Problem statement

Westland is a densely populated area known for its large-scaled greenhouse horticulture as shown in Figure 1.1. The waterboard of Delfland controls the water levels of the Westlands polder areas. The entire control area of Delftland covers 39000 ha. About 10 % of this area is occupied by greenhouses (Rainlevelr, 2024). This makes the waterboard of Delfland the waterboard with the largest greenhouse area in the Netherlands.

Figure 1.1: Aerial photo of Westland (Hoogheemraadschap van Delfland, 2024).

A schematic diagram of the polder including greenhouses, reservoirs and ditches is given in Figure 1.2. Water collected in the reservoir is used to irrigate the crops in the greenhouses.

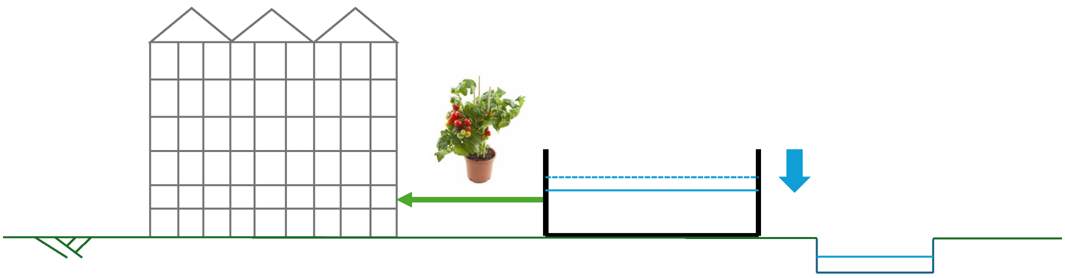


Figure 1.2: Irrigation.

Because most of the area in Delfland is impermeable due to the presence of greenhouses and urbanization, water hardly infiltrates into the ground . This increases the risk of urban flooding. The consequences are shown as an urban area in de Lier is flooded as shown in Figure 1.3. As rain showers are getting heavier, more variable and harder to predict due to climate change, especially in Zuid-Holland (Beersma et al., 2019), the problem will worsen in the future. The risk of flooding also increases due to expansion of the greenhouse horticulture (Jouwersma, 2016).

Figure 1.3: Urban flooding in de Lier (Schut, 2016).

As the space is limited and the risk of urban flooding is increasing, the water board needs to find small-scale solutions (Jouwersma, 2016). One of the initiatives to solve the problem is the Rainlevelr project. Rainlevelr was initiated as a collaborative effort between the water board of Delfland, the greenhouse owners, the municipality of Westland and Glastuinbouw Nederland. The greenhouse horticulturists participate in Rainlevelr on a voluntary basis (Rainlevelr, 2024). The aim of Rainlevelr is to resolve flood related problems, addressing bottlenecks at the local level, reducing water levels in polders, and facilitating discharge to the surrounding boezem (de Vette and Berkhout, 2020; Jouwersma, 2016). The diagrams in Figures 3.2, 3.4 and 3.5 illustrate the Rainlevelr concept.

In Figure 1.4 the effect of precipitation is given. Rain falling on the greenhouse is collected in the reservoir. This results in a rising water level in the reservoir. Rain falling in the polder area results in a rising water level in the ditch.

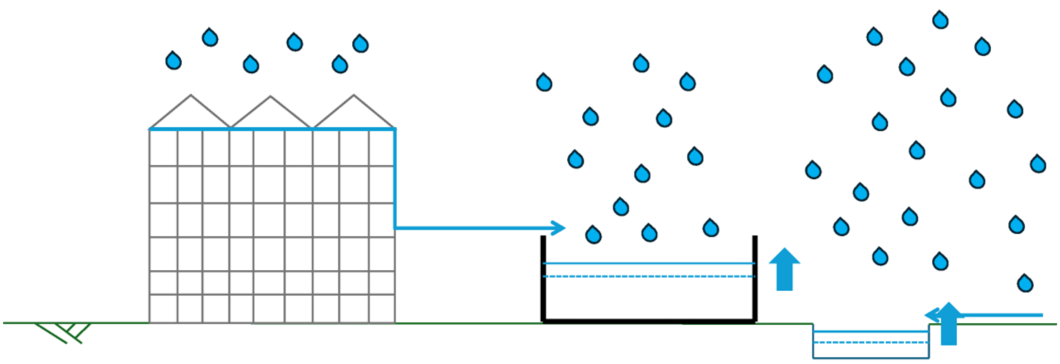


Figure 1.4: Precipitation.

The effect of the spill is shown in Figure 1.5. If the water level in the reservoir gets too high, the reservoir spills into the ditches. This may create problems during heavy rain events. The water level in the ditches may then already be high and the addition of the spilled water could cause local flooding in the polder.

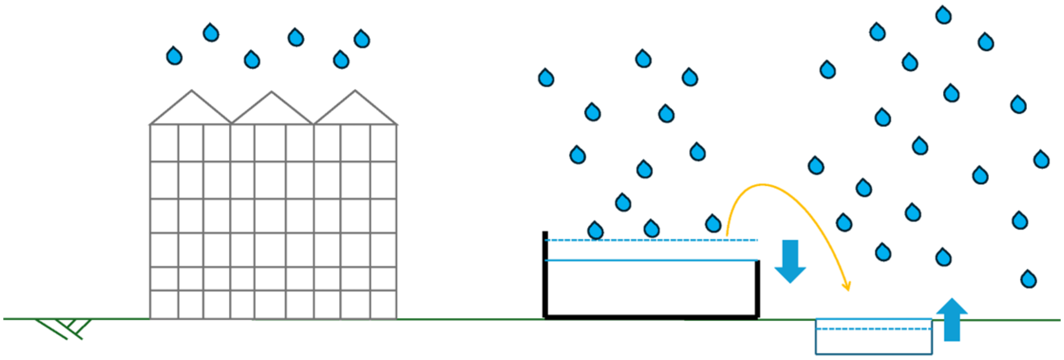


Figure 1.5: Spill.

In Figure 1.6 the effect of the Rainlevelr action is shown. The reservoir is connected to the polder ditches by a Rainlevelr pipe. The pipe includes a valve that can be operated by remotely. Prior to a predicted rain event, water can be released from the reservoir into the ditches by opening the valve. The water level in the ditches increases and can be lowered via weirs and pumping stations before the actual rain event is takes place. This additional control creates storage in the reservoir that can be used during the rain event.

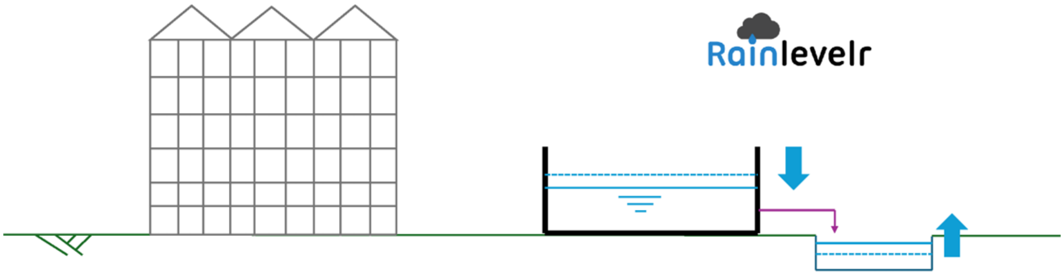


Figure 1.6: Rainlevelr action.

An example of a Rainlevelr installation at a greenhouse is shown in Figure 1.7. When raining, the pipes (2) are guiding the rainwater from the greenhouse (1) to the reservoir (3). Water from the reservoir discharges via the Rainlevelr pipe (5) to the ditch (6). If the automatic system fails then the greenhouse horticulturist can manually adjust the valve setting with the Rainlevelr manual control center (4).

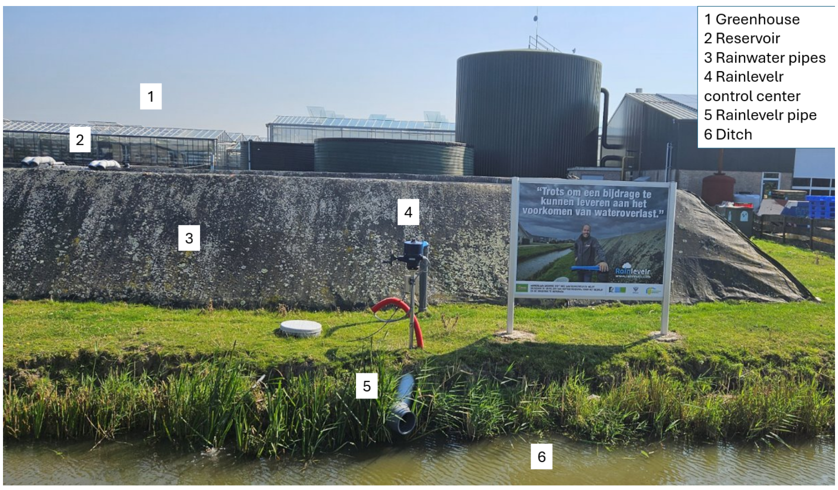


Figure 1.7: Rainlevelr setup at Ammerlaan Growers (Adapted from Picture: Sabine van Esch).

Although both horticulturists and the water board aim to mitigate flooding, greenhouse horticulturists also aim to retain as much water as possible in their reservoirs for irrigation. Rainlevelr uses weather predictions to estimate an amount of water that should be released. This amount may not fit the actually needed to prevent the polder from flooding or prevent reservoir water to be wasted. This raises the question of how to define an optimal control strategy as it is likely that trade-offs should be made.

1.2. Design decisions

The goal of this thesis is to design a Model Predictive Control (MPC) strategy for a polder system in Delfland by optimizing the Rainlevelr valve setting. The MPC strategy aims to mitigate flood risks in the polder while assuring enough irrigation water in the reservoirs. With the proposed strategy the risks can be reduced, and possible trade-offs could be identified. Risks are quantified by the exceedance of a threshold water level. False positives occur when rain is expected and there is no rain event. This results in a waste of reservoir water. False negatives occur when no rain is expected and a rain event takes place. This results in polder water levels that are too high.

The polder system and the reservoirs will be modeled as buckets in a closed hydrological system. Polder water levels and reservoir water levels follow from weather predictions. The control strategy model determines the optimal setting of the valves. The number of realizations should provide an accurate optimization. Objective weights, which are used in the target function, will favor the polder sections as the aim is to prevent the polder from flooding. The MPC strategy includes a weather prediction update and a feedback loop on the reservoir and polder water levels. The control strategy model will be implemented in Python.

1.3. Research questions

This is research driven by a request for a controller design for polders in Delfland. In this thesis the model will be set up for a single polder system within Westland: the Kralingerpolder. The polder will be schematized in polder sections, reservoirs and their connections. For the case study the following research questions will be answered:

1. How does the polder respond to rain fall events?
2. What is the impact of inaccurate weather prediction?
3. Which feedback update window should be selected?
4. To what extent can the Rainlevelr participants contribute to mitigate urban flooding?

In order to assess the performance of the model predictive controller water level thresholds are set. A polder section is said to fail when the water level exceeds a given threshold and a reservoir is said to fail when the water level gets below a threshold.

1.4. Thesis layout

The report is structured in the following way. First, in Chapter 2 a literature survey about control strategies is given. Next the model setup is presented in Chapter 3. Chapter 4 outlines the case study of this report; the Kralingerpolder. Chapter 5 presents the results of Model Predictive Control applied to the Kralingerpolder for different scenarios. Conclusions on the optimal MPC settings, the impact of inaccurate weather prediction, the effect of the feedback update window and sensitivity to the number of Rainlevelr participants are given in Chapter 6. In Chapter 7 the discussion together with recommendations are presented. The appendices contain input files and the plots of the results of different scenarios.

2

Literature survey

In this chapter a literature review is presented to provide background on Model Predictive Control systems and to support the design decisions made in the introduction. In this study the hydraulic model gives a numerical description of a polder that contains several polder sections, reservoirs and their connections. The polder section water levels and the reservoir water levels are the unknowns in the model and need to be calculated. Predicted precipitation and evaporation drive the model. A Model Predictive Control (MPC) system operates on the model. The MPC system adds a controller to the model that sets components of the model based on predictions. In this study precipitation and evaporation predictions are used to determine valve settings. The outcome of the model, when using these settings, are collected by the controller to optimize the control strategy and to predicted water levels.

In Section 2.1 the control system is explained. Applications of model control systems in water management is reviewed in Section 2.2. The outcome of the literature survey supports the design decisions made previously.

2.1. Control systems

The polder system consists of multiple hydraulic structures and a control strategy for these structures must balance the conflicting interest of the greenhouse owners and the waterboard. To manage these challenges, an optimal coordination of control actions is needed. In this thesis the valve settings in the Rainlevelr reservoir are considered the control actions. In optimal control a reference control objective is reached. The objective function represents the desired behavior in terms of costs. The costs capture the deviation between a reference value and the computed output value. Over a given prediction horizon, the objective function is minimized by varying future control actions while still conforming to the systems dynamics and constraints. To indicate the controller's priority, weights are set for both the greenhouse reservoir and the polder sections. The control actions in this operation take into account predicted rain events and evaporation. Uncertainty in the weather forecast means that multiple control action sequences should be tested to find an optimal operation. This introduces Model Predictive Control. As new weather forecasts become available, the controller will recalculate new control actions over the prediction horizon to adapt to the changed inputs. The Model Predictive Control technique is shown in Figure 2.1 (Mathworks, 2024).

Lee (2011) reviewed the development of Model Predictive Control since the 1980s till the 2010s. In the first decade, Model Predictive Control was quickly adopted in the refining and petrochemical industry. In the decade that followed a better understanding of Model Predictive Control was achieved, focusing on the theoretical side such as state-space interpretations and stability proofs. In the next decade the main interest for Model Predictive Control was to increase the computation speed. Systems that require fast sampling rates are then suitable for MPC.

The book by Kouvaritakis and Cannon (2016) explains Classical, Robust and Stochastic Model Predictive Control. The authors mention that classical MPC, which deals with discrete linear time invariant systems without uncertainty, is already a mature field unlikely to undergo major developments. Robust and Stochastic MPC are however still subjects of ongoing research.

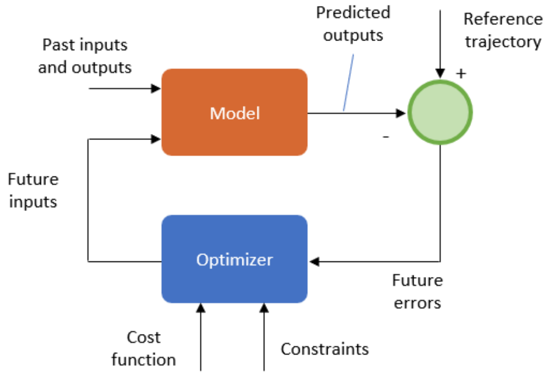


Figure 2.1: General principle of Model Predictive Control in diagram form (Mathworks, 2024).

Castelletti et al. (2023) systematically reviewed 149 peer-reviewed journal articles published over the last 25 years on Model Predictive Control applied in the field of water management. They identified common trends and challenges in research and practice. Due to system uncertainty, challenges posed by climate change and a growing world population the use of control systems became more important. In water systems, multiple stakeholders with sometimes conflicting objectives, influence the control system. This gives rise to trade-offs which should be explored in the control strategy. MPC has several advantages according to Castelletti et al. (2023): MPC is usable for non-linear applications (which is often the case in the field of water management), MPC is flexible in using constraints and MPC has a lower dimension of state and control vectors.

Although the use of water reservoirs is much older, Van Nooijen et al. (2021) described how water reservoir control is only fully understood since the 1950s. Due to the increase in computational power in the recent decades, control models have become more accurate. They explained the basics of control theory in water systems and discussed different control strategies, such as open loop control, feed forward and feedback controls, and optimal strategies like Model Predictive Control.

As real-time control in water systems demands significant computation time, Lobbrecht and Solomatine (2002) suggested using machine-learning approaches, like neural networks. They trained the controllers and showed that machine-learning can reproduce centralized control behavior while only using local data.

2.2. Polder applications

Weijs (2007) looked at how predictions of rainfall influence the water levels in a polder of Delfland, considering pumping capacity constraints. Here, Model Predictive Control is used to find the optimal pumping settings. Weijs (2007) combines two different ways for predicting the inflow. First, he uses a lumped runoff model to make a first estimation and then compensates for slow varying inflow using the mass balance of the boezem water.

Model Predictive Control was implemented by Van Overloop et al. (2008) for a water system in Delfland. They proposed to schematize the water system as a bucket with a water level and an uncertain inflow and outflow. To deal with the uncertain inflow, they proposed Multiple Model Predictive Control, using three different scenarios where the inflow can be high, average or low.

Keizer (2017) investigated the delays and losses of a precipitation collection system of greenhouses in situ. Based on measured data he created a model to determine the volume of annual precipitation that is usable for irrigation.

Maleki (2022) developed a Model Predictive Control strategy for the Oranjepolder as part of the Rainlevelr project. He simulated the polder water level and reservoir level for one day, neglecting evaporation and irrigation from the reservoirs. His newly derived strategy was compared to the implemented Rainlevelr strategy.

To find an optimum in multiple objectives for a polder system in Delfland, Horváth et al. (2022) used Model Predictive Control. They prioritized water levels between the allowed boundaries over minimizing the pumping costs by using a hierarchy of objectives. They regulated the water levels in the system with weirs, pumps and gates. To implement the MPC strategy they used RTC-Tools (Deltares, 2024b).

3

Polder model and controller

This chapter describes the setup of the numerical model of the polder and the Model Predictive Controller for a polder system. Section 3.1 presents the bucket model, which is used to model the water balance of the reservoirs and the polder sections. The reservoir model is outlined in Section 3.2 and the polder section model is presented in Section 3.3. In order to access the performance of the model predictive controller water level thresholds are set in Section 3.4. The newly developed Model Predictive Controller is outlined in Section 3.5. Section 3.6 gives a technical overview of the Python implementation of the model and its controller.

3.1. Bucket model

The reservoirs and polder sections are set up as buckets. This term is borrowed from hydrology: water is collected in the bucket, flow of water within he bucket is not considered and water can enter and leave the bucket as a function of time. According to this schematization water levels ζ of both the reservoirs and polder sections follow from a simple water balance:

$$A\,\frac{d\zeta}{dt} = Q_{\text{in}}(t) - Q_{\text{out}}(t) \tag{3.1}$$

where:

A	Bucket area	[m^2]
t	Time	[min]
$Q_{\text{in}}(t)$	Inflow at time t	[m^3/min]
$Q_{\text{out}}(t)$	Outflow at time t	[m^3/min]

This equation is discretized as:

$$\zeta(t + \Delta t) = \zeta(t) + \frac{Q_{\text{in}}(t) - Q_{\text{out}}(t)}{A}\Delta t \tag{3.2}$$

In this research the time step Δt is chosen such that the model remains stable and is precise enough. To meet these requirements the time step is set one minute. Initially the water levels for both the polder sections and the reservoirs are set at a reference water level.

In Figure 3.1 a simplified polder model setup with only two polder sections and one reservoir per polder section is given. A greenhouse reservoir is discharging water via a valve or a spill to its related polder section. The polder sections themselves are connected by a weir or culvert. The pumping station is discharging water from a polder section to a boezem.

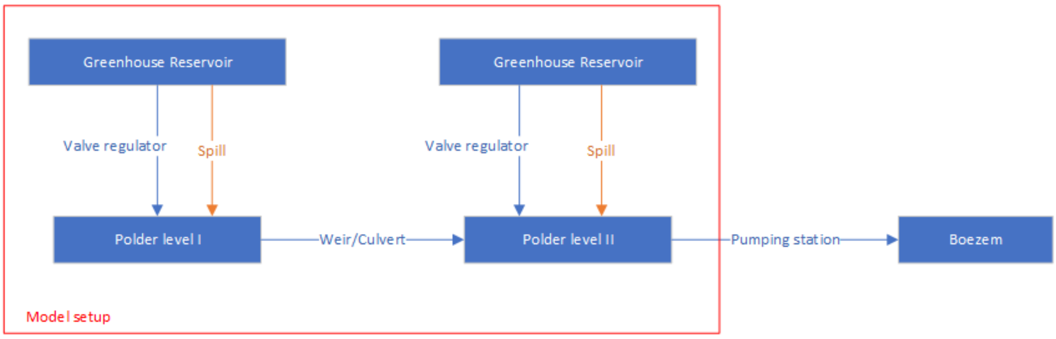


Figure 3.1: Simplified polder system.

To check if the implementation is correct, a water balance of the reservoirs, the polder sections and the polder is set up. The total incoming, outgoing and stored water volumes should add up to zero according to:

$$V_{\text{balance}} = V_{\text{in}} - V_{\text{out}} - V_{\text{storage}} \approxeq 0.0 \tag{3.3}$$

where:

V_{balance}	Balanced water volume	[m^3]
V_{in}	Incoming water volume	[m^3]
V_{out}	Outgoing water volume	[m^3]
V_{storage}	Storage water volume	[m^3]

The incoming and outgoing volume follows from discharges $Q_{\text{in}}(t)$ [m^3/min] and $Q_{\text{out}}(t)$ [m^3/min] integrated over time. The change in stored volume for the reservoir or polder section is given by:

$$V_{\text{storage}} = (\zeta(t) - \zeta(t - \Delta t))A \tag{3.4}$$

where:

$\zeta(t)$	Water level at time t	[m] or [mNAP]
$\zeta(t-\Delta t)$	Water level at time $t-1$	[m] or [mNAP]
A	Bucket area	[m^2]

3.2. Reservoir model

The potential inflows $Q_{\text{reservoir,in}}$ [m^3/min] is given by:

$$Q_{\text{reservoir,in}} = Q_{\text{P}} \tag{3.5}$$

where:

Q_{P}	Rain discharge to the reservoir	[m^3/min]

The reservoir outflow $Q_{\text{reservoir,out}}$ [m^3/min] follows from:

$$Q_{\text{reservoir,out}} = Q_{\text{E}} + Q_{\text{I}} + Q_{\text{v}} + Q_{\text{s}} \tag{3.6}$$

where:

Q_{E}	Evaporation discharge from the reservoir	[m^3/min]
Q_{I}	Irrigation discharge from the reservoir	[m^3/min]
Q_{v}	Rainlevelr discharge from the reservoir	[m^3/min]
Q_{s}	Spill discharge from the reservoir	[m^3/min]

In Figure 3.2 the schematization of the inflow and the outflow of the reservoir bucket is displayed. The inflow is indicated by a green line. Each outflow is indicated by a orange line. In the model both Rainlevelr reservoirs and non-Rainlevelr reservoirs are considered. The non-Rainlevelr reservoirs correspond to the Rainlevelr reservoirs but lack the valve outflow. Non-Rainlevelr reservoirs only lose water by spilling, irrigation or evaporation. The model calculates the water level in the reservoir in meters above the reservoir bottom.

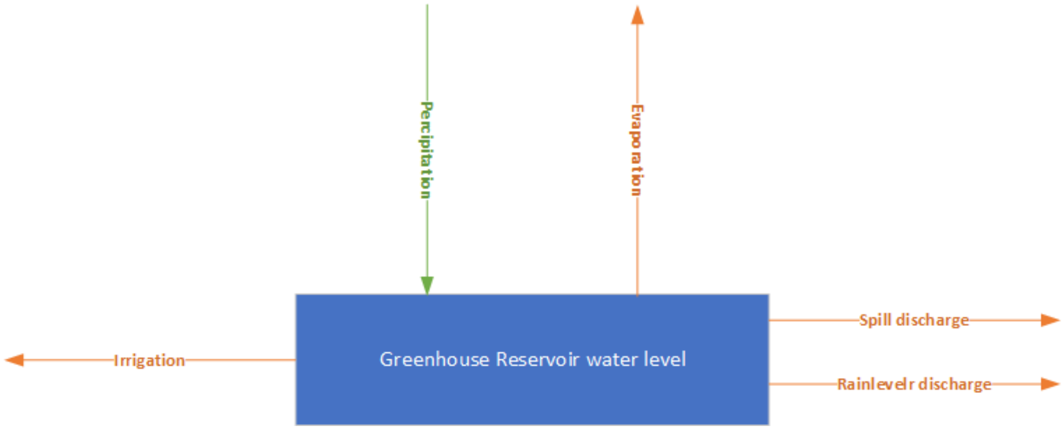


Figure 3.2: Reservoir bucket.

Precipitation

The discharge from precipitation Q_P [m^3/min] is added to the reservoir as follows:

$$Q_P = P\left(A_r + \eta_k A_k\right) \;/\; 1000 \tag{3.7}$$

where:

P	Precipitation	[mm/min]
A_r	Area of the reservoir	[m^2]
η_k	Runoff coefficient from greenhouses	[$\approx$ 0.7] (Keizer, 2017)
A_k	Area of the greenhouse	[m^2]

The discharge coefficient weights the rainfall on the greenhouse roofs reaching the reservoir is derived from Keizer (2017).

Evaporation

The discharge from evaporation Q_E [m^3/min] out of the reservoir is defined as:

$$Q_E = E_T A_r \;/\; 1000 \tag{3.8}$$

where:

E_T	Potential evaporation	[mm/min]

With the Penman formula (Penman, 1948) the potential evaporation E_T [mm/min] is calculated:

$$E_T = \frac{sR_n + C_a\rho_a(e_s - e_a)/r_a}{\rho_w\lambda_w(s+\gamma)}\,. \tag{3.9}$$

where:

s	Change in saturated vapor in temperature	[kPa/°C]
R_n	Net short-wave radiation	[J/m^{2}s]
ρ_w	Water density	[$\approx$ 1000 kg/m^3]
λ_w	Latent heat of vaporization	[$\approx 2.45\cdot10^6$ J/kg^2]
c_a	Specific heat moist air	[$\approx$ 1.013 kJ/kg/°C]
ρ_a	Air density	[$\approx$ 1.2 kg/m^3]
e_s	Saturated vapor pressure	[kPa]
e_a	Actual vapor pressure	[kPa]
r_a	Aerodynamic resistance	[s/m]
γ	Psychrometric constant	[0.067 kPa/°C]

For the calculation of the evaporation with the Penman method several factors should be determined which are: vapor pressures, radiation and aerodynamic resistance. The steps required to calculate Penman are given in appendix A. Atmospheric temperature, humidity, wind speed and in-coming radiation need to be collected in a weather station.

Irrigation

The irrigation use of the greenhouse Q_I [m^3/min] is stated as:

$$Q_I = IA_k\ /\ 1000 \tag{3.10}$$

where:

I	Irrigation	[mm/min]
A_k	Area of the greenhouse	[m^2]

Depending on the cultivation of the greenhouse, the irrigation method differs per greenhouse. In Figure 3.3 a water floor in a greenhouse that is used for irrigation is shown. The floor is flooded for some minutes while the plants take up water. The remaining water will afterwards flow via the gutter back to the reservoir.

Figure 3.3: Irrigation using water floors in a greenhouse (Picture: Sabine van Esch).

Valve flow

The discharge from a Rainlevelr pipe Q_v [m^3/min] (Deltares, 2024a) is modeled as discharge through a gate:

$$Q_v = \frac{1}{4}\pi(D_v v)^2 \mu_v \sqrt{2g\left(\zeta_r - (z_v + D_v v)\right)} \cdot 60 \tag{3.11}$$

Where:

D_v	Gate diameter	[m]
v	Valve dimension	[-] ($v \leq v_{max}$)
μ_v	Contraction coefficient in a gate	[$\approx \frac{2}{3}$]
g	Gravity acceleration	[≈ 9.81 m/s^2]
ζ_r	Water level upstream of the gate - Reservoir water level	[m]
z_v	Valve height	[m]

As the reservoir water level is always higher than the polder water level, free flow through the pipe is valid. In the model the valve dimension v [-] is determined as the opening percentage of the valve diameter D_v [m]. Additional friction is neglected as the pipe dimensions in the application that will be considered in the next chapter are unknown.

In Figure 3.4 the calculated reservoir water level with the respective valve flows for three different valve openings over 48 hours are given. The blue line indicates a valve which is 100 % opened, the orange line corresponds to a opening of 80 % and the green line indicates a 60 % opening. The bigger the opening the faster the water level in the reservoir drops.

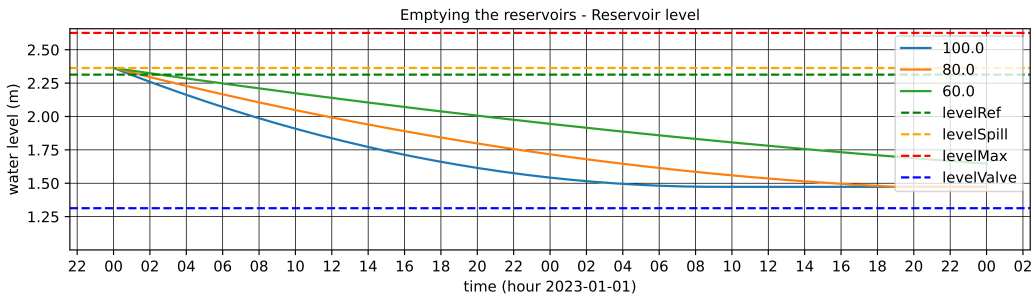


Figure 3.4: Valve influence on water level.

The analytical solution for the discharge is derived from Equation 3.1 and Equation 3.11. With an initial level at spill height z_s [m] the solution can be expressed as:

$$Q_v(t) = Q_v(0) - \frac{a^2 g}{A_r} t \tag{3.12}$$

$$a = \tfrac{1}{4}\pi\,(D_v v)^2 \mu_v \quad Q_v(0) = a\sqrt{2g(z_s - c)} \quad c = z_v + D_v v$$

In Appendix A the derivation for the discharge is given. Figure 3.5 shows this linear discharge in time that was calculated numerically. The vertical parts in the orange and green line of the valve flows indicate that the water level has reached the top of the valve. At that moment valve flow is set to zero. The bigger the opening the faster the water volume is discharging.

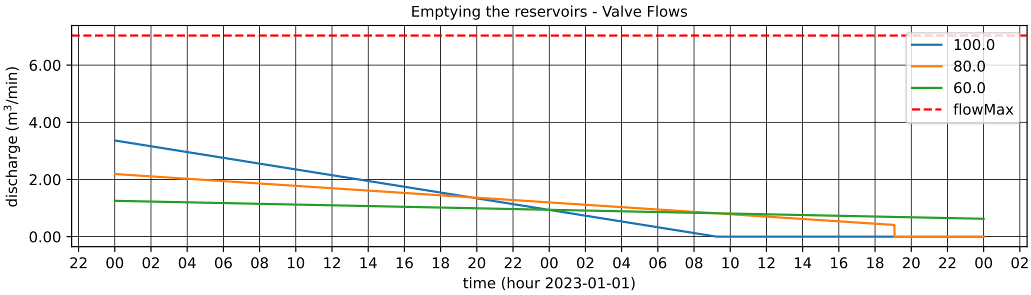


Figure 3.5: Valve discharges.

Spill flow

The discharge from the spill Q_s [m^3/min] (Van Nooijen et al., 2021) is modeled as flow over a weir:

$$Q_\mathrm{s} = C_\mathrm{s}\, B_\mathrm{s} \sqrt{g}\, (\zeta_\mathrm{r} - z_\mathrm{s})^{1.5} \cdot 60 \tag{3.13}$$

where:

C_s	Spill discharge coefficient	$[\approx \frac{2}{3}^{1.5}]$
B_s	Spill width	[m]
z_s	Spill height	[m]

As the reservoir water level is higher than the polder water level, the assumption of free flow over the weir is valid. In Figure 3.6 and Figure 3.7 the calculated reservoir water level and spill flow for a period of 48 hours are given. The drop in water level for the spill is faster than the drop for valve flow. The reservoir water level drop behaves non-linear in time according to Equation 3.13.

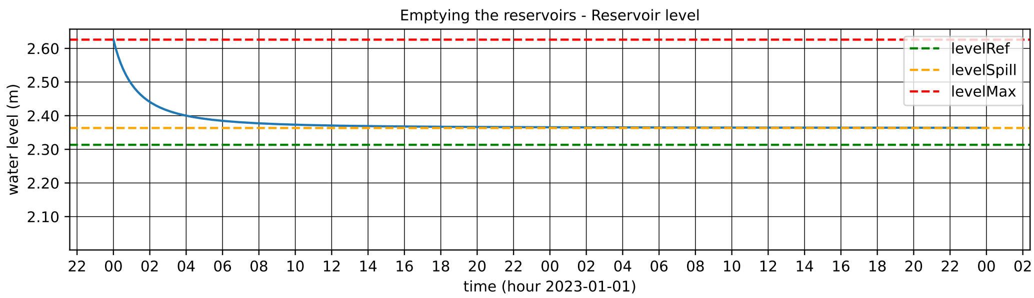


Figure 3.6: Spill influence on water level.

The total discharge over the spill is bigger than the valve discharges. The spill discharge is exponential shaped as expected from Equation 3.13. Figure 3.8a presents the discharge due to spilling.

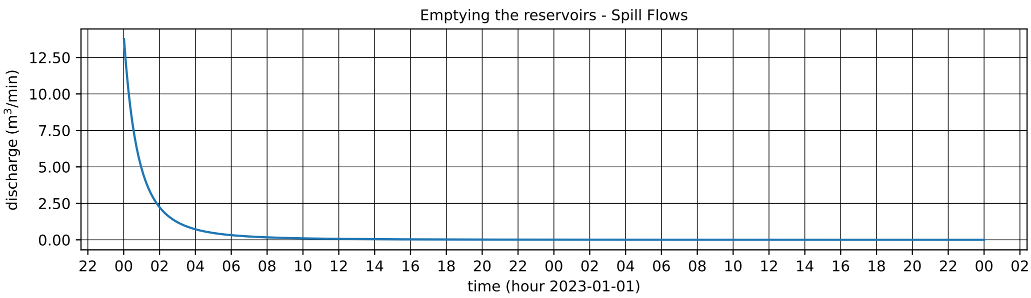


Figure 3.7: Spill discharges.

Single reservoir simulation

In Figure 3.8 the combined effect of precipitation, evaporation, irrigation, spill flow and valve flow of the reservoir water level over a week in November is given. Figure 3.8a presents the rain intensity with a precipitation peak on day 3 with a maximum of 0.15 mm/min. The calculated evaporation on a daily base is shown in Figure 3.8b. Evaporation is small in November compared to precipitation. Irrigation takes place over one hour per day: plants are watered from 4:00 until 5:00. Spill flow of the reservoir occurs at the same time as the rainfall peak on day 3. In this example the valve flow is set per hour in order to prevent the polder from flooding. In the figure it can be seen that valve flow takes place before a rain event.

The reservoir water level is shown in Figure 3.8f. Precipitation causes an increase in the reservoir water level. Just before the rain event on day 3 the water level drops due the opening of the valve. This reduces the impact of the precipitation peak. However, the water level still gets above the spill level and causes spill flow. Irrigation is responsible for small dips in the water level.

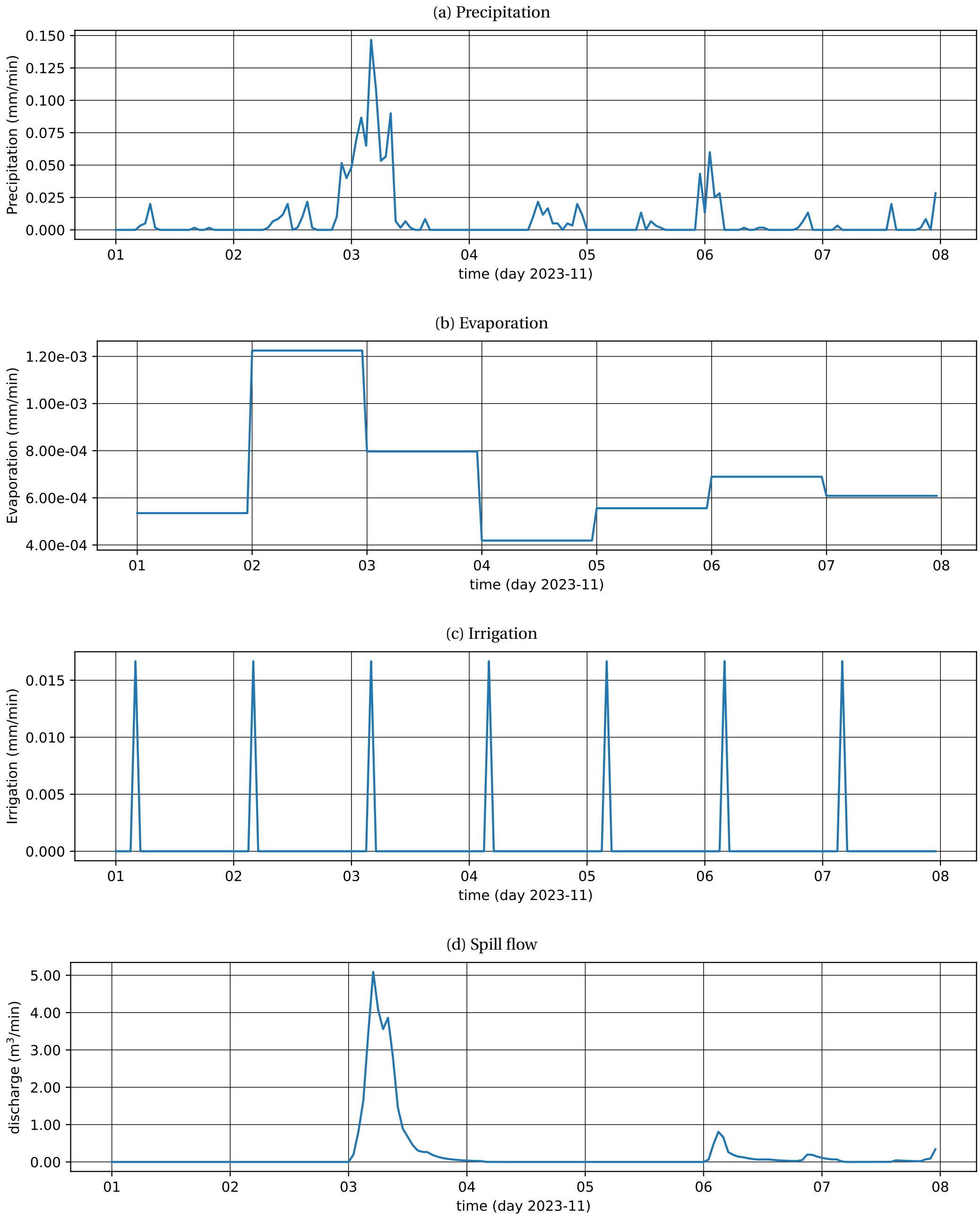


Figure 3.8: Reservoir example.

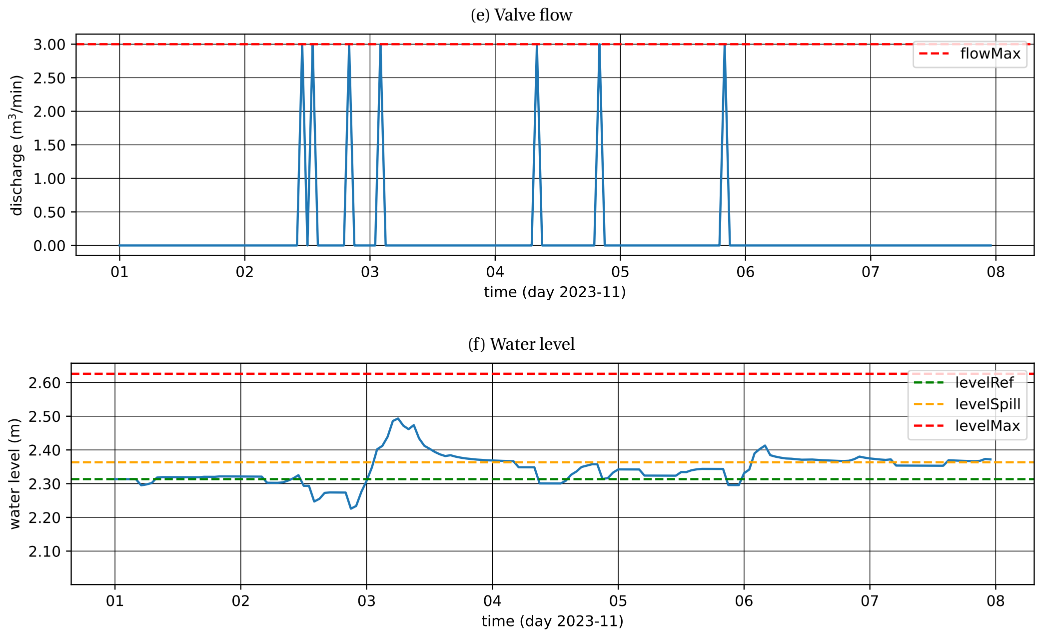


Figure 3.8: Reservoir example.

In Figure 3.9 the cumulative inflow, outflow and storage of water volumes for the reservoir are shown. The heavy rain event on the third day results in a sharp increase of inflow and outflow. The difference between in and outflow is plotted as storage. The storage line corresponds to the reservoir water level line in Figure 3.8f as storage follows from the product of water level and the reservoir area. The increase is measured relative to a reference level and for this reason the storage can become negative. The water balance should be zero.

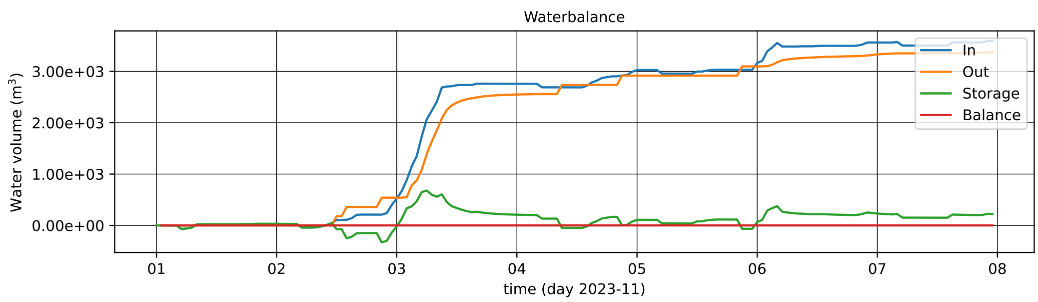


Figure 3.9: Water balance reservoir.

3.3. Polder section model

The inflow $Q_{\text{poldersection,in}}$ [m^3/min] and outflow $Q_{\text{poldersection,out}}$ [m^3/min] considered for a polder section are summarized in Equation 3.14 and 3.15 respectively. The water volumes from inflow and outflow are collected in the ditch area A_{ditch} [m^2] of the polder section. Inflow $Q_{\text{poldersection,in}}$ [m^3/min] is given by:

$$Q_{\text{poldersection,in}} = Q_P + Q_v + Q_s + Q_{w,up} + Q_{c,up} \tag{3.14}$$

where:

Q_P	Rain discharge to the polder section	[m^3/min]
Q_v	Rainlevelr discharge from the reservoirs to the polder section	[m^3/min]
Q_s	Spill discharge from the reservoirs to the polder section	[m^3/min]
$Q_{w,up}$	Weir discharge from the upstream polder section to the polder section	[m^3/min]
$Q_{c,up}$	Culvert discharge from the upstream polder section to the polder section	[m^3/min]

Inflow from the reservoirs either through the Rainlevelr valve Q_v [m^3/min] or the spill Q_s [m^3/min] were given by Equations 3.11 and 3.13 in Section 3.2, respectively.

Outflow $Q_{poldersection,out}$ [m^3/min] is written as:

$$Q_{poldersection,out} = Q_E + Q_g + Q_{w,down} + Q_{c,down} \tag{3.15}$$

where:

Q_E	Evaporation discharge from the polder section	[m^3/min]
Q_g	Pumping station discharge from the polder section to the boezem	[m^3/min]
$Q_{w,down}$	Weir discharge from the polder section to the downstream polder section	[m^3/min]
$Q_{c,down}$	Culvert discharge from the polder section to the downstream polder section	[m^3/min]

In Figure 3.10 the schematization of the polder section as a bucket is displayed. The inflowing fluxes are indicated by green lines. Each outflow is indicated by a orange line. Spill discharge and Rainlevelr discharge from all the reservoirs located in the polder section are collected in the ditch. The same holds for each weir and culvert in the system. Perculation and infiltration of groundwater is neglected in the model as it is assumed that the considered polder sections are mostly paved.

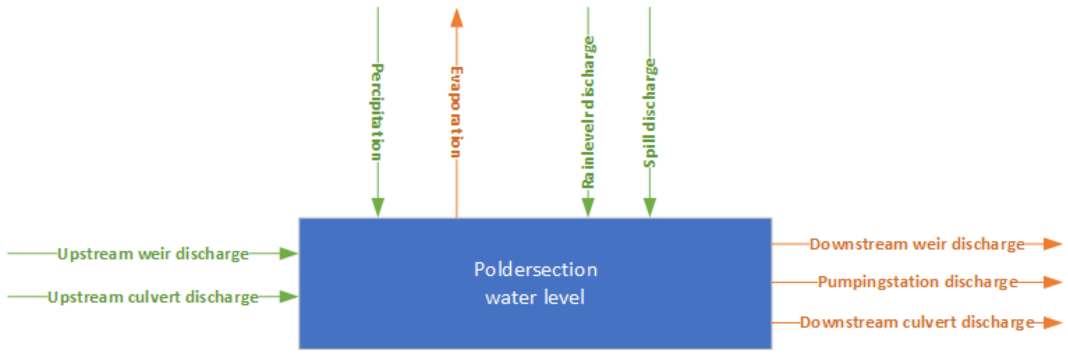


Figure 3.10: Polder section bucket.

The model calculates the water level in the polder section in meter NAP.

Precipitation

The precipitation flux Q_P [m^3/min] follows from:

$$Q_P = P\left(A_{ditch} + \eta_{paved} A_{paved} + \eta_{unpaved} A_{unpaved}\right) / 1000 \tag{3.16}$$

where:

A_{ditch}	Ditch area	[m^2]
η_{paved}	Runoff coefficient from paved area	[≈ 0.7]
A_{paved}	Paved area	[m^2]
$\eta_{unpaved}$	Runoff coefficient from unpaved area	[≈ 0.3]
$A_{unpaved}$	Unpaved area	[m^2]

The discharge coefficient is chosen in consultation with the waterboard of Delfland.

Evaporation

The evaporation in the polder sections Q_E [m^3/min] given by:

$$Q_\mathrm{E} = E_\mathrm{T} A_\mathrm{ditch} / 1000 \tag{3.17}$$

where:

E_T	Potential evaporation	[mm/min]

The potential evaporation follows from Equation 3.9.

Culvert flow

The discharge from culverts Q_c [m^3/min] (Deltares, 2024a) is modeled as flow through a gate:

$$Q_\mathrm{c} = \mu_\mathrm{c} B_\mathrm{c} \zeta_\mathrm{down} \sqrt{2g\left(\zeta_\mathrm{up} - \zeta_\mathrm{down}\right)} \cdot 60 \tag{3.18}$$

Where:

μ_culvert	Contraction coefficient in a bridge	[-]
B_c	Width under culvert	[m]
g	Gravity acceleration	[$\approx$ 9.81m/s^2]
ζ_up	Water level in the upstream polder section	[m]
ζ_down	Water level in the downstream polder section	[m]

The discharge coefficient underneath a bridge μ_culvert [-] (Deltares, 2024a) is given as:

$$\mu_\mathrm{c} = \frac{1}{\sqrt{\xi_\mathrm{in} + \xi_\mathrm{out}}} \tag{3.19}$$

Where:

ξ_in	Entrance loss coefficient	[$\approx \frac{2}{3}^{1.5}$ -]
ξ_out	Exit loss coefficient	[-]

The exit loss coefficient in a culvert ξ_out [-] (Deltares, 2024a) follows from:

$$\xi_\mathrm{out} = \left(1.0 - \frac{B_\mathrm{c}}{B_\mathrm{d}}\right)^2 \tag{3.20}$$

Where:

B_d	Width of the ditch next to the culvert	[m]

In Figure 3.11 the discharge through a culvert is given over a period of 48 hours.

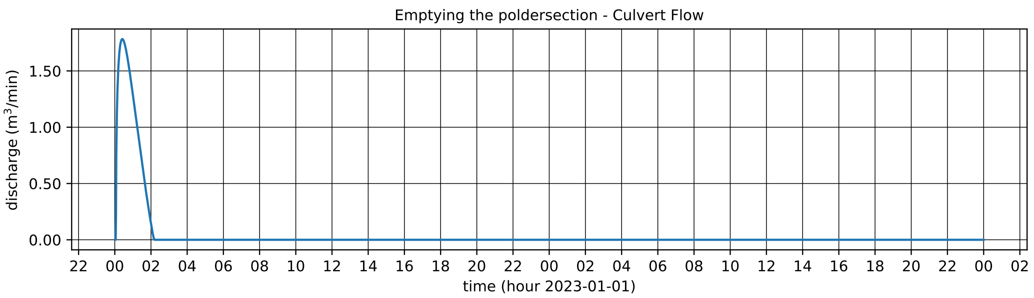


Figure 3.11: Culvert discharges.

Weir flow

The discharge from a weir Q_w [m^3/min] (Van Nooijen et al., 2021) is described as:

$$Q_w = C_w\, B_w \sqrt{g}\, (\zeta_p - z_w)^{1.5} \cdot 60 \tag{3.21}$$

where:

C_w	Weir discharge coefficient	[$\approx \frac{2}{3}^{1.5}$]
B_w	Weir width	[m]
ζ_p	Water level upstream of the weir - Polder section water level	[m]
z_w	Weir height	[m]

This formula was already used to simulate the spill flow (Equation 3.13) where the weir width was replaced by the spill width.

In Figure 3.12 the calculated polder section water level change due to weir discharge. The weir discharge is presented in Figure 3.13 over a period of 48 hours.

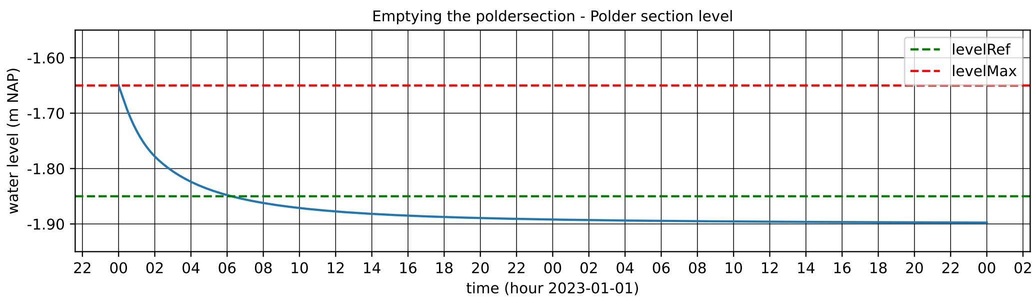


Figure 3.12: Weir influence on water level.

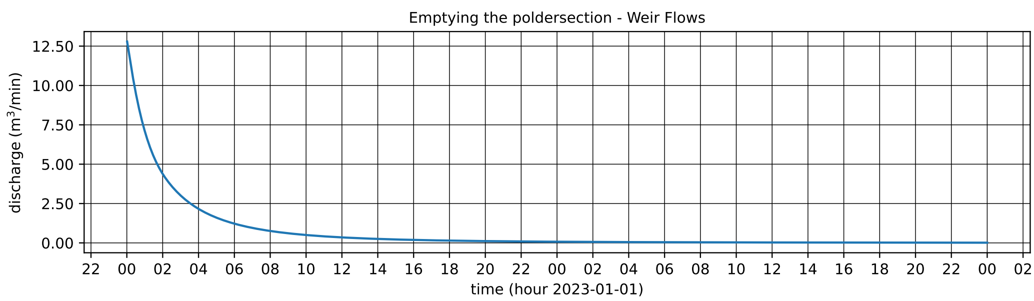


Figure 3.13: Weir discharges.

In the model free flow over the weir is assumed. Free flow (Deltares, 2024a) can be applied when:

$$\zeta_1 - z_w > \frac{3}{2}\,(\zeta_2 - z_w) \tag{3.22}$$

where:

ζ_1	Upstream water level	[m NAP]
ζ_2	Downstream water level	[m NAP]

Pumping station discharge

The discharge from the pumping station Q_g [m^3/min] (Deltares, 2024a) is described as:

$$Q_g = Q_{g,max} n \qquad [m^3/min] \tag{3.23}$$

where:

$Q_{g,max}$	Maximum discharge capacity per pump	[m^3/min]
n	Number of pumps	[-]

In Figure 3.14 the water level of the polder section that is connected to the pumping station is given. The corresponding pumping station discharges are presented in Figure 3.15. The pumping station works with pump start level. The pumps are activated when the water level in the upstream polder section is five centimeters above reference level. The pumps are deactivated when the water level in the upstream section is five centimeters below reference level.

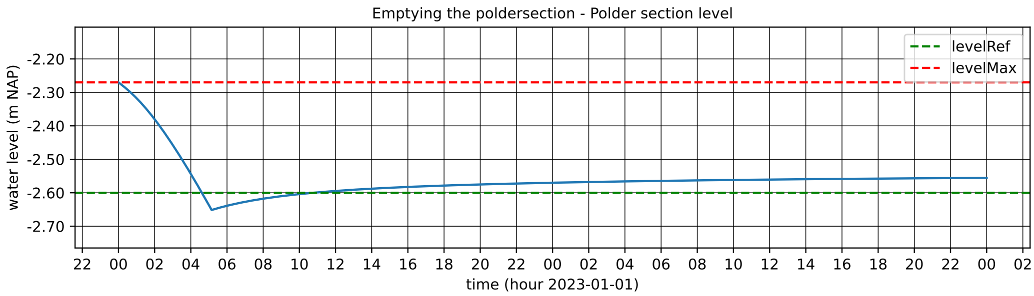


Figure 3.14: Pumping station influence on water level.

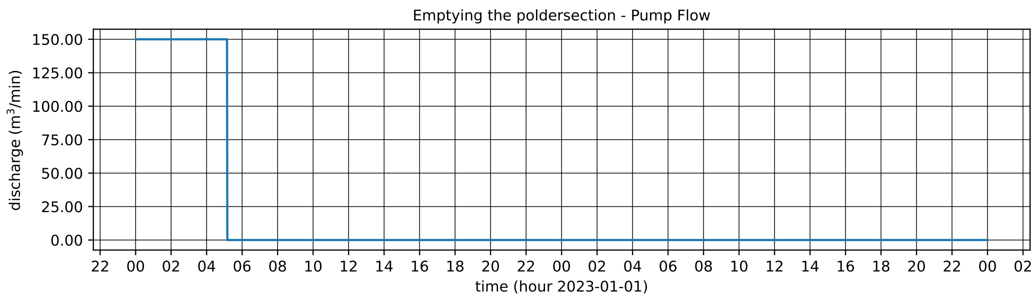


Figure 3.15: Pumping station discharges.

Single polder section simulation

In Figure 3.16 the influences of precipitation, reservoir valve flow, spill flow, weir flow and culvert flow on the polder section water levels is shown over a week in November. Figure 3.16a presents rain with a peak in precipitation on day 3 and a maximum of 0.15 mm/min. This figure was already shown in the previously discussed reservoir summary. The calculated daily evaporation is applied to the polder just as in the reservoir but it is not depicted here as its effect is small. The spill flow and the valve flow from a Rainlevelr reservoir belonging to the polder section were also depicted in the previous summary (Figure 3.8).

The water level change is the result of precipitation and spill flow. The valve flow before the peak of the precipitation event increases the polder water level temporarily. The additional storage that is created by this Rainlevelr action reduces the polder water level during the actual rainfall peak event. As the weir and culvert both transport water to a lower part of the polder, weir flow and culvert flow reduce the polder water level. As weir flow and culvert flow increase with a larger difference in water levels between the polder sections, the flux of both is larger for higher water levels as can be seen in the figure.

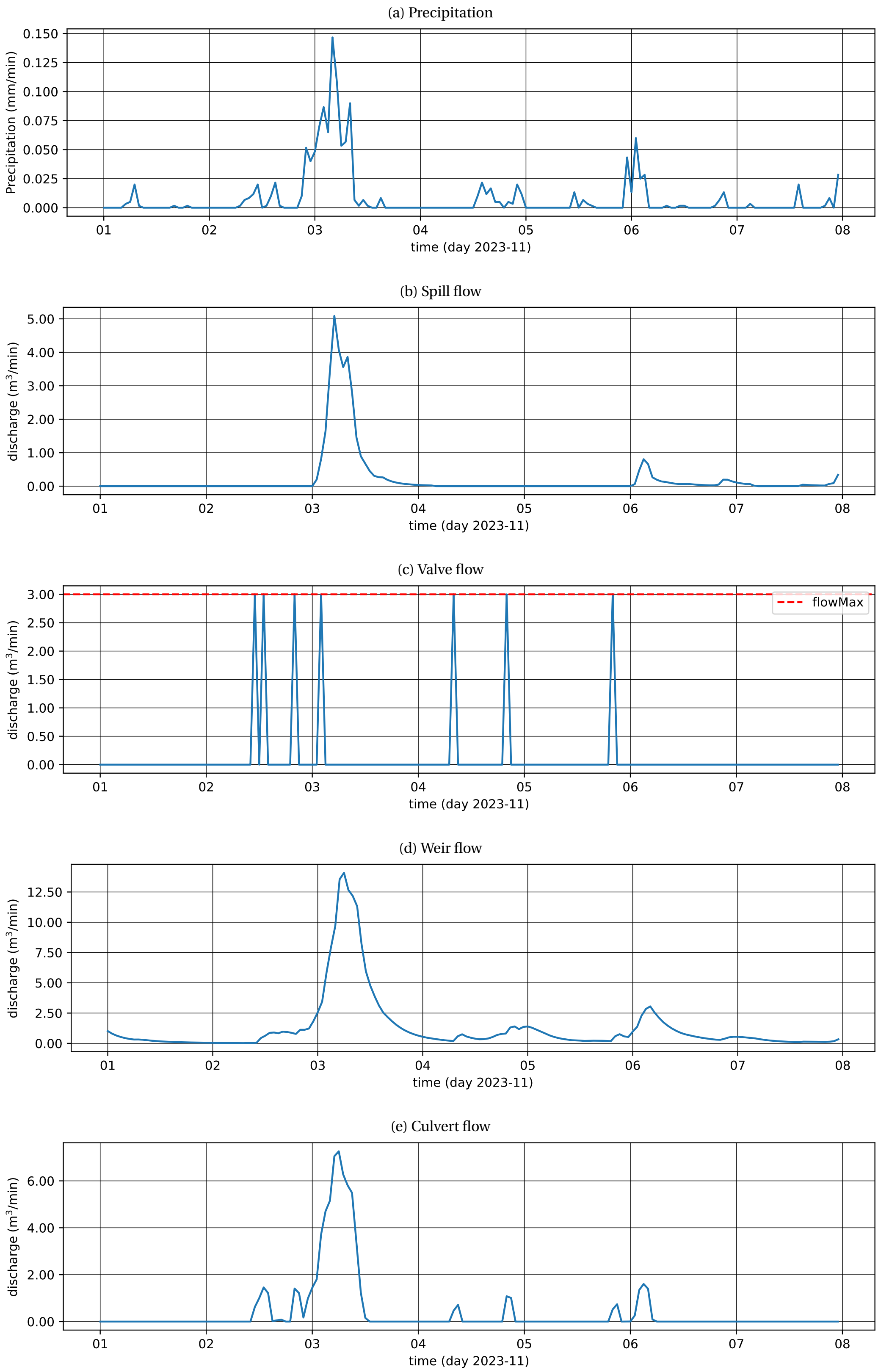


Figure 3.16: Polder section example.

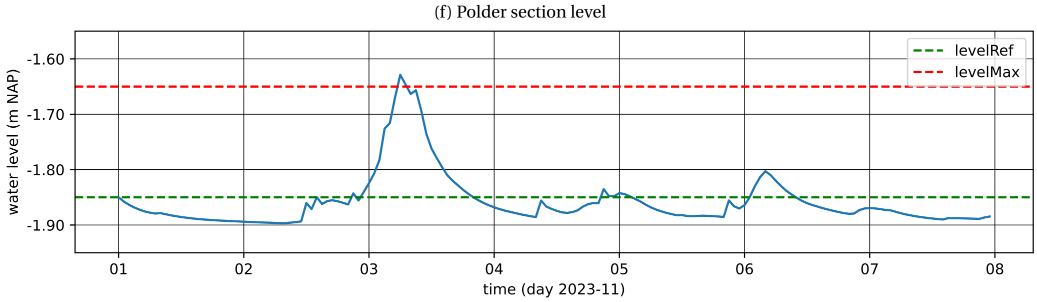


Figure 3.16: Polder section example.

In Figure 3.17 the cumulative inflow and outflow of the polder section is given. The storage of water resembles the difference between inflow and outflow. The water balance is given by the inflow minus outflow and storage.

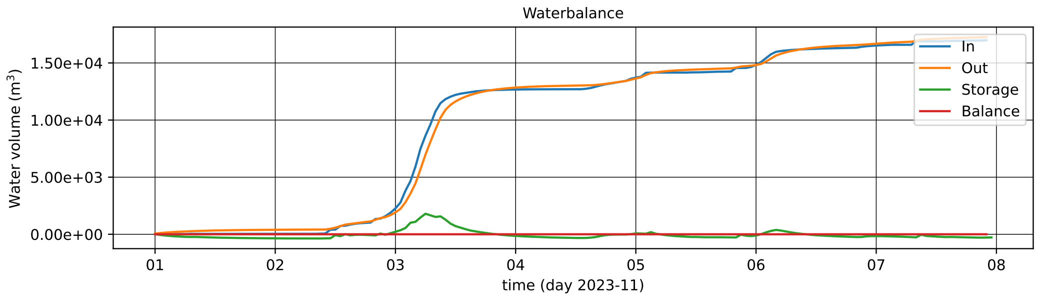


Figure 3.17: Water balance polder section.

3.4. Polder threshold exceedance

In order to assess the performance of the model predictive controller that will be introduced in the next section water level thresholds are set. Figure 3.18 shows the number of threshold exceedances in 2023 under the assumption that polder sections fail when the water level get above a threshold and the water levels in the reservoirs get below a threshold. The threshold for the polder sections is chosen at 10 cm below ground level and the threshold for the reservoirs is set to 20 cm below the reference level of the reservoirs. The graph shows that all reservoirs fail in March and June when the water in the reservoirs is used for irrigation and no rain events occur. In autumn three 'threshold exceedances' take place due the irrigation. The polder sections exceed the threshold criteria in four rainfall events.

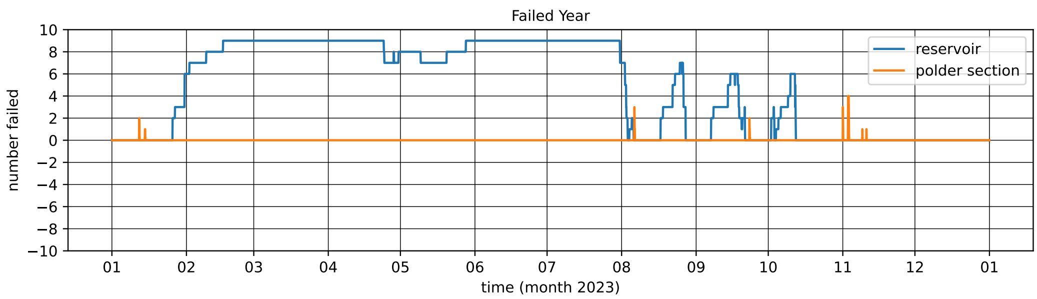


Figure 3.18: Threshold exceedance.

3.5. Model Predictive Controller

Valves in the reservoirs are used to regulate the reservoir water levels and the polder section water levels. Valve settings determine the water discharge from the reservoirs to the polder sections. The controller proposes hourly based valve settings for a period of 24 hours and uses a weather forecast over the same period. Valves can be either fully opened or fully closed. Figure 3.19 illustrates a valve setting sequence over 24 hours, 1 indicates an open valve and 0 represents a closed valve.

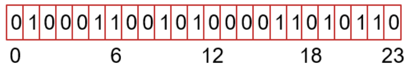


Figure 3.19: Valve settings.

The Model Predictive Controller selects the optimal valve settings out of a set 100 realizations. The forecast horizon is set to 24 hours, the control time step is one hour and the internal model time step is set to one minute. The generation of random valve settings is performed by a multi-step random generator. First a floating point number is generated between zero and one that determines the time over which the valve is opened in the period of 24 hours. This generator draws from a continuous uniform distribution and generates the probability that a valve should be open in a given control time step. In the next step the hours during which the valve is opened is randomly chosen given the probability that was generated in the first step. The following code explains this procedure:

```
rng = np.random.Generator(generatorState)
p = rng.random()
valveSet = rng.choice([0, 1], size=(period, len(polder.poldersectionclassList)),
p=[p, (1.0-p)])
```

The controller generates different valve settings for each polder section. In this way the control strategy remains well executable as the hydraulic behavior of each polder section differs. Different valve settings for each polder section makes the water system more robust than using one valve setting for the whole polder. The water peaks are spread more evenly in the time space for example, if reservoirs in the downstream polder sections open their valve earlier than the reservoirs in the upstream polder sections.

The predicted water levels for the optimal settings are compared with measured water levels when they become available after some time. The controller uses these measurements to update the model in a feedback loop.

Objective function

The control strategy aims to keep the reservoir water level ζ_r close to the reference water level $\zeta_\mathrm{r,ref}$ and to keep the polder section water level ζ_p close to the reference polder section water level $\zeta_\mathrm{p,ref}$. In order to measure the effect of a proposed valve setting over 24 hours an objective function is considered, which gathers penalty points in a cost function. A cost function $l()$ (Van Nooijen et al., 2021) evaluates the difference of the modeled value with the reference in the reservoir and in the polder for each time step t_k using positive weights for the reservoirs w_r and the polder w_p:

$$l(t_k, \zeta_\mathrm{r}(t_k), \zeta_\mathrm{p}(t_k)) = w_\mathrm{r} \min\left[0, \left(\zeta_\mathrm{r}(t_k) - \zeta_\mathrm{r,ref}\right)\right]^2 + w_\mathrm{p} \max\left[0, \left(\zeta_\mathrm{p}(t_k) - \zeta_\mathrm{p,ref}\right)\right]^2 \tag{3.24}$$

No penalty points are given if the reservoir level is higher than its reference level as this poses no problem to the reservoir. For the case in which the polder section level is lower than its reference level no penalties are given either as the strategy is not designed to increase the polder water level during dry periods. Under the restriction of Equation 3.24 only polder water levels above the reference level and reservoir levels below the reference level contribute to the cost function.

The objective function J is given by the sum of the individual cost functions for the control time steps up to the time horizon N_{hor} of 24 hours:

$$J(t_{\mathrm{n}}, \zeta_{\mathrm{r}}(t_k), \zeta_{\mathrm{p}}(t_k)) = \sum_{k=0}^{N_{\mathrm{hor}}-1} \left(l(t_k, \zeta_{\mathrm{r}}(t_k), \zeta_{\mathrm{p}}(t_k)) \right) \tag{3.25}$$

The reference level for each polder section corresponds to its target level according to the water board (peilbesluit). From water management perspectives a lower polder target level introduces extra storage in the polder that can reduce the effect of heavy rainfall. The target water level of the reservoirs are set five centimeters below their spill height. This separates valve flow events from spill flow events; the reservoirs do not contribute to the cost function if their water level is above the target level. A reservoir water level at reference height guaranties sufficient water for irrigation.

Figure 3.20 shows how the optimization strategy works. In this example three different valve settings are tested over a period of 24 hours: sim 1, sim 2 and sim 3. Zero values indicate a closed valve and one's represent a fully opened valve. All valve settings are tested in the model and provide a penalty score. The optimal valve setting is found for the lowest value of the objective function.

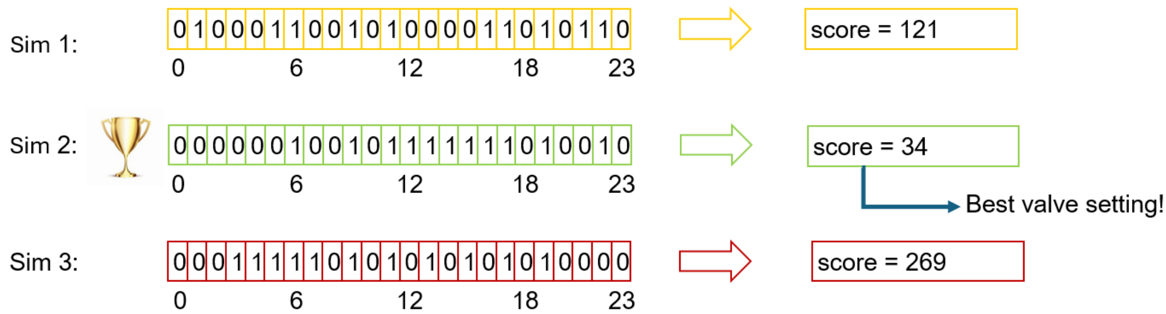


Figure 3.20: Monte Carlo simulations with valve settings.

The algorithm used to approximate the optimal control settings is shown in Figure 3.21.

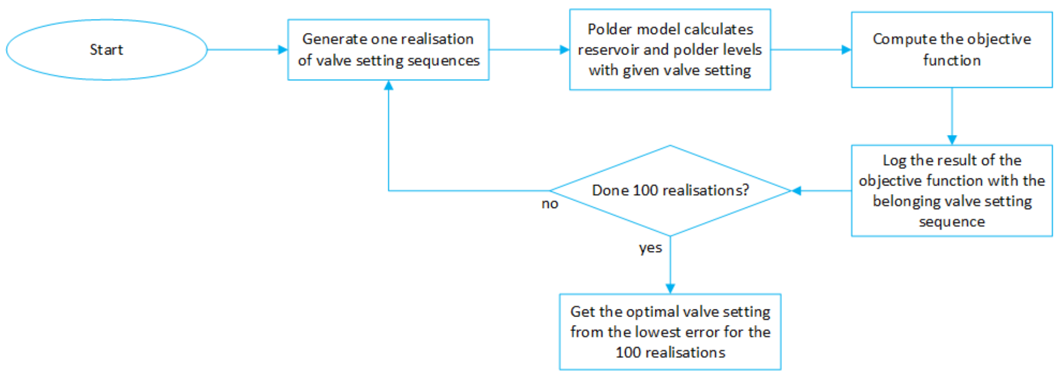


Figure 3.21: Flowchart of the Model Predictive Control.

In the case of Delfland, weather predictions are given for a period of 24 hours and updated every six hours. The valve setting generation follows the same pattern, as illustrated in Figure 3.22.

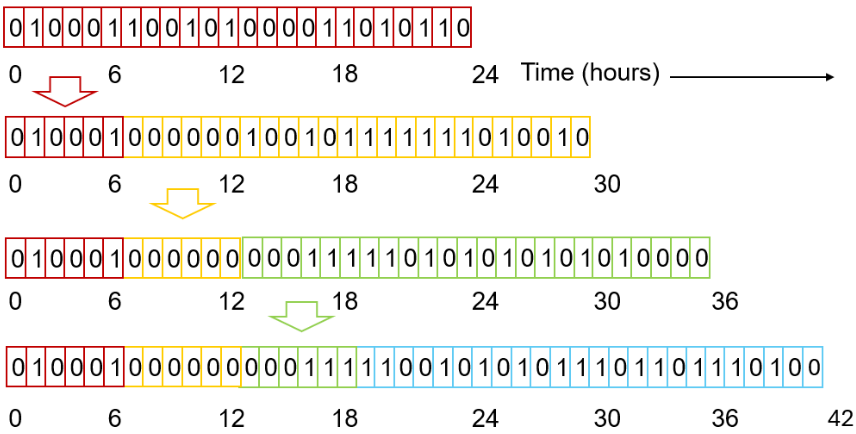


Figure 3.22: Valve settings update in time.

After six hours, the valve settings are recalculated based on the updated weather prediction. The previously determined settings are overwritten with the new calculated settings.

Feedback loop

Based on the weather forecast and the selected valve settings, a prediction of the reservoir water levels and the polder section water levels is made. Since this prediction may differ from the actual measurement data, measurements can be used to correct the prediction when they become available. The controller implements this by updating the predicted water levels at the end of an feedback window. This enables the controller to construct a better valve setting for the prediction that follows. The shorter the feedback window the better the predictions will be.

Figure 3.23 illustrates how this feedback loop works. In Figure 3.23a a predicted and a measured rainfall signal is shown. The measured (actual) rainfall as input for the numerical model which then generates water levels that are used in the feedback loop on a daily basis. In Figure 3.23b and Figure 3.23c the reservoir water level and the polder section water level are shown. A correction of the predicted water level takes place at the start of each day.

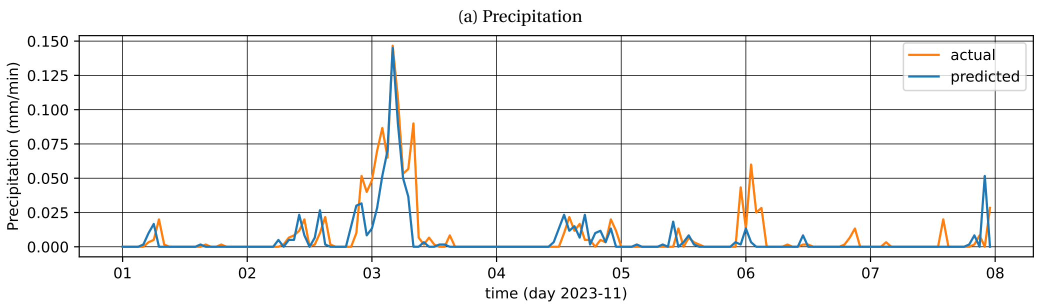


Figure 3.23: Feedback loop polder.

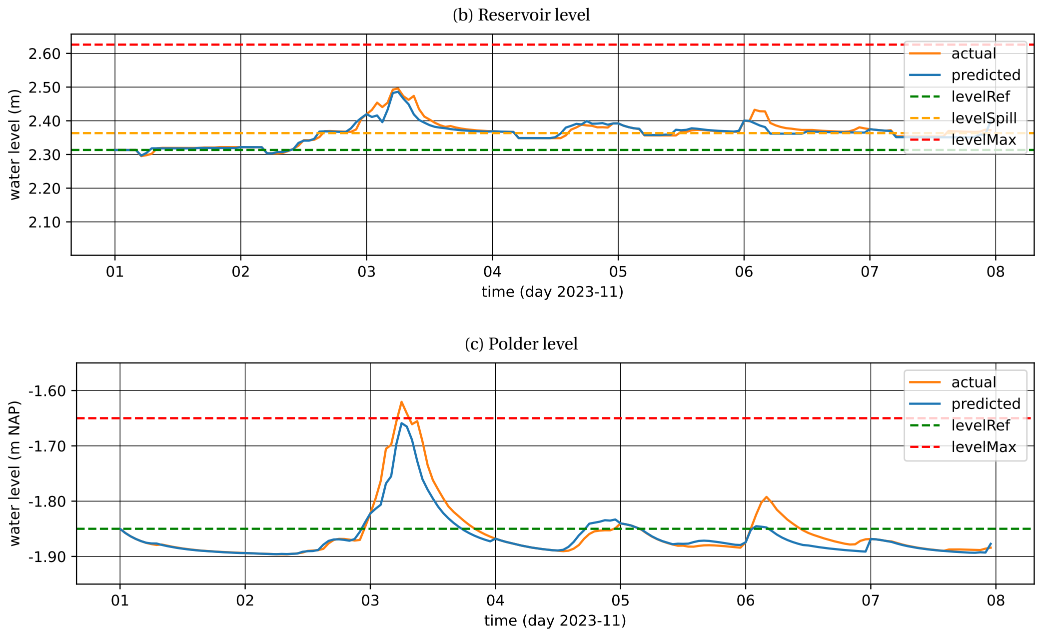


Figure 3.23: Feedback loop polder.

3.6. Implementation

The Python model POKKA (POlder Klep KAs) is constructed to simulate the polder system and to control the valve settings. The code contains the following Python classes: Weather class, Reservoir class, Polder section class, Culvert class, Weir class, Pumping station class, Polder class and Controller class.

The weather class gathers KNMI data (precipitation, temperature, humidity, wind speed, radiation) over the simulation period and computes evaporation. In a function the irrigation schedule is setup.

The reservoir class contains reservoir properties like reservoir height, reservoir area, valve diameter, valve height, spill width and spill height. It also includes the actual water level that is updated every time step.

The polder section class contains geometric properties of the section and a dynamic water level that is updated every time step. The polder area is split into a paved area, an unpaved area and a ditch area. The class is linked to the reservoir objects that are present in the polder section. The class includes a connection to weirs and culverts with a reference to the downstream polder sections. Polder section objects that are derived from this class can be connected to a pumping station.

The culvert class contains the culvert width, the ditch width and the loss coefficient.

The weir class members are width and height. The class also supports automatic weirs with the members minimum weir height, maximum weir height and their actual height per time step. For the simulations presented in this thesis only static weirs are considered.

The pumping station class collects the number of pumps in a station and their minimum and maximum pumping capacity. The class also contains the water level at which the pumps are switched on and switched off.

A polder object collects all reservoir, polder section, culvert, weir and pumping station objects that are present in the polder. The polder class also contains methods that capture the reservoir model and the polder section models and links them together.

The controller class generates random valve settings and calculates the cost functions of different valve settings in a parallel way by calling the polder class method. The class keeps track of valve setting for a set of best score settings.

The main part of the program iterates over days in the simulation interval. Within this iteration an inner iteration takes place over the update interval. For each update interval a calculation is made over a forecast horizon of one day. The control time step is one hour and the internal model time step is set to one minute. The controller calls a method of the polder object. This calculation provides the predicted water levels in the polder sections and the reservoirs. Next a method of the polder object is called with the optimal valve settings and the measured weather data in order to compute the artificially generated measured water levels. These water levels are used at the end of a feedback interval. If for example a period of four weeks needs to be calculated then the outer iteration is performed over 28 days. With an update interval of 6 hours, the inner iteration contains four steps per day. Within the inner iteration the start time is set to 0:00, 6:00, 12:00 and 18:00 respectively. At the end of the day, the inner iteration is set on the same start time a day later. For a feedback time of 12 hours the predicted water levels are replaced by the measured water levels twice in the inner iteration loop. The simulation structure of the whole system is given in Figure 3.24.

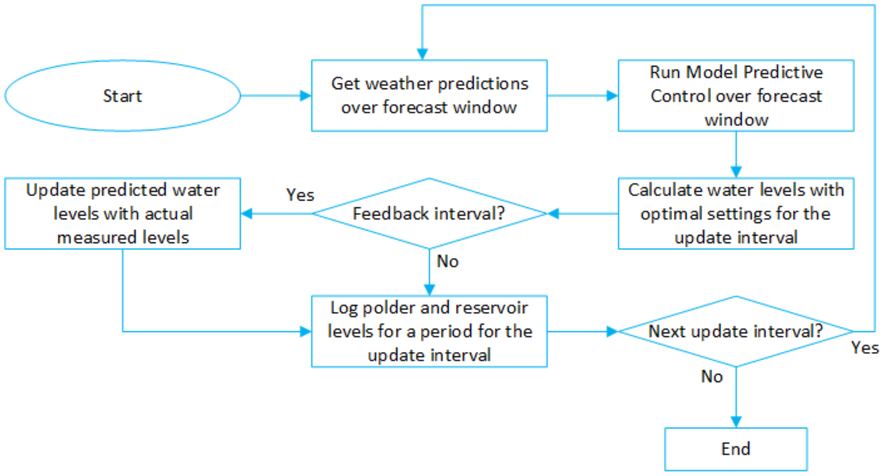


Figure 3.24: Flowchart of the total system.

Appendix B gives an example of the input files that will be used for the model calculation that will be outlined in the next chapter.

4

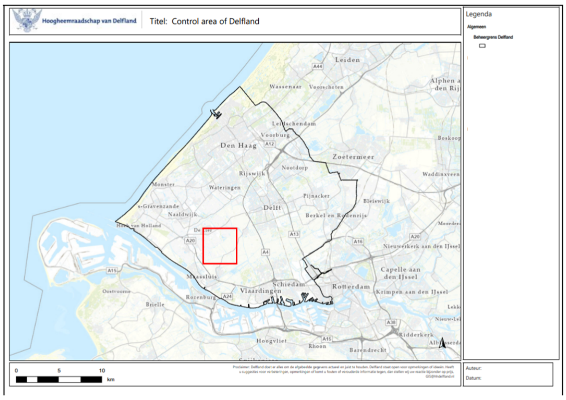
Kralingerpolder

In this chapter the case study, Kralingerpolder, is presented. The Kralingerpolder is selected for its known water issues during heavy rain events. First an overview of the Kralingerpolder will be given in Section 4.1. In order to get insight in the hydraulic behavior of the polder a simulation is performed with the newly developed model without control in Section 4.2. This section presents the outcome for a single polder section and a single reservoir. Appendix C includes the outcome for all reservoirs and polder sections over a year and Appendix D contains these results for a single month.

4.1. Polder layout

In Figure 4.1a the boundaries of the territory of Delfland are given. In red lines the location of the Kralingerpolder is indicated. The Kralingerpolder lies to the south of the village of de Lier and to the southwest of Delft.

In Figure 4.1b an aerial map that zooms in on the Kralingerpolder is given. The boundary is given in red. The northern section primarily consists of greenhouses, while the southern area is dominated by pasture fields. Water can enter the polder via a waterway called the Lee in the north and leave the polder via the water retention area Kraaiennest in the east or to the boezem (de Gaag) in the south.



(a) Control area of Delfland with the Kralingerpolder in red box

(b) Kralingerpolder outlined

Figure 4.1: Location of the Kralingerpolder (both taken over from Hoogheemraadschap van Delfland (2024)).

The polder is divided into multiple polder sections. Each polder section has its own reference water level. In this case study only the polder section are considered where Rainlevelr participants are present. For short the polder section codes GPG2013KRN1, GPG2015KRZ1, GPG2015KRZ4 and GPG2015KRZ5 used by the waterboard will be abbreviated as KRN 1, KRZ 1, KRZ 4 and KRZ 5. The left part and the right part of polder section

KRN 1 are connected with a waterway. For this reason the polder section will be split in two separate polder sections: KRN 1 Left and KRN 1 Right in this research. In Figure 4.2 the different polder sections are outlined. By considering only these sections about half of the total polder area size is used in this thesis.

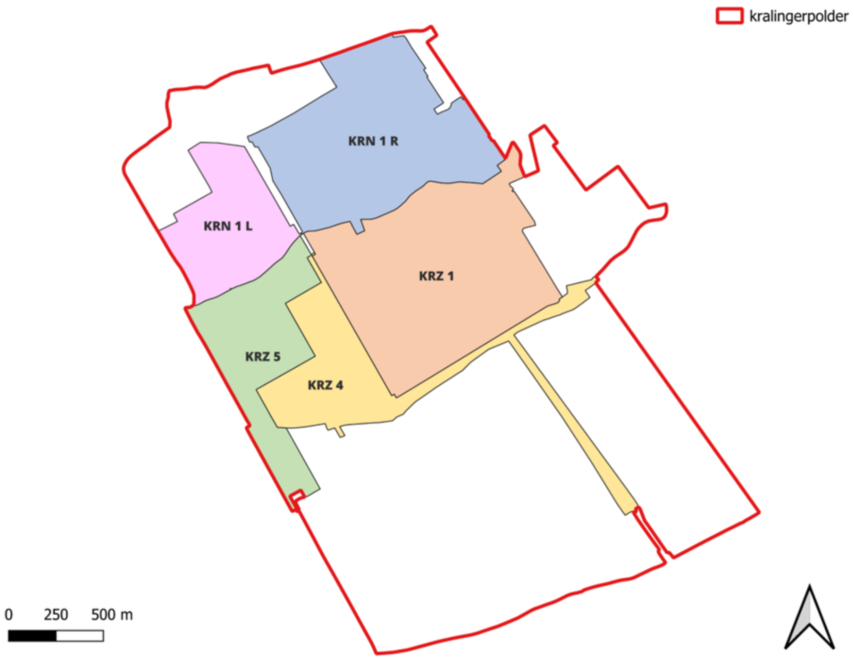


Figure 4.2: Name of polder sections in the Kralingerpolder (Adapted from Hoogheemraadschap van Delfland (2024)).

In Table 4.1 the water levels for each polder section are given. The reference level and the maximum level are set by the Waterboard of Delfland.

Table 4.1: Water levels in the polder sections (Hoogheemraadschap van Delfland, 2024) (Van der Kruijs et al., 2012).

Name	Reference level (m NAP)	Maximum level (m NAP)
KRN1 left	-1.85	-1.65
KRN1 right	-1.85	-1.65
KRZ1	-2.35	-2.02
KRZ5	-2.20	-2.03
KRZ4	-2.60	-2.27

Land use

A land use map is used to determine the areas with distinct hydraulic properties, five categories are identified: greenhouses, reservoirs, ditches, paved area and unpaved area. Reservoirs and ditches are modeled as buckets, the remaining areas are characterized by run-off coefficients.

In Figure 4.3 the land use of the considered part of the Kralingerpolder in 2019 is given (Geofabrik, 2024). In the village de Lier in the north there is more paved area. The ditch area in the polder is small compared to the large extend of greenhouses.

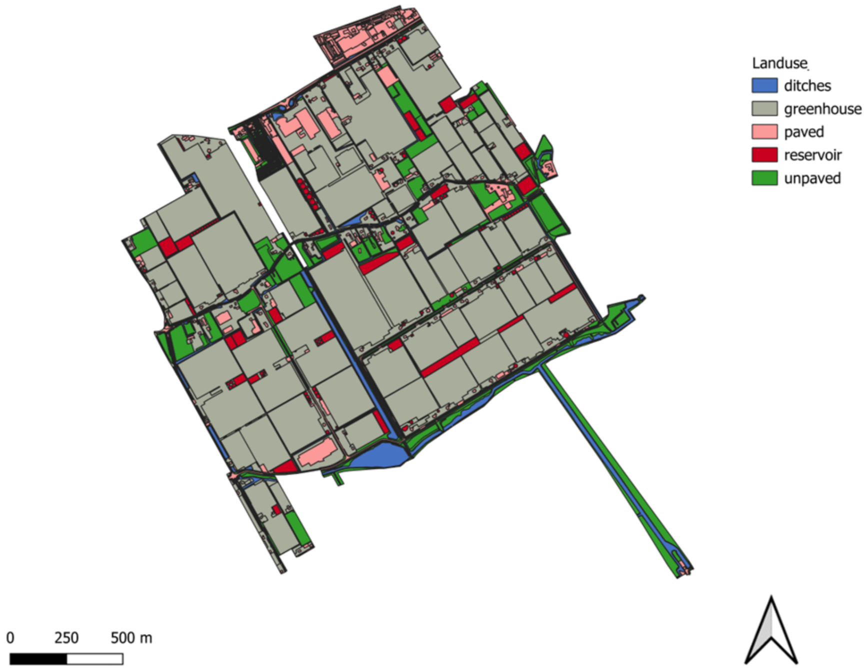


Figure 4.3: Land use in the Kralingerpolder (Adapted taken over from Geofabrik (2024)).

In Table 4.2 the areas of the different types of land use are summarized per polder section. About 70 % of the considered polder sections are covered by greenhouses, 6 % of the area consists of ditches.

Table 4.2: Land use in the Kralingerpolder per polder section (Geofabrik, 2024) (Hoogheemraadschap van Delfland, 2024).

Polder sections (m^2)	Ditch (m^2)	Greenhouse (m^2)	Paved (m^2)	Reservoir (m^2)	Unpaved (m^2)	Total (m^2)	Total (%)
KRN1 left	8,117	304,275	8,677	11,259	24,573	356,901	12.1
KRN1 right	31,626	517,913	140,243	21,341	77,022	788,146	26.8
KRZ 1	26,023	708,759	48,668	43,863	109,359	936,673	31.8
KRZ 5	17,733	277,190	24,992	12,761	72,925	405,600	13.8
KRZ 4	79,431	221,429	27,950	10,716	118,350	457,830	15.5
Total [m^2]	162,929	2,029,567	250,531	99,893	402,229	2,945,149	
Total [%]	5.5	68.9	8.5	3.4	13.7		100.0

Reservoirs

In Figure 4.4 the Rainlevelr participants are indicated in the polder by green stars. There are nine operational Rainlevelr participants in total.

Figure 4.4: Overview operational participants of Rainlevelr (Adapted from Hoogheemraadschap van Delfland (2024))

In Table 4.3 maximum volumes and areas of the reservoirs are summarized per polder section. A distinction is made between Rainlevelr participants and non-Rainlevelr participants. Both types of reservoirs can spill. Rainlevelr participants can also control the reservoirs with valve settings. The effect of spilling does influence the water level of the polder sections. The participants are indicated by their names. The maximum volumes and areas are gathered from Hoogheemraadschap van Delfland (2024).

The non-Rainlevelr participants are characterized by the name 'other' together with the polder section in which they are located. The greenhouses that do not participate in the Rainlevelr initiative are assembled as one greenhouse with a representative reservoir per polder section. The areas of the assembled reservoirs follow from land use information presented by Geofabrik (2024) in Table 4.2 and the sum of the areas of the participating reservoirs given by Hoogheemraadschap van Delfland (2024) in Table 4.3. For polder section KRZ 4 the assembled non-Rainlevelr participant has no greenhouse area or plot area because of the mismatch in sources Hoogheemraadschap van Delfland (2024) and Geofabrik (2024).

As the maximum reservoir volume of the non-participants is unknown an estimation has to be made. For participants the reservoir volume is three times the reservoir area on the average. For otherKRN1 left and otherKRZ5 this proportion is chosen. OtherKRZ4 has no greenhouse area, for this reason the height of this reservoir is set to the arbitrary value of one meter (in the calculation only rain that falls directly into the reservoir is considered). The greenhouse areas of both otherKRZ 1 and otherKRZ5 are relatively big compared to the greenhouse areas of the other reservoirs. So, the reservoir volume for otherKRN1 right is set to four times the reservoir area. For otherKRZ 5 the proportion between volume and area is set to 3.5.

Table 4.3: Dimensions of the reservoirs in the Kralingerpolder (Hoogheemraadschap van Delfland, 2024) (Geofabrik, 2024).

Name	Polder section	Reservoir volume (m^3)	Reservoir area (m^2)	Greenhouse area (m^2)	Plot area (m^2)
Kwekerij Bergcamp	KRN1 left	9,900	3,770	68,000	68,000
van Dijk Flowers		7,600	3,050	35,500	35,500
otherKRN1 left		13,317	4,439	200,775	200,775
Rijk Zwaan	KRN1 right	10,000	5,700	50,000	50,000
otherKRN1 right		62,564	15,641	467,913	467,913
Greenvalley	KRZ1	8,000	3,000	120,000	120,000
Ammerlaan Growers		6,000	1,500	51,000	51,000
SVco Kreekrug		4,000	1,600	33,500	33,500
otherKRZ1		132,171	37,763	504,259	504,259
Lans Scheeweg	KRZ4	20,000	5,660	125,000	125,000
U Grand		8,000	2,500	103,000	103,000
otherKRZ4		2,510	2,510	0	0
Lans Burgerweg	KRZ5	20,000	5,660	128,550	128,550
otherKRZ5		15,030	5,010	148,640	148,640

In Table 4.4 the reservoir properties are given. The maximum water level corresponds to the volume divided by the reservoir area as given in Table 4.3. Given that the water level should not exceed the maximum water level. The height of the spill is set to 90 % of the maximum height. The reference water level is five centimeters below the spill height. The valve height is set to 50 % of the maximum height (de Vette and Berkhout, 2020).

Table 4.4: Reservoir properties with respect to the bottom of the reservoirs (Hoogheemraadschap van Delfland, 2024) (Geofabrik, 2024).

Name	Maximum level (m)	Spill height (m)	Reference level (m)	Valve height (m)
Kwekerij Bergcamp	2.63	2.36	2.31	1.31
Van Dijk Flowers	2.49	2.24	2.19	1.25
otherKRN1 left	3.00	2.70	2.65	-
Rijk Zwaan	1.75	1.58	1.53	0.88
otherKRN1 right	4.00	3.60	3.55	-
Greenvalley	2.67	2.40	2.35	1.33
Ammerlaan Growers	4.00	3.60	3.55	2.00
Svco Kreekrug	2.50	2.25	2.20	1.25
otherKRZ 1	3.50	3.15	3.10	-
Lans Scheeweg	3.53	3.18	3.13	1.77
U Grand	3.20	2.88	2.83	1.6
otherKRZ 4	1.00	0.90	0.85	-
Lans Burgerweg	3.53	3.18	3.13	1.77
otherKRZ 5	3.00	2.70	2.65	-

In Table 4.5 the valve dimensions of the Rainlevelr reservoirs are given. The larger reservoirs such as Greenvalley and U Grand have larger valve diameters and higher maximum valve discharges than smaller reservoirs. Kwekerij Bergcamp is limited in its maximum valve setting and maximum valve discharge. These limitations are set to ensure that the ditch where both Kwekerij Bergcamp and van Dijk Flowers is not flooded. The ditch is shown in Figure 4.5.

Table 4.5: Dimensions of the valve in Rainlevelr reservoirs (Hoogheemraadschap van Delfland, 2024).

Name	Valve diameter (m)	Max valve opening (%)	Max flow (m^3/hour)
Kwekerij Bergcamp	0.16	40	22
Van Dijk Flowers	0.16	100	-
Rijk Zwaan	0.16	100	180
Greenvalley	0.20	100	432
Ammerlaan Growers	0.20	100	468
Svco Kreekrug	0.16	100	252
Lans Scheeweg	0.20	100	468
U Grand	0.25	100	684
Lans Burgerweg	0.20	80	270

Figure 4.5: Ditch next to Kwekerij Bergcamp and van Dijk Flowers (Adapted from Picture: Sabine van Esch).

Hydraulic structures

The polder sections are connected to each other via structures like weirs and culverts. These structures regulate water levels but also introduce delays of water flow in the system. Pumping stations transport the water out of the polder.

In Figure 4.6 the structures are indicated by dots at the edges of the polder sections. In the Kralingerpolder there are nine weirs, one culvert and one pumping station. Polder sections KRN 1 left and KRN 1 right are connected with an open culvert.

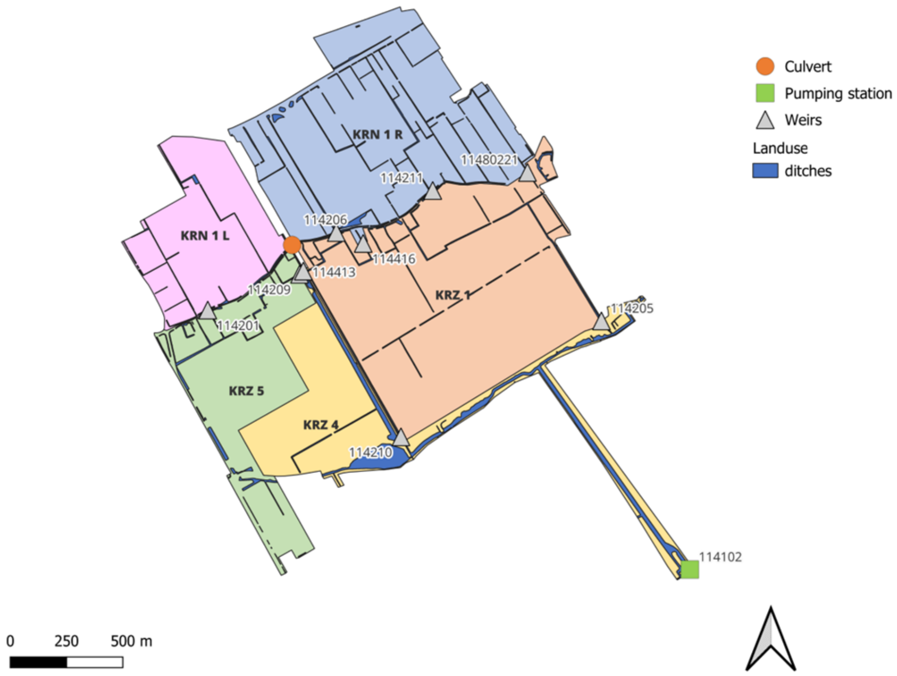


Figure 4.6: Structures in the Kralingerpolder (Adapted from Hoogheemraadschap van Delfland (2024)).

In Table 4.6 the weir dimensions in the system are given. Three types of weirs can be found in the system: fixed weirs, manually controlled weirs and automatically controlled weirs. The height of controllable weirs can be changed over time, by this the polder system can hold more water during droughts and release more water during flood events. An example of an automatically controlled weir is shown in Figure 4.7.

Table 4.6: Dimensions of the weirs (Hoogheemraadschap van Delfland, 2024).

Code	Weir width (m)	Max height (m NAP)	Min height (m NAP)	Regulation height (m NAP)
114201	1.00	-1.63	-2.34	-1.90
114205	1.00	-1.47	-2.47	-2.40
114206	1.00	-1.28	-2.23	-1.90
114209	1.50	-2.00	-2.60	-2.25
114210	2.00	-2.10	-3.00	-2.40
114211	0.60	-1.59	-2.28	-1.90
114413	0.50	-2.30	-2.30	-2.30
114416	4.00	-1.86	-1.86	-1.86
11480221	1.04	-1.31	-2.19	-1.82

Weirs 114413 and 114416 are fixed, weir 11480221 is manually controlled and the remaining weirs are automatically controllable. However, in the model it is assumed all weirs are fixed in height. For the controllable weirs the weir height is set to five centimeters below the reference water level of the upstream polder section.

Table 4.7 collects the upstream and downstream water level from Table 4.1 and the regulation height from Table 4.6.

Figure 4.7: Automatic weir 114210 (Picture: Sabine van Esch).

Table 4.7: Free flow over weirs check (Hoogheemraadschap van Delfland, 2024).

Code	Upstream water level (m NAP)	Crest height (m NAP)	Downstream max water level (m NAP)
114206	-1.85	-1.90	-2.02
114211	-1.85	-1.90	-2.02
114416	-1.85	-1.86	-2.02
11480221	-1.85	-1.82	-2.02
114201	-1.85	-1.90	-2.03
114205	-2.35	-2.40	-2.55
114210	-2.35	-2.40	-2.55
114209	-2.20	-2.25	-2.55
114413	-2.20	-2.30	-2.55

With this information free flow conditions can be checked. Free flow (Deltares, 2024a) holds when:

$$\zeta_1 - z_w > \frac{3}{2}(\zeta_2 - z_w) \tag{4.1}$$

where:

ζ_1	Upstream water level	[m NAP]
ζ_2	Downstream water level	[m NAP]
z_w	Crest level	[m NAP]

According to this equation free flow is justified for all weir structures.

The dimensions of the culvert in the system are given in Table 4.8. The loss coefficient is set to one as the entry and exit losses are neglectable because the difference in the culvert width is small compared to the ditch width.

Table 4.8: Dimensions of the culvert (Hoogheemraadschap van Delfland, 2024).

Code	Culvert width (m)	Ditch width (m)	Contraction coefficient (-)
Kralingerpad	3.10	3.85	1.00

Only one pumping station is present in the system namely the 'Gemaal van de Kralingerpolder' (Pumping station of the Kralingerpolder). This pumping station removes water from the polder to the Gaag boezem. The pumping station is located in southern part of the system in polder section KRZ4 (Figure 4.3). In Table 4.9 the dimensions of the pumping station are given. The pumping station has a maximum and minimum discharge per pump. In the model only the maximum discharge is used. The maximum and minimum water level indicate the water level at which the pumping station is turned on or off.

Table 4.9: Dimensions of the pumping station (De Nederlandse Gemalen Stichting, 2024) (Hoogheemraadschap van Delfland, 2024).

Code	Min pump flow (m^3/min)	Max pump flow (m^3/min)	Pump amount (-)	Max level (m NAP)	Min level (m NAP)
114102	63	75	2	-2.55	-2.65

Water storage

In Figure 4.8 water levels are shown for all polder sections as a function of precipitation. The lines that are indicated by 'polder with all reservoirs' account for the situation where all reservoirs are able to store the precipitation during a rain fall event and the water level in the ditches is only raised due to the precipitation on paved and unpaved area. The lines 'polder without reservoirs' correspond to the situation where the reservoirs are completely filled before the rain fall event and the water level in the ditches also rises due to spill flow out of the reservoirs. Finally the lines indicated by 'polder with only Rainlevelr reservoirs' show the increase in ditch water level height if there is sufficient storage in the Rainlevelr reservoirs and non-Rainlevelr reservoirs are spilling.

In this analysis no time delay is considered and the polder sections do not interact. However, the figure gives an indication of the maximum reduction of the polder water level for the case in which all reservoirs have enough storage capacity before a rainfall event (distance between orange and blue line) and for the case in which only Rainlevelr reservoirs have enough capacity (distance between green and blue line).

For a rainfall intensity of 30 mm the ditch water levels increase in polder sections KRN1 left, KRN1 right, KRZ1, KRZ5 and KRZ4 by respectively 94, 72, 87, 49 and 12 cm if the Rainlevelr reservoirs have sufficient storage capacity (green line).

In Figure 4.9 the water levels in the reservoirs are given per polder section as a function of rain fall intensity. The water height results from the product of rainfall and catchment area divided by the reservoir area. Time delay is not considered in this analysis. From the graphs it can be concluded that a rain event of 30 mm result in an increase in reservoir water level of about 0.5 to 1.0 meter.

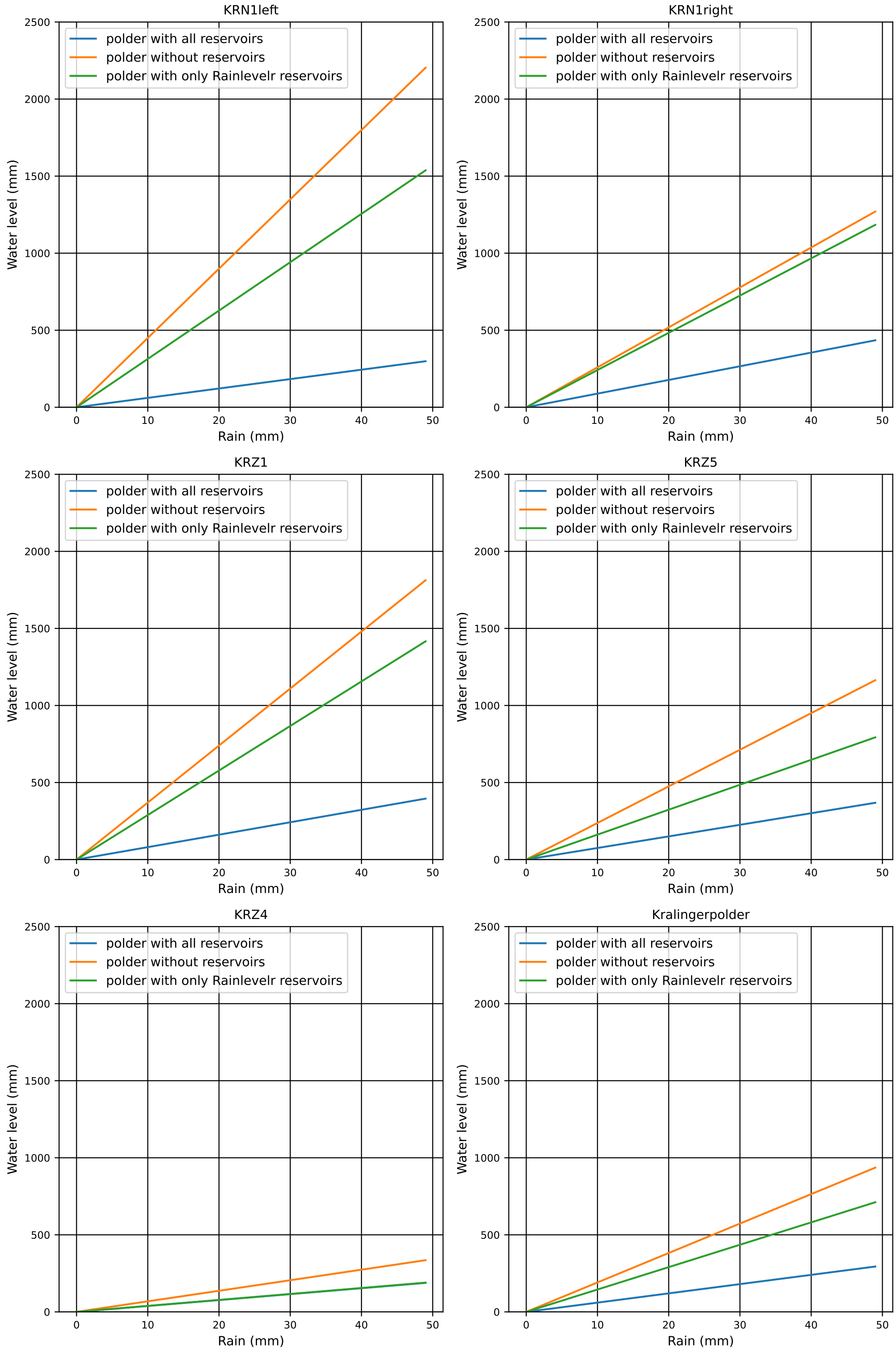


Figure 4.8: Proportions water level and catchment area in polder sections (Geofabrik, 2024) (Hoogheemraadschap van Delfland, 2024).

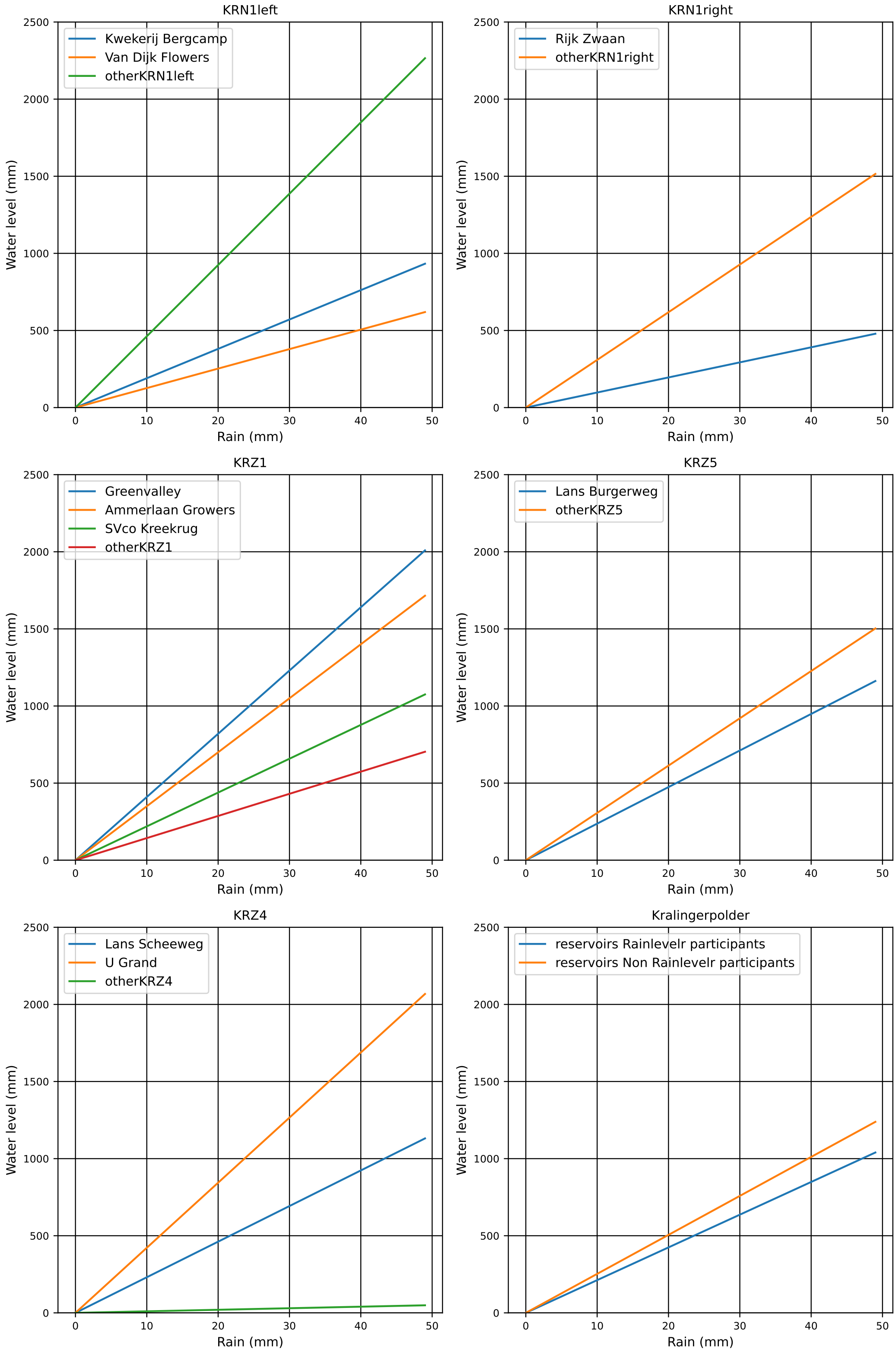


Figure 4.9: Proportions water level and catchment area in reservoirs (Geofabrik, 2024) (Hoogheemraadschap van Delfland, 2024).

4.2. Reference simulation

In this section the hydraulic behavior of the polder will be studied. Figure 4.10 shows the polder system in a schematic way. The polder consists of five polder sections that are connected to each other with nine weirs and one culvert. In polder section KRZ 4 a pumping station is present. The model layout will be used in the next sections to simulate the water levels. In the reference calculation that will be presented in this section all reservoirs operate in the same way, the release of water by Rainlevelr pipes is not considered.

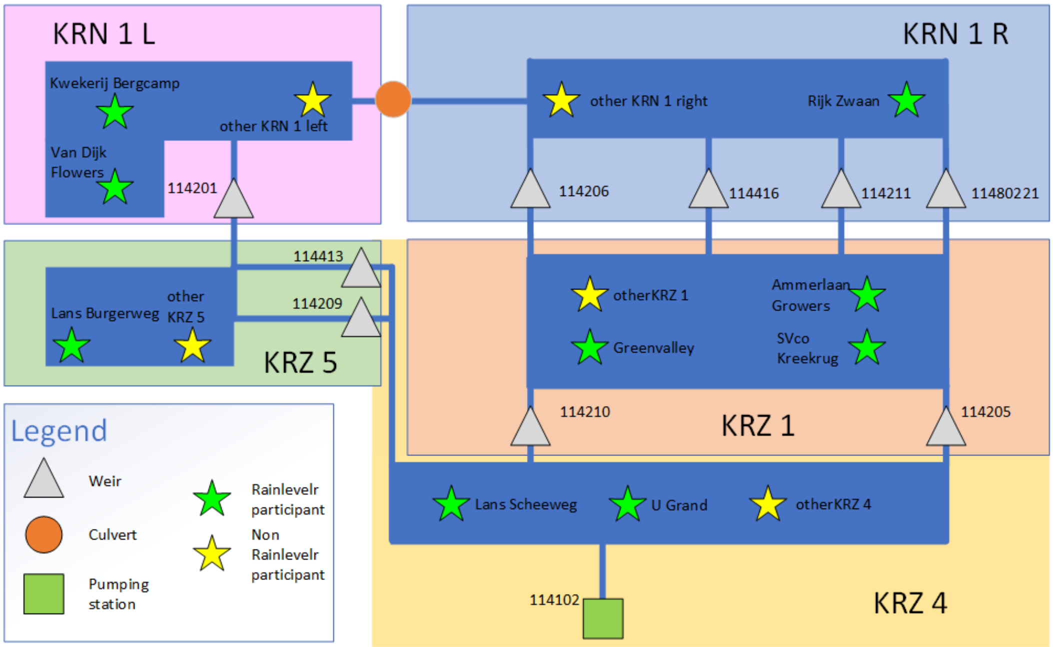


Figure 4.10: Schematisation.

This section presents the outcome of this simulation for reservoir Kwekerij Bergcamp and polder section KRN1 Left. Appendix C includes the outcome for all reservoirs and polder sections over a year and Appendix D contains these results for a single month. Polder section KRN1 Left was selected because this section mainly causes water issues during heavy rain events in the Kralingerpolder. Reservoir Kwekerij Bergcamp is located in Polder section KRN1. The water balance for the polder is given in the last subsection. This part also considers threshold exceedance of the reservoirs and polder sections.

Weather condition

In this subsection the weather condition for the model simulation is given. The year 2023 is selected, because this year is characterized by heavy rainfall in January and November. This year also has a dry period from February till March and from May till July. The effect of evaporation is larger in the months June and July than in the rest of the year.

In Figure 4.11 rain and evaporation are given in millimeters per minute. The rain is derived from the rain gauge Kerkpolder-Zuid. This rain gauge is located about 5 kilometers from the Kralingerpolder. The precipitation is measured every 15 minutes. Evaporation is calculated according to the Penman method. The data needed to calculate evaporation is derived from the Royal Dutch Meteorological Institute (KNMI) at weather station Rotterdam (KNMI, 2024). Evaporation is calculated on a daily basis.

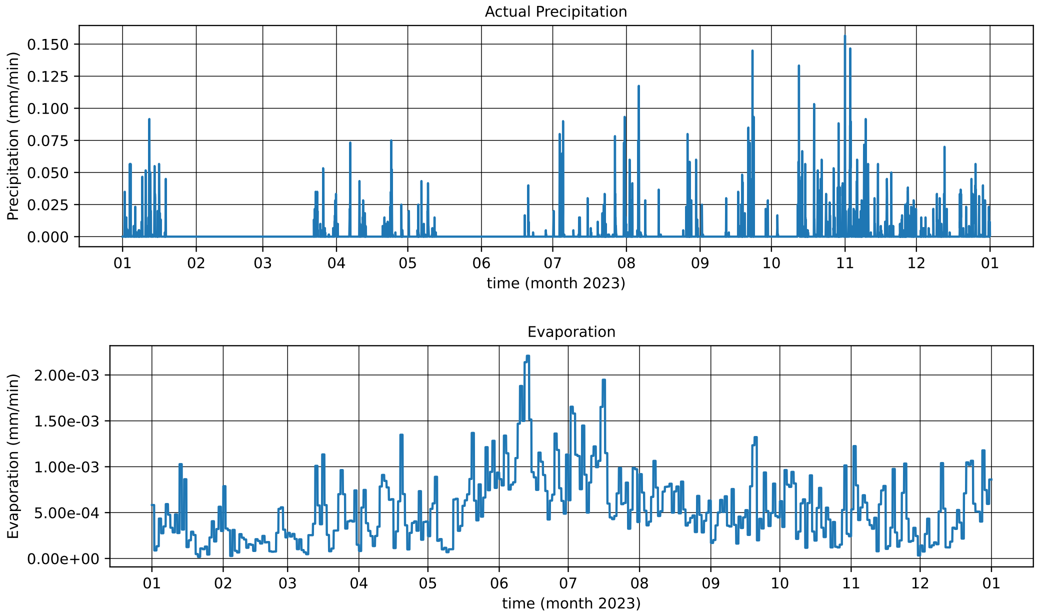


Figure 4.11: Weather data 2023.

To study the effects of heavy rain events in more detail November was selected for an additional computation. In Figure 4.12 the measured precipitation and evaporation calculated for November 2023 is given. In November the evaporation is small due to lower temperatures.

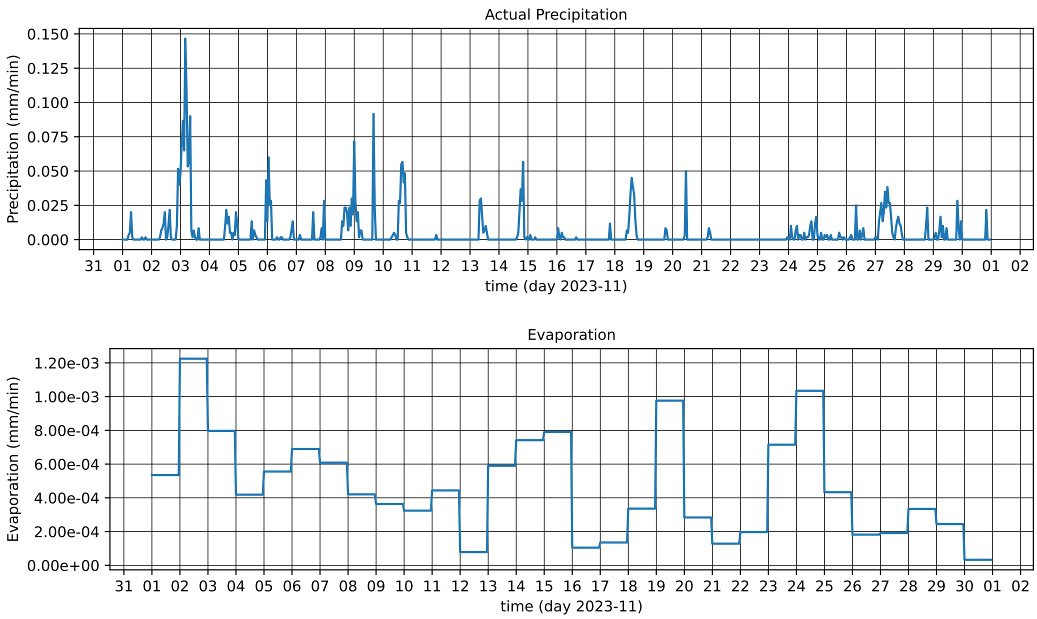


Figure 4.12: Weather data November 2023.

Reservoir response

This subsection presents the results for the evolution of the reservoir water level in time at Kwekerij Bergcamp. Figure 4.13 presents the precipitation over the year 2023, the spill flow of the reservoir, the water level of the reservoir and the water balance. The spill is activated by rain events and the water level exceeds the spill height. A maximum of six cubic meters per minute is leaving the reservoir via the spill. The spill flow is zero if the reservoir water level is lower than the crest of the spill. Irrigation and evaporation lower the water level until mid march. After this period the water level recovers due to precipitation. The rain events in January and in autumn strongly increase the reservoir water level. Storage follows from the water level in the reservoir. The cumulative water balance of the reservoir follows from inflow minus outflow and storage. The water balance remains zero over the year. According to the graph a total amount of 25 thousand cubic meters of water enters and exits the reservoir in a year.

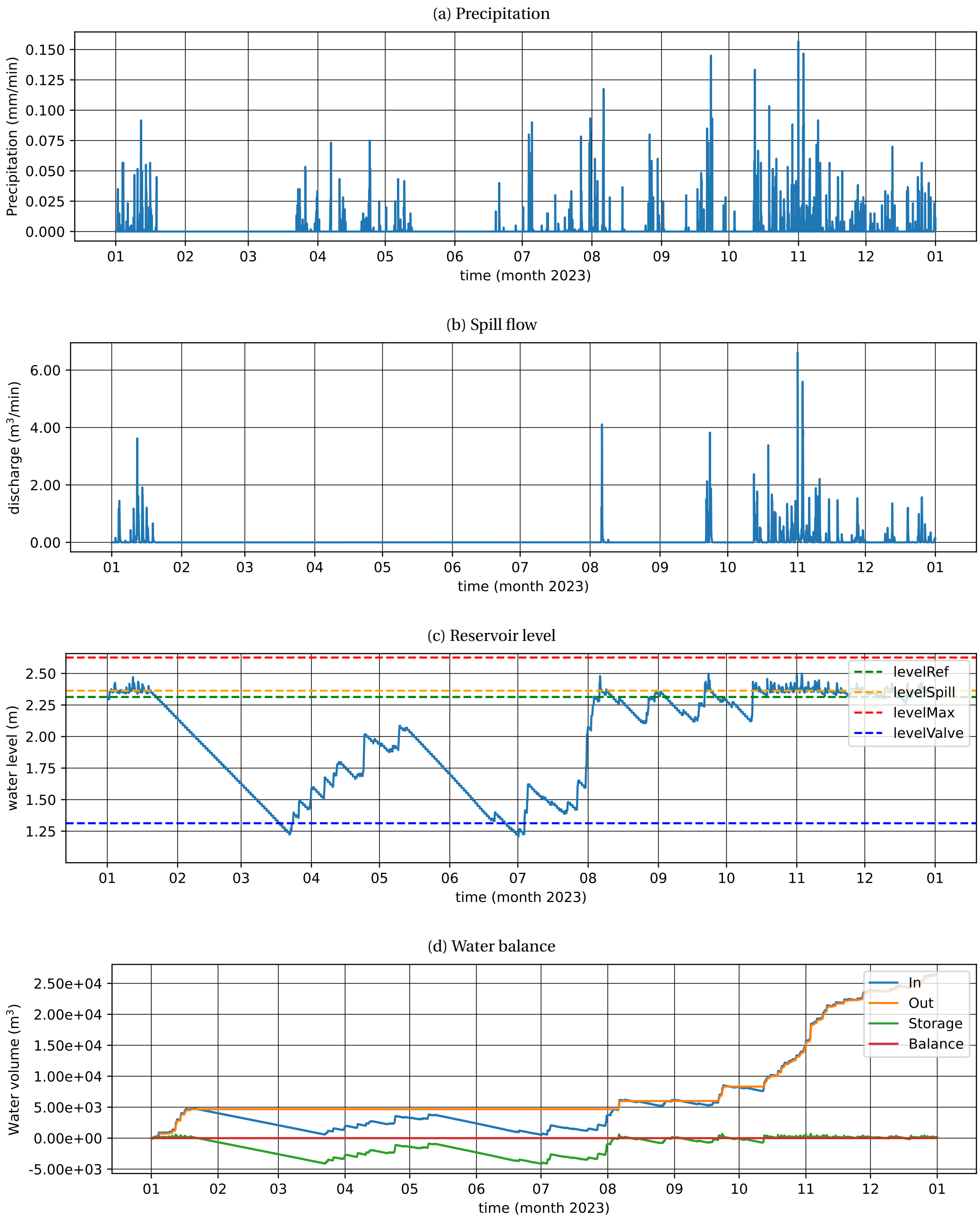


Figure 4.13: Reservoir Kwekerij Bergcamp, 2023 without Rainlevelr.

In Figure 4.14 the outcome of a simulation for the Kwekerij Bergcamp reservoir is depicted in more detail for November 2023. The effect of spill flow on the water level evolution can be observed in more detail on this shorter time frame. The effect of irrigation on the water level is less noticeable but can still be observed. The rain event on the third of November adds around 3000 cubic meters of water to the reservoir.

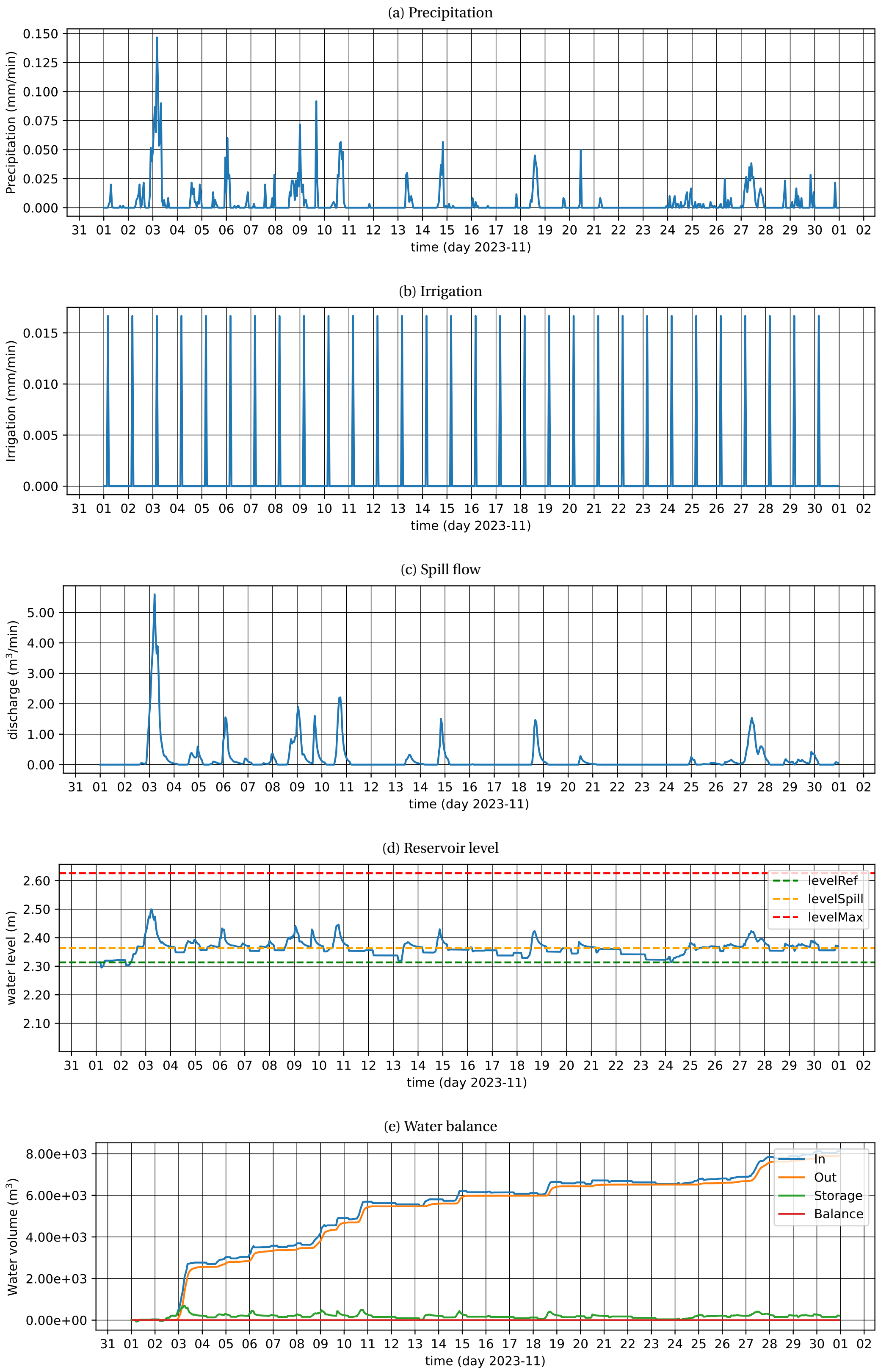


Figure 4.14: Reservoir Kwekerij Bergcamp, November 2023 without Rainlevelr.

Polder section response

In this subsection the water level for polder section KRN1 left is given for the reference simulation.

In Figure 4.15 the graph of the precipitation and the previously calculated spill flow of the Kwekerij Bergcamp reservoir are plotted as this reservoir is located in polder section KRN1 left. Below these graphs the weir flow, the culvert flow and the ditch water level are shown.

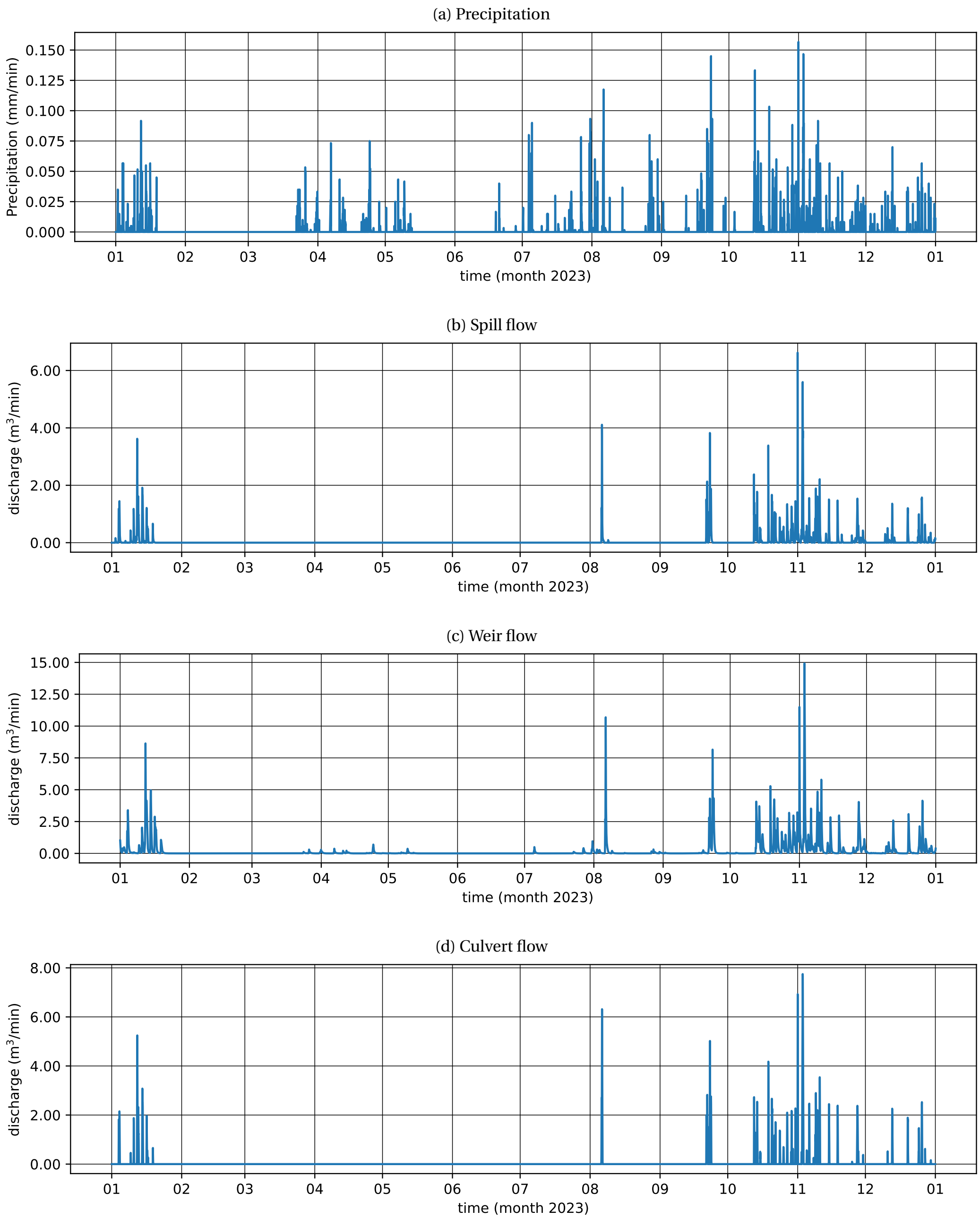


Figure 4.15: KRN1 left, 2023 without Rainlevelr.

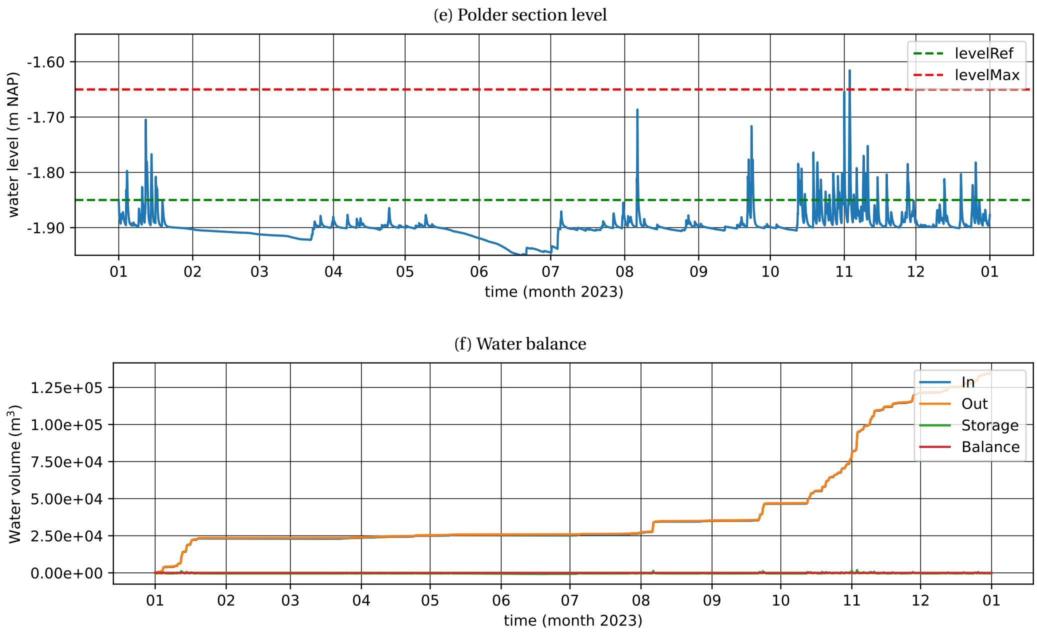


Figure 4.15: KRN1 left, 2023 without Rainlevelr.

The rain events in January and those in autumn increase the polder water level. The weir flow is neglectable in the dry periods when the polder level is lower than the crest of the weir due to evaporation. During this period reservoir water was used for irrigation. Rain events in April have less effect on the polder water level because the reservoirs in this period have a large storage capacity. In autumn rain events have more effect on polder water levels and a maximum of 15 cubic meters per minute is flowing over the weir, out of the polder section. At that moment the culvert flow out of KRN1 left is 8 cubic meters per minute. The maximum values are reached when the polder level is at its maximum as the water difference between the polder section and the crest height drives the outflow. Storage in the system is small as the input and output are about the same. A total amount of 0.15 million cubic meters of water enters and exits the polder section in a year.

Figure 4.16 shows the same model parameters in more detail for November 2023. The heavy rain event on the third of November floods the polder section; the ditch water level gets above the ground level (levelMax). The effect of weir flow and culvert flow on the water level and vice versa can be observed in this figure in more detail. The polder water level lowers exponentially to -1.90 m NAP. This level corresponds to the weir height. The rain event on the third of November adds about 10,000 cubic meters of water to the polder section.

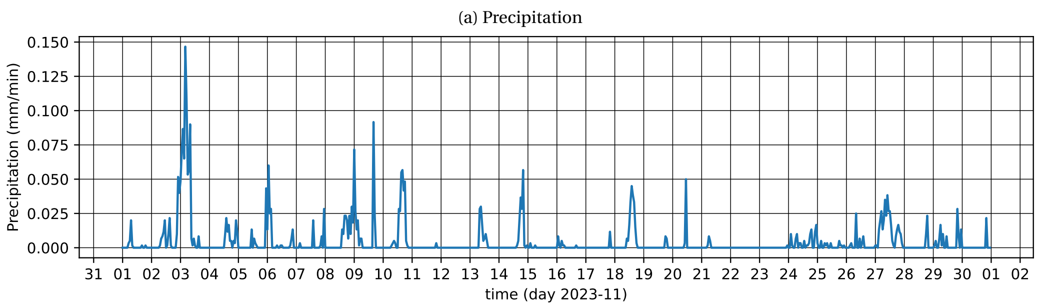


Figure 4.16: KRN1 left, November 2023 without Rainlevelr.

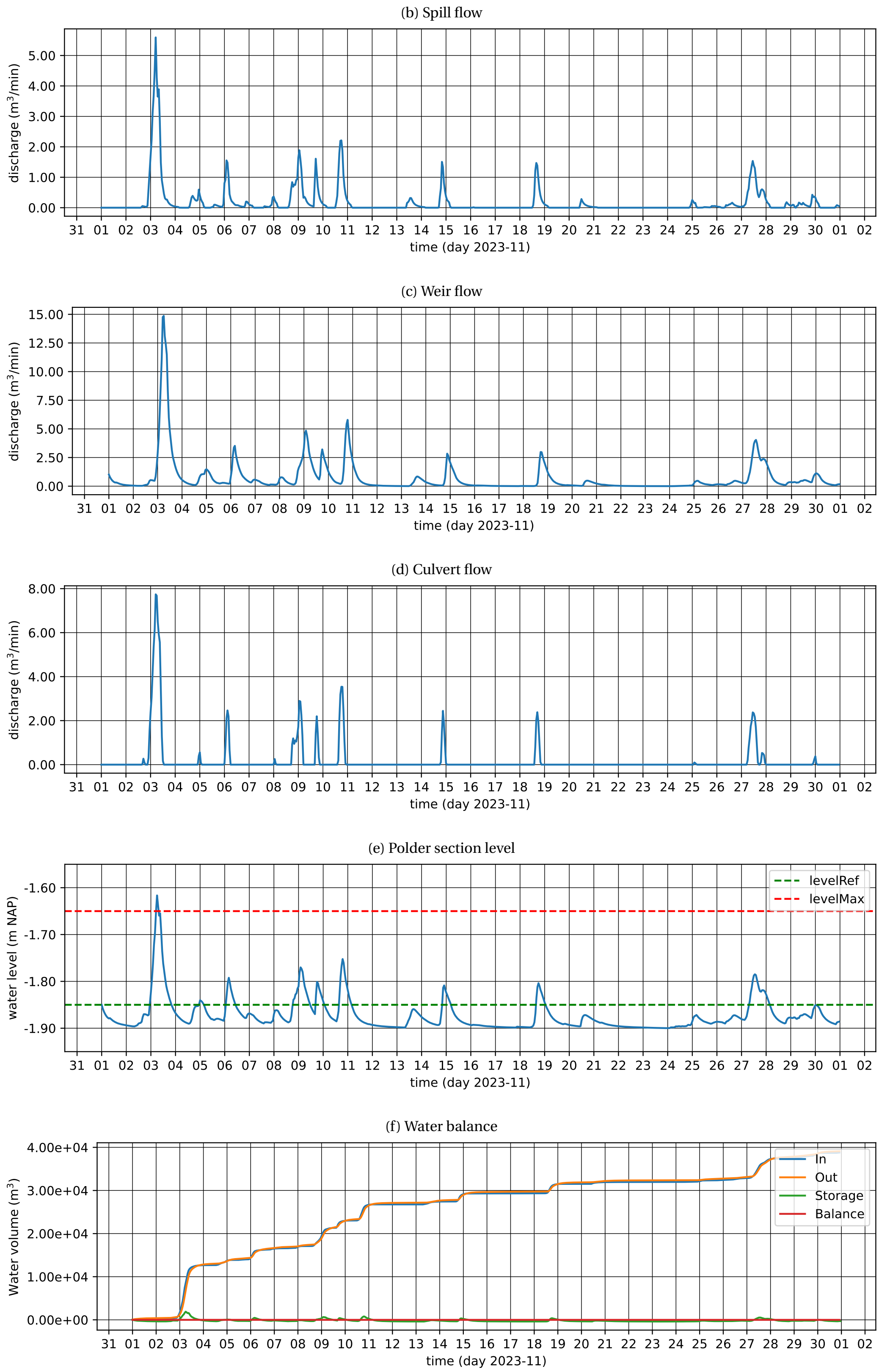


Figure 4.16: KRN1 left, November 2023 without Rainlevelr.

Polder response

In this subsection the hydraulic behavior of the polder as a whole is given. Figure 4.17 collects the reservoir water levels that were already presented in Figure 4.13 and the polder section water levels that were presented in Figure 4.15. Figure 4.17d depicts the number of threshold exceedances in 2023 under the assumption that polder sections fail when the water level get above a threshold and the water levels in the reservoirs get below a threshold. The threshold for the polder sections is chosen at 10 cm below ground level and the threshold for the reservoirs is set to 20 cm below the reference level of the reservoirs. The graph shows that all reservoirs fail in March and June when the water in the reservoirs is used for irrigation and no rain events occur. In autumn three 'threshold exceedances' take place due the irrigation. The polder sections exceed the threshold criteria in four rainfall events.

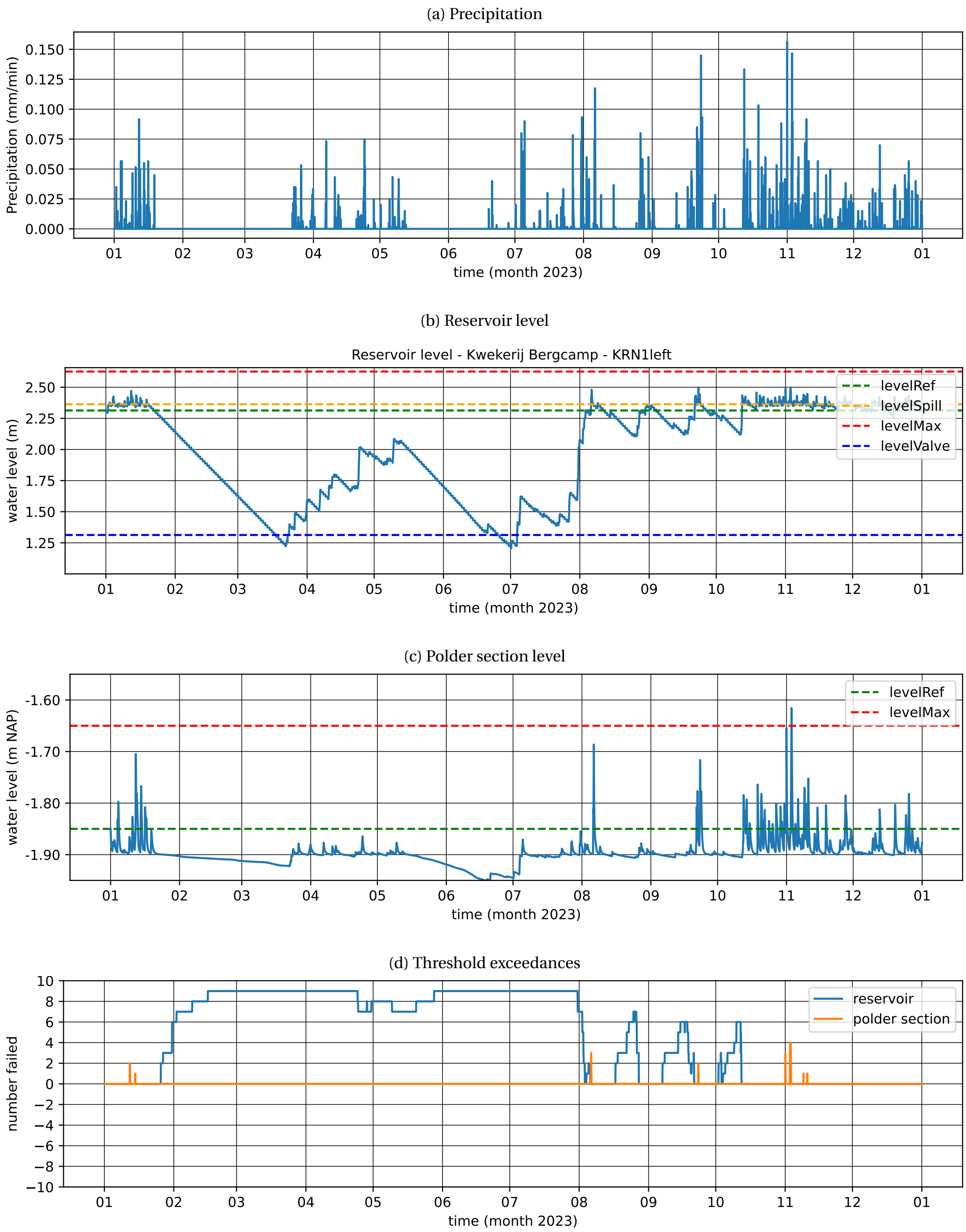


Figure 4.17: Threshold exceedance in Kralingerpolder 2023 without Rainlevelr.

In Figure 4.18 the water balance is given. The storage is small compared to the cumulative inflow and outflow. In total about 1.2 million cubic meters of water enters and exits the polder per year.

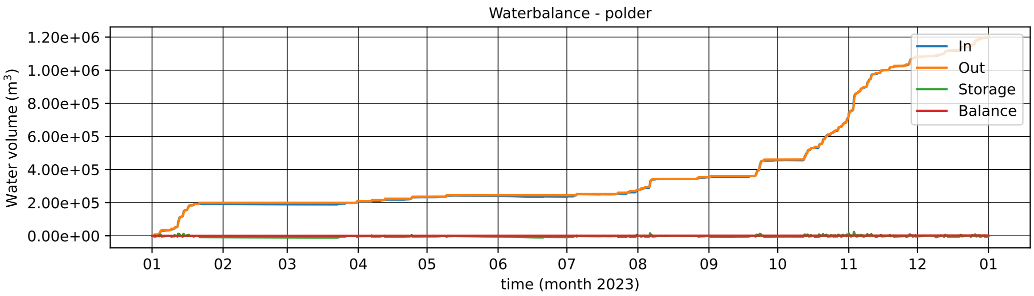


Figure 4.18: Water balance Kralingerpolder 2023 without Rainlevelr.

5

MPC applied to Rainlevelr

In this chapter Model Predictive Control is added to the Kralingerpolder model that was presented in the previous chapter. In Section 5.1 the valve settings are optimized. The basic control system is explained in Section 5.2 and in the next two sections different aspects of the MPC are tested; an increased number of realizations is studied in Section 5.3 and the effect of different weights for the polder sections and the reservoirs is investigated in Section 5.4. In Section 5.5 the effect of a less accurate weather prediction of 24 hours is investigated. In Section 5.6 the effect of the feedback update frequency, over which the water level are corrected, is studied. Finally in Section 5.7 a scenario is simulated for which all reservoirs in the Kralingerpolder operate a MPC Rainlevelr valve. Table 5.1 gives an overview of the simulations and the settings used.

Table 5.1: Scenarios settings.

Scenario	Polder weight	Reservoir weight	Realizations	Weather	Feedback time (h)	Participants
Rainlevelr MPC	0.7	0.3	100	actual	-	9
Realizations	0.7	0.3	1000	actual	-	9
Weights	0.95	0.05	100	actual	-	9
Weather	0.7	0.3	100	predicted	24	9
Feedback	0.7	0.3	100	predicted	6	9
Participants	0.7	0.3	100	actual	-	14

In this chapter results will be given for the Kwekerij Bergcamp reservoir and the KRN1 left polder section. Results for the remaining reservoirs and polder sections can be found in the appendices.

5.1. Valve dimension synchronization

In the current implementation of the MPC system, valve setting of reservoirs are generated per polder section. An example of these valve settings can be found in Figure 3.17. However, due to the different dimensions of each reservoir and the dimension of the valve itself, the same valve setting may result in different discharges for different reservoirs. This causes some reservoirs to lose more water than other reservoirs. To resolve this the valve dimensions of participants for which the water level drops faster need to be synchronized with valve dimensions of slower reacting reservoirs. The valve dimensions can be modified by reducing the opening by a percentage.

In Figure 5.1 three different valve dimensions are evaluated to look at the effect on the reservoir level. The simulations are made with valve openings of 100 %, 80 % and 60 %. In these simulations the effect of the valve dimensions are tested with a starting water level at spill height.

Reservoir water levels of the participants in polder section KRN1 left, Kwekerij Bergcamp and van Dijk Flowers, are depicted in the figure. As van Dijk Flowers empties faster than Kwekerij Bergcamp, the valve dimensions for van Dijk Flowers is set to 80 % to anticipate with Kwekerij Bergcamp. For these settings the water levels in both reservoirs are 1.5 m after 24 hours of valve flow, 0.25 m above their reference level.

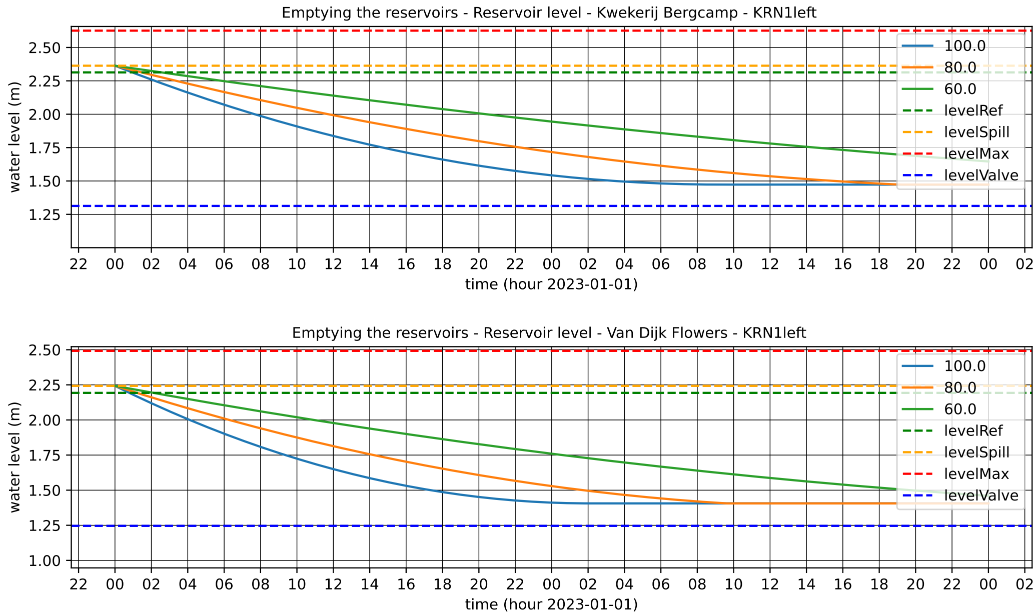


Figure 5.1: Calculated reservoir water levels of KRN 1 left with different valve settings over 24 hours.

A summary of original and synchronized valve dimensions is given in Table 5.2 together with the time needed to empty the reservoirs. In appendix E the emptying of all reservoirs with different valve settings are given.

Table 5.2: Valve dimensions for equal discharge per polder section.

Polder section	Reservoir particpant	Valve time (hours)	Original valve setting (%)	Synchronized valve setting (%)
KRN1 left	Kwekerij Bergcamp	28	40	100
	Van Dijk Flowers	30	100	80
KRN1 right	Rijk Zwaan	30	100	100
KRZ1	Greenvalley	12	100	100
	Ammerlaan Growers	12	100	80
	SVco Kreekrug	12	100	100
KRZ4	U Grand	18	100	60
	Lans Scheeweg	28	100	100
KRZ5	Lans Burgerweg	22	100	100

5.2. Rainlevelr MPC setup

For the first simulation that is presented in this section the controller used 0.7 as polder weight and 0.3 as reservoir weight. The number of valve setting realizations is 100. Precipitation was measured with the rain gauge near by the polder. The calculation used a 24 hour prediction of the rainfall, which was updated every six hours. The number of Rainlevelr participants is nine. Water levels are given for November, Appendix F presents the results for all polder sections and all reservoirs.

Reservoir response

In Figure 5.2 calculation results for the Kwekerij Bergcamp reservoir are given. The figure shows that the valve is opened prior to a rainfall event and the water level in the reservoir drops before the event. The difference in water level height for the case with MPC and the reference case without MPC is shown in Figure 5.3. The calculated reservoir level for the reference simulation, which can be found in Figure 4.14 was discussed in the Chapter 4. For the reference case the valves were deactivated. This graph shows that the maximum reduction of the water level achieved by the controller is 140 mm.

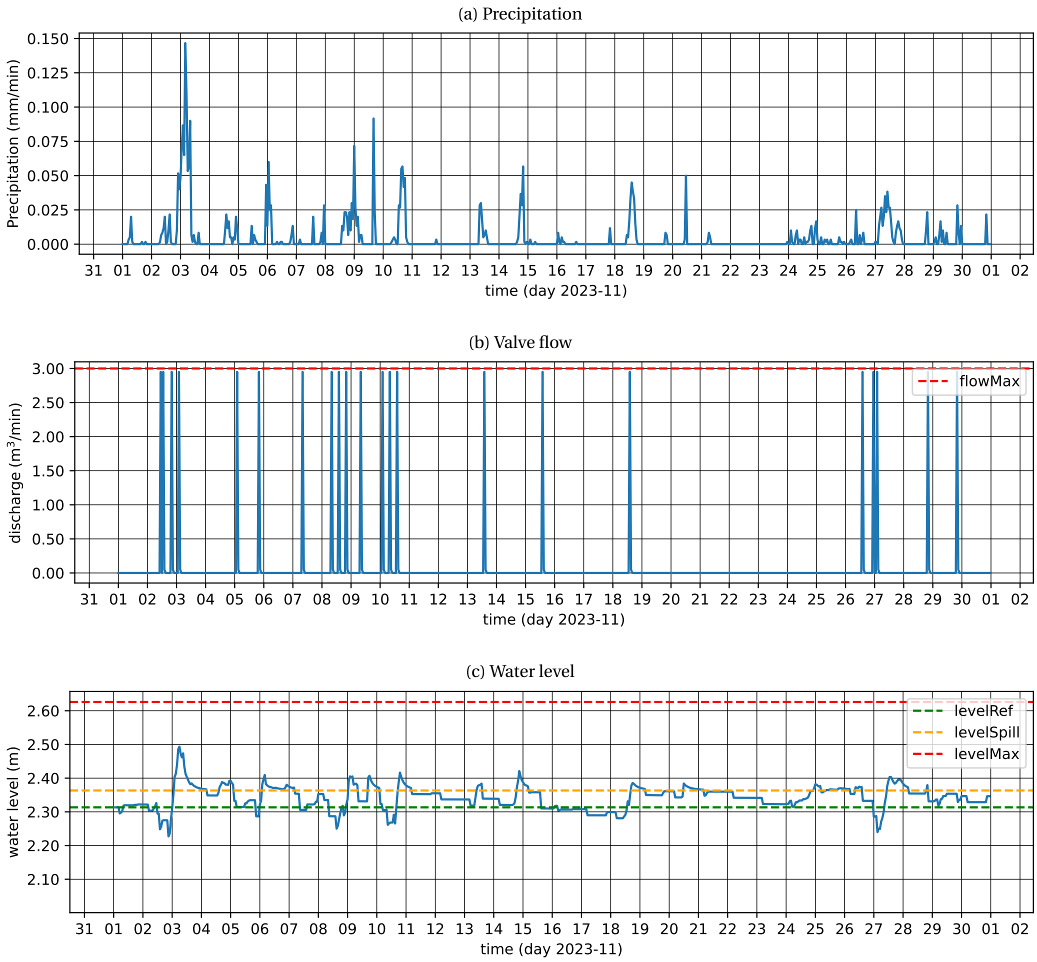


Figure 5.2: Reservoir Kwekerij Bergcamp, Rainlevelr MPC setup.

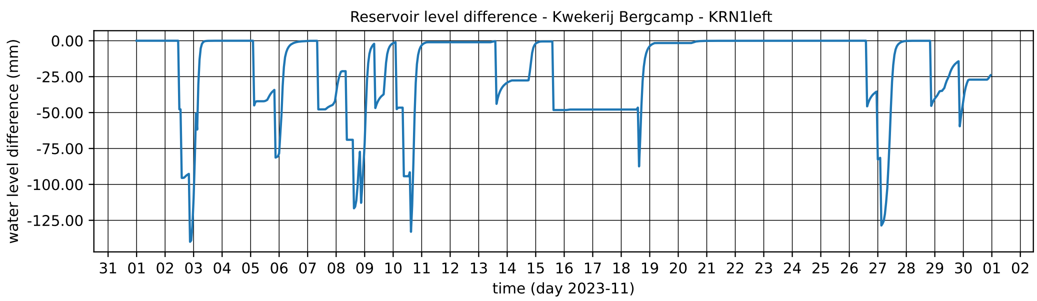


Figure 5.3: Reservoir Kwekerij Bergcamp, Rainlevelr MPC setup compared to reference case.

Polder section response

In Figure 5.4 the calculated water level in polder section KRN1 left is given. The effect of the reservoir water discharge can be observed in the calculated water levels. For instance prior to the rainfall event on November third the polder water level increases. Figure 5.5 shows the difference between the polder section levels with and without control. It can be seen that the controller increases the water level by 40 mm prior to heavy precipitation and decreases the water level by a maximum of 20 mm during the rain fall event.

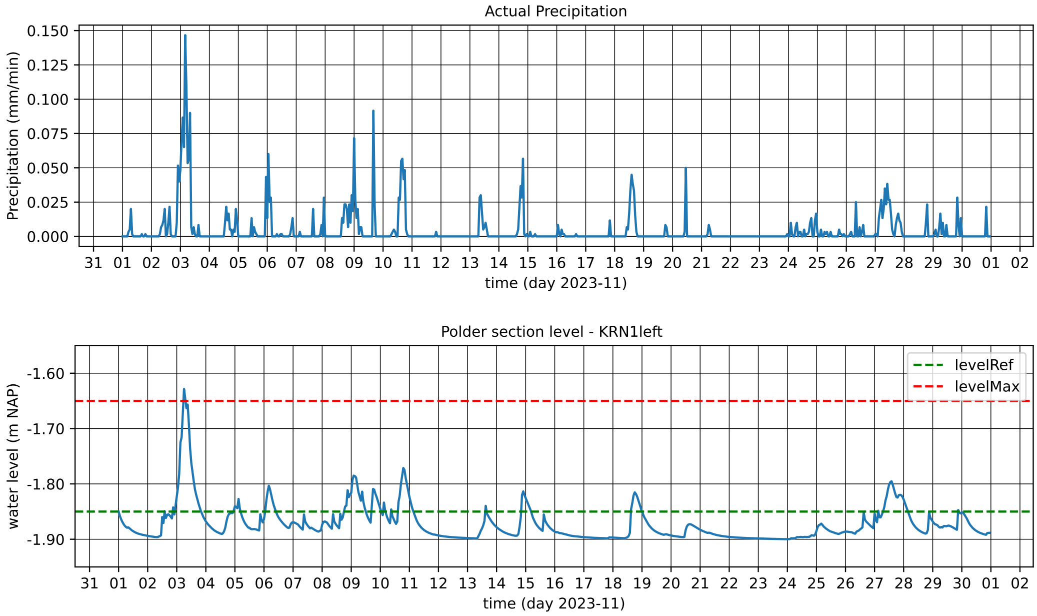


Figure 5.4: KRN1 left, Rainlevelr MPC setup.

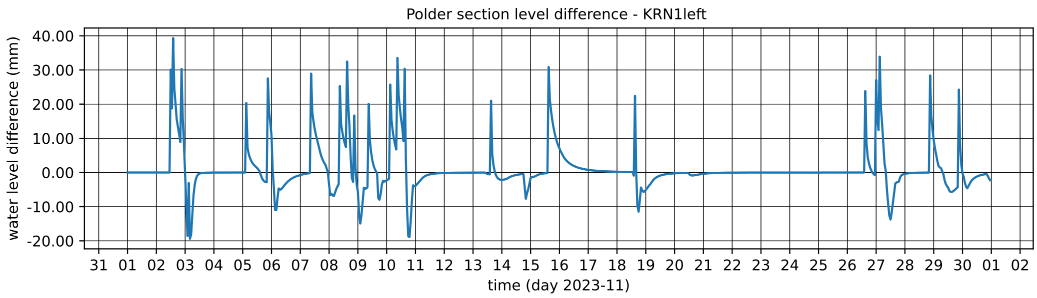


Figure 5.5: KRN1 left, Rainlevelr MPC setup compared to reference case.

Polder response

Table 5.3 gathers the maximum decrease in reservoir water levels for the first MPC simulation. In Table 5.4 the maximum decrease and the maximum increase in polder section water level are collected. All extremes are calculated over a year.

Table 5.3: Maximum reservoir water level decrease Rainlevelr MPC setup.

Name	Decrease (mm)
Kwekerij Bergcamp	150
Van Dijk Flowers	133
Rijk Zwaan	50
Greenvalley	
Ammerlaan Growers	
SVco Kreekrug	
Lans Scheeweg	81
U Grand	117
Lans Burgerweg	153

Table 5.4: Maximum polder section water level change Rainlevelr MPC setup.

Name	Decrease (mm)	Increase (mm)
KRN1 left	31	40
KRN1 right	5	14
KRZ1	5	8
KRZ5	20	33
KRZ4	101	97

Figure 5.6 presents the number of threshold exceedances in 2023 under the assumption that polder sections fail when the water level get above a threshold and the water levels in the reservoirs get below a threshold. The threshold for the polder sections is chosen at 10 cm below ground level and the threshold for the reservoirs is set to 20 cm below the reference level of the reservoirs. According to the definition of the threshold exceedance criterion still four polder sections fail in November.

Figure 5.7 compares the graph with the results found for the reference computation (Figure 4.17c). The graph shows the difference between both simulations. As can be seen, the MPC system is able to reduce the number of polder section threshold exceedances at the expense of a number of reservoir threshold exceedances.

Table 5.5 shows the total threshold exceedance time per month. If for example 2 reservoirs fail over 4 hours in a certain month, then a threshold exceedance time of 8 hours is reported. In total the polder sections do not fail because of Rainlevelr actions for 14 hours (KRN1 left 3 hours, KRN1 right 2 hours and KRZ5 9 hours). As a consequence the water level in the reservoirs gets less than 20 cm below reference level over 805 hours. This is due to the bad performance of the reservoirs Kwekerij Bergcamp, Lans Burgerweg and Van Dijk Flowers.

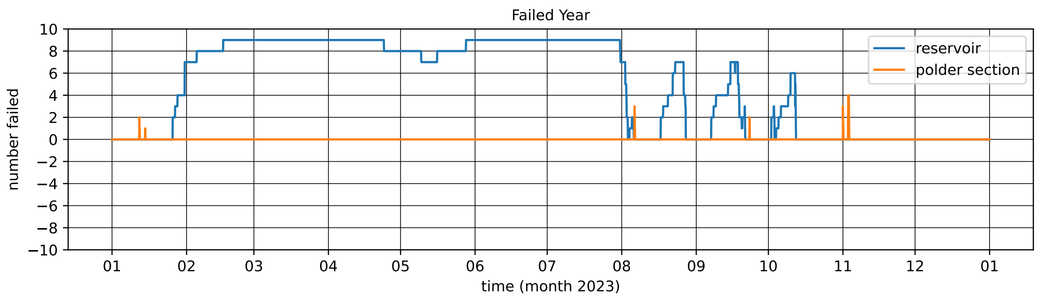


Figure 5.6: Threshold exceedance Rainlevelr MPC setup.

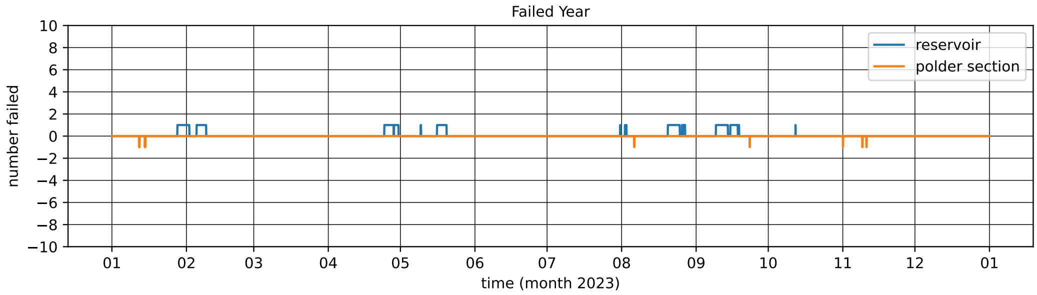


Figure 5.7: Net threshold exceedance Rainlevelr MPC setup with reference case.

Table 5.5: Hours failed Rainlevelr MPC setup compared to reference case.

Component	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Polder sections failed	0	0	0	0	0	0	0	0	0	0	0	0
Polder sections saved	-4	0	0	0	0	0	0	-2	-1	0	-7	0
Reservoirs failed	91	125	0	139	100	0	2	148	199	1	0	0

The simulation shows that the Model Predictive Controller is able to reduce the number of polder section threshold exceedances at the expense of the reservoir threshold exceedances. However, the controller was not able to mitigate the flooding of the polder during the heavy rain event at the beginning of November.

5.3. Increased number of realizations

Similar to the first simulation the Model Predictive Controler sets the polder weight to 0.7 and the reservoir weight to 0.3. Precipitation was measured with the rain gauge near by the polder. The calculation used a 24 hour prediction of the rainfall, which was updated every six hours. The number of Rainlevelr participants is nine, similar to the first simulation.

In this simulation however, the number of valve setting realizations is increased to 1000 in order to test the accuracy of the first MPC simulation. The first 100 realizations of this set of 1000 realizations are the same as in the previous simulation, as the seed of the random generation remains the same. In this section water levels are given for November for a single reservoir and polder section, Appendix G presents the results for all polder sections and all reservoirs.

Reservoir response

Figure 5.8 shows the results for the Kwekerij Bergcamp reservoir and Figure 5.9 compares the result with the reference case presented in Chapter 4. According to this graph the maximum decrease in water level is 130 mm, 10 mm less than the simulation with 100 valve setting realizations.

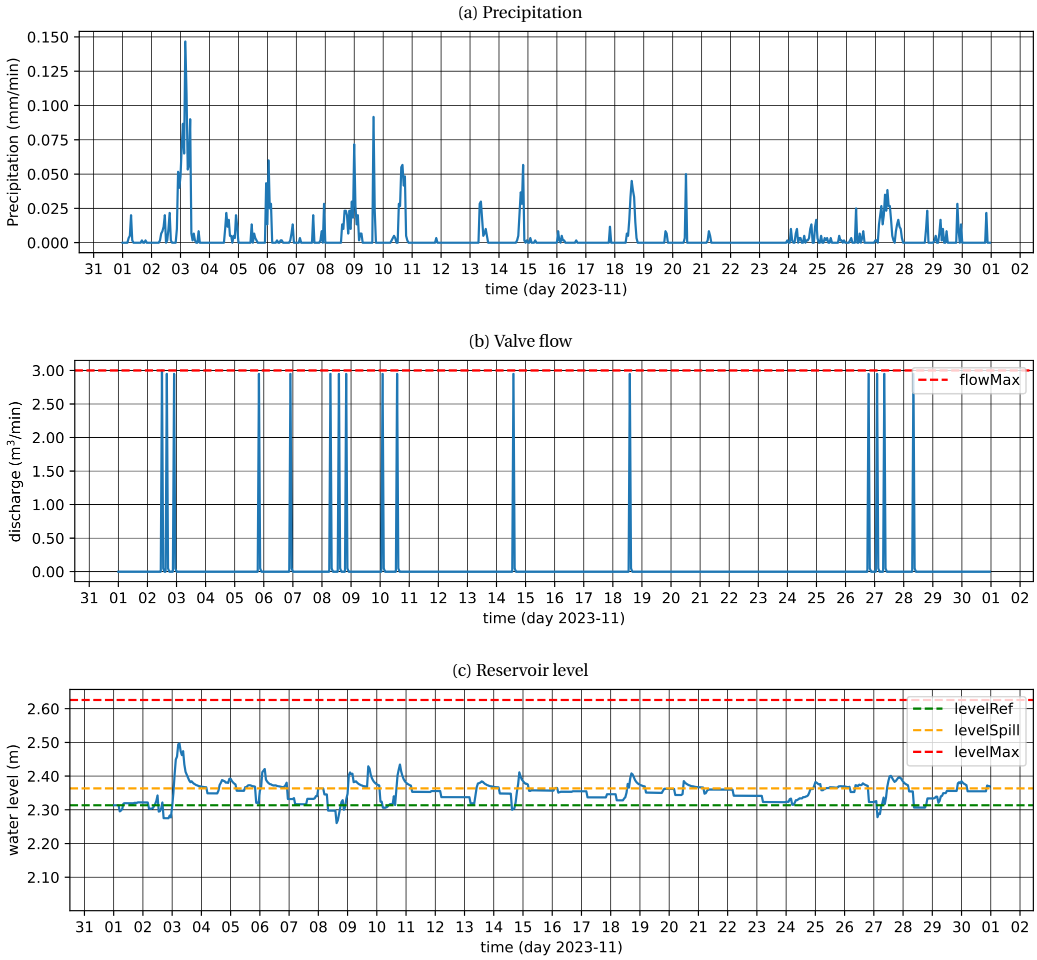


Figure 5.8: Reservoir Kwekerij Bergcamp, increased number of realizations.

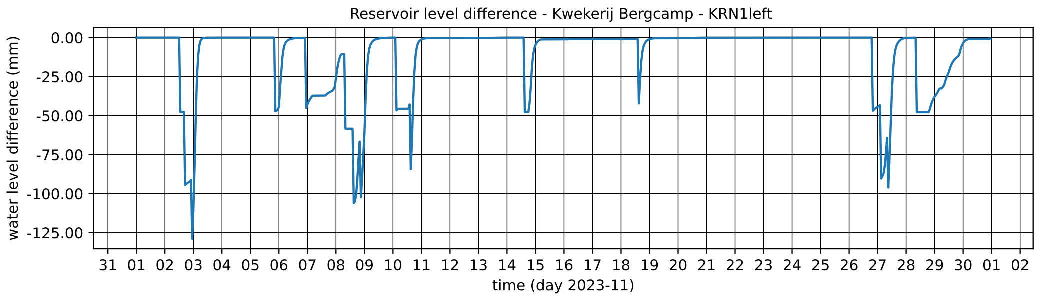


Figure 5.9: Reservoir Kwekerij Bergcamp, increased number of realizations compared to reference case.

Polder section response

In Figure 5.10 the water level in polder section KRN1 left is given. The controller reduces the peaks in the water level in the same order of magnitude as the first MPC simulation, and is not able to prevent the polder section from flooding on the third of November. Figure 5.11 compares the results with the reference case without Model Predictive Control. The graph shows a maximum increase of 31 mm and decrease of 20 mm. The decrease in water level is the same as the decrease found for 100 realizations.

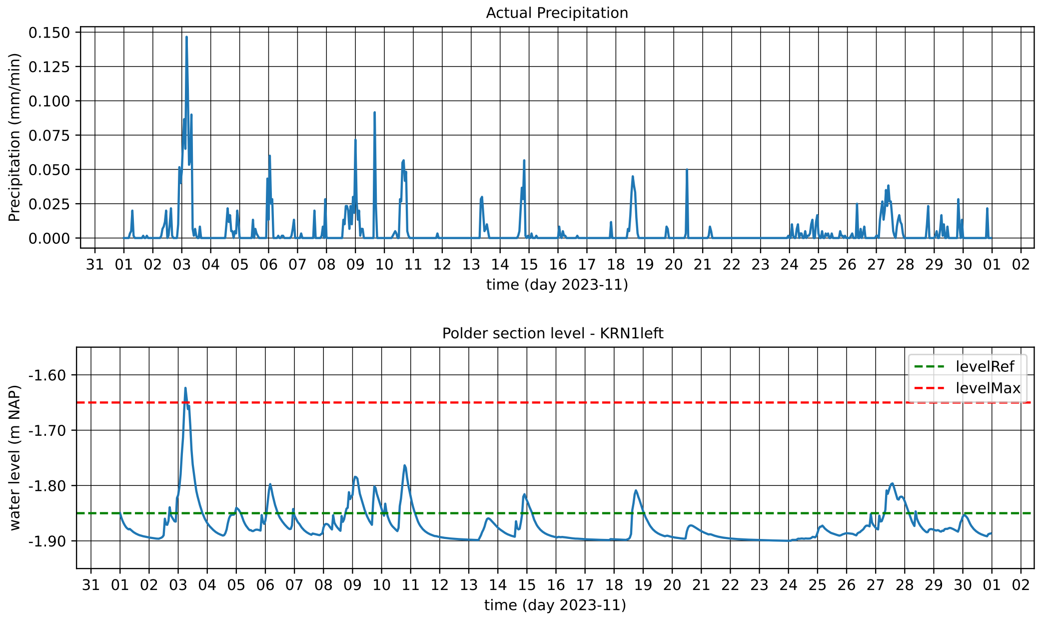


Figure 5.10: KRN1 left, increased number of realizations.

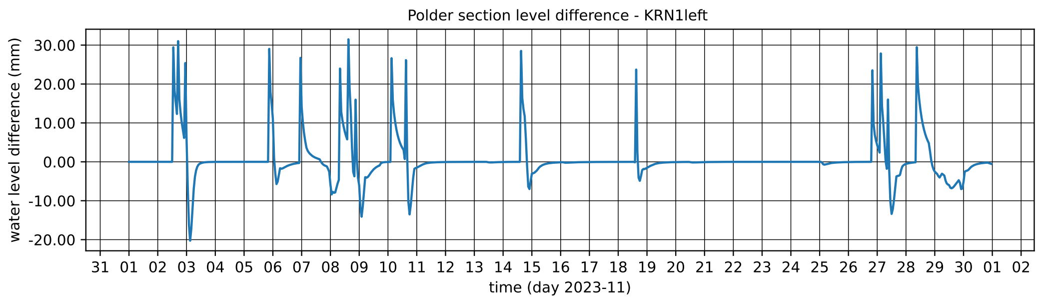


Figure 5.11: KRN1 left, increased number of realizations compared to reference case.

Polder response

Table 5.6 gathers the maximum decrease in reservoir water levels for this MPC simulation and compares it to the decrease found for the Rainlevelr MPC setup simulation (Table 5.3). The table shows that the maximum decrease in water level found for 1000 realization differs less than 2 cm with the extreme values found for 100 realizations. In Table 5.7 the maximum decrease and the maximum increase in polder section water levels are collected. Also this table shows a maximum difference with the 100 realization simulation of less than 2 cm (Table 5.4). All extreme values are calculated over a year.

Table 5.6: Maximum reservoir water level decrease increased number of realizations.

Name	1000 realizations Decrease (mm)	100 realizations Decrease (mm)
Kwekerij Bergcamp	154	150
Van Dijk Flowers	124	133
Rijk Zwaan	53	50
Greenvalley	99	
Ammerlaan Growers	196	
SVco Kreekrug	157	
Lans Scheeweg	69	81
U Grand	120	117
Lans Burgerweg	170	153

Table 5.7: Maximum polder section water level change increased number of realizations.

	1000 realizations		100 realizations	
Name	Decrease (mm)	Increase (mm)	Decrease (mm)	Increase (mm)
KRN1 left	25	35	31	40
KRN1 right	4	8	5	14
KRZ1	10	30	5	8
KRZ5	23	38	20	33
KRZ4	99	101	101	97

Figure 5.12 presents the number of threshold exceedances in 2023 under the assumption that polder sections fail when the water level get above a threshold and the water levels in the reservoirs gets below a threshold. Figure 5.13 compares the graph with the results found for the reference computation (Figure 4.17).

Table 5.8 shows the total threshold exceedance time per month. The table indicates that polder sections do not fail because of Rainlevelr actions for 9 hours (14 hours for 100 realizations). As a consequence the water level in the reservoirs drops more than 20 cm below reference level over 626 hours (805 hours for 100 realizations). From these numbers it is concluded that more realizations favor the behavior of the reservoirs. The table also shows that one false-negative event takes place where to polder exceeds the threshold that was set at 10 cm below ground level. The reason for this might be that a first Rainlevelr action prevents the polder section from threshold exceedance but generates a threshold exceedance two hours later. The event takes place in polder section KRZ5.

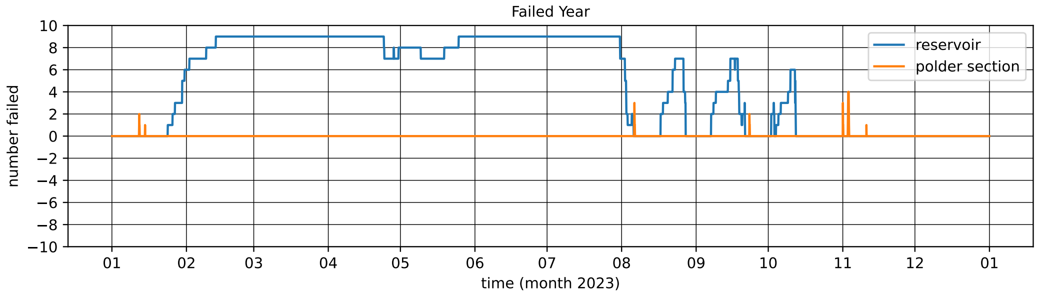


Figure 5.12: Threshold exceedance increased number of realizations.

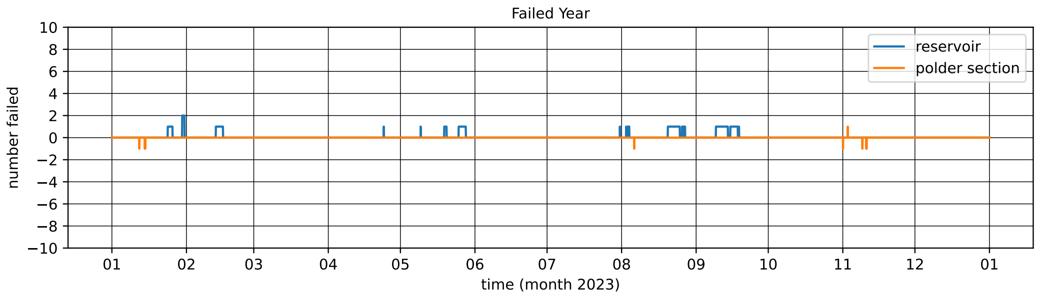


Figure 5.13: Net threshold exceedance increased number of realizations with reference case.

Table 5.8: Hours failed increased number of realizations compared to reference case.

Component	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Polder sections failed	0	0	0	0	0	0	0	0	0	0	1	0
Polder sections saved	-3	0	0	0	0	0	0	-1	0	0	-5	0
Reservoirs failed	96	72	0	1	97	0	1	160	199	0	0	0

It is concluded that the difference in predicted water levels with 1000 realization and 100 realization is small. However, the computation time increases with a factor 10, a computation over a period of a year takes about 2 hours for 100 realizations and about 20 hours for a 1000 realization simulation. For this reason it was decided that further computations would use 100 realizations.

5.4. Higher weighting for polder level deviations

The objective weight simulation that is reported in this section sets the number of valve setting realizations to 100. Precipitation was measured with the rain gauge close to the polder. The calculation used a 24 hour prediction of the rainfall, which was updated every six hours. The number of Rainlevelr participants is nine. For the simulation that is presented in this section the Model Predictive Controller sets the polder weight to 0.95 and the reservoir weight to 0.05. In this way the polder gets a higher priority compared to the first MPC simulation. Water levels are given for November, Appendix H presents the results for all polder sections and all reservoirs.

Reservoir response

In Figure 5.14 the results for the reservoir Kwekerij Bergcamp are given. The smaller weight on the reservoirs results in larger water level drops. According to Figure 5.15 the Rainlevelr actions lead to a maximum decrease of the water level of 209 mm. The first MPC simulation used a polder weight of 0.7 and the reservoir weight of 0.3 and gave a maximum decrease of 140 mm.

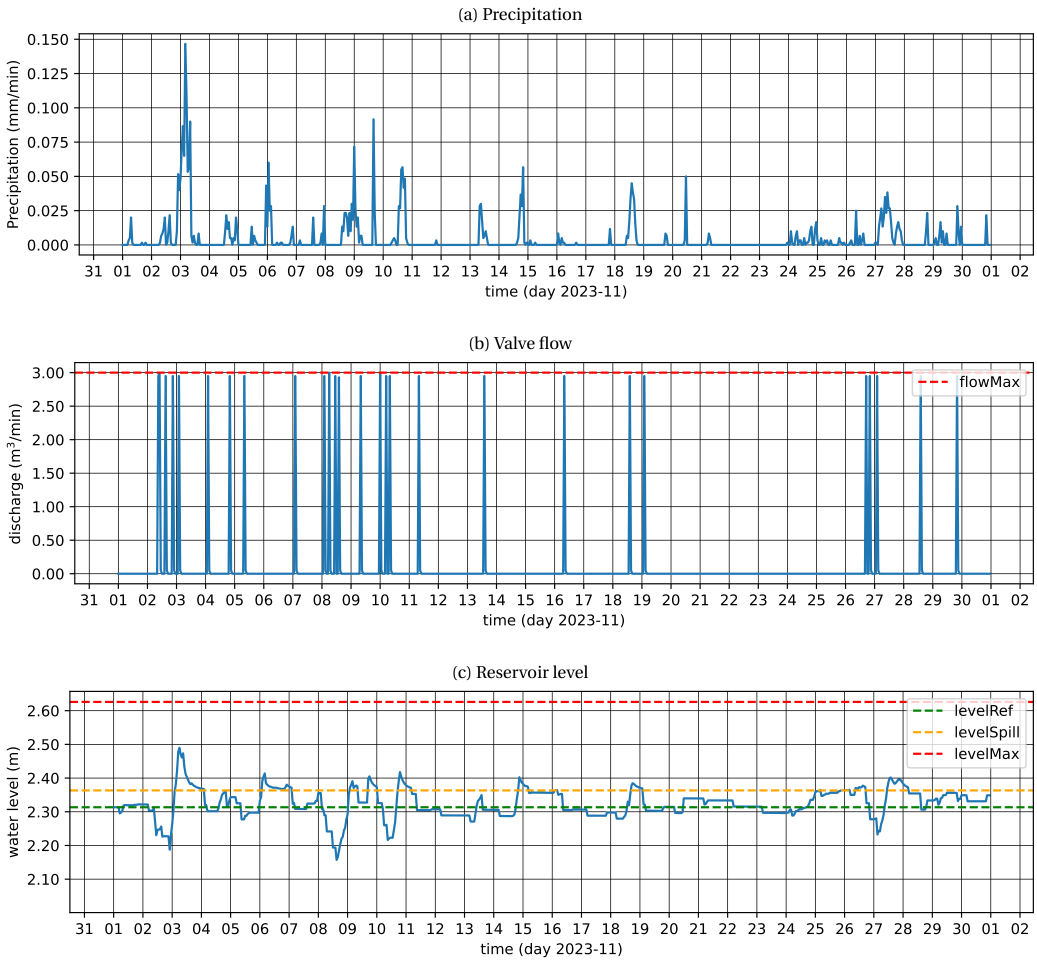


Figure 5.14: Reservoir Kwekerij Bergcamp, higher weighting for polder level deviations.

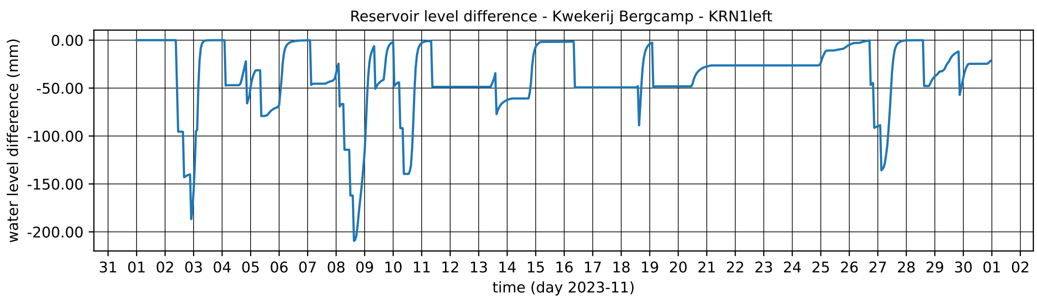


Figure 5.15: Reservoir Kwekerij Bergcamp, higher weighting for polder level deviations compared to reference case.

Polder section response

In Figure 5.16 the water level in polder section KRN1 left is given. The higher weight on the polder sections results in smaller water level peaks in the polder sections. However, The figure indicates that the rain event on the third of November still causes flooding. Figure 5.17 shows that the maximum increase of the water level is 44 mm and the maximum decease is 27 mm. Compared to the 0.7 polder weight and 0.3 reservoir weight simulation the polder section increase is 4 mm more and the is decrease is 7 mm less.

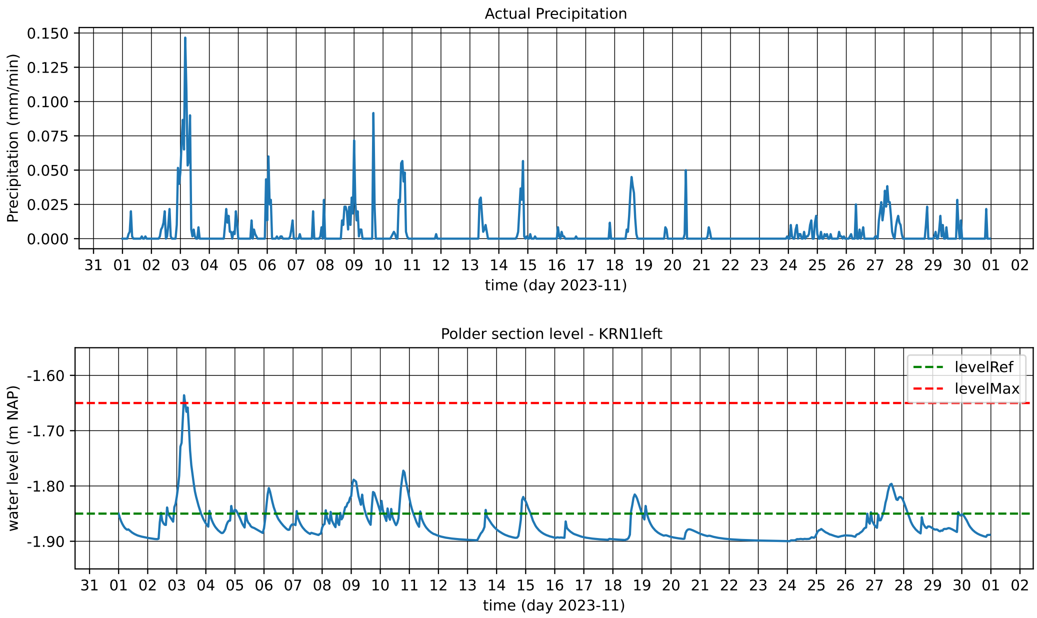


Figure 5.16: KRN1 left, higher weighting for polder level deviations.

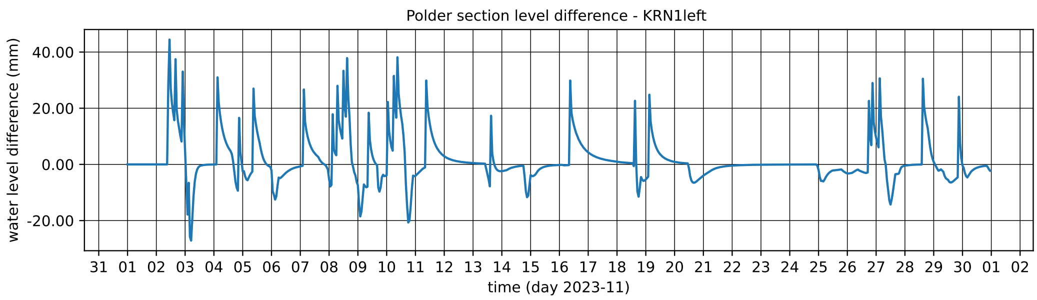


Figure 5.17: KRN1 left, higher weighting for polder level deviations compared to reference case.

Polder response

Table 5.9 gathers the maximum decrease in reservoir water levels for this MPC simulation. In Table 5.10 the maximum decrease and the maximum increase in polder section water level are collected. All extreme values are calculated over a year. The tables show that the decrease of reservoir levels is larger if the weights for the polder sections is set to 0.95 instead of 0.7 and the decrease of polder water levels is also larger.

Table 5.9: Maximum reservoir water level decrease higher weighting for polder level deviations.

Name	0.95 - 0.05 Decrease (mm)	0.7 - 0.3 Decrease (mm)
Kwekerij Bergcamp	223	150
Van Dijk Flowers	194	133
Rijk Zwaan	113	50
Greenvalley	186	
Ammerlaan Growers	316	
SVco Kreekrug	223	
Lans Scheeweg	100	81
U Grand	153	117
Lans Burgerweg	238	153

Table 5.10: Maximum polder section water level change higher weighting for polder level deviations.

	0.95 - 0.05		0.7 - 0.3	
Name	Decrease (mm)	Increase (mm)	Decrease (mm)	Increase (mm)
KRN1 left	37	49	31	40
KRN1 right	7	18	5	14
KRZ1	16	45	5	8
KRZ5	26	42	20	33
KRZ4	100	99	101	97

Figure 5.18 presents the number of threshold exceedances in 2023 when the water levels in the reservoirs get below a threshold. Figure 5.19 compares the graph with the results found of the reference computation (Figure 4.17).

Table 5.11 shows the total threshold exceedance time per month. The table indicates that polder sections do not exceed the threshold because of Rainlevelr actions for 18 hours (14 hours for 100 realizations). As a consequence the water level in the reservoirs never drops more than 20 cm below reference level over 876 hours (805 hours for 100 realizations).

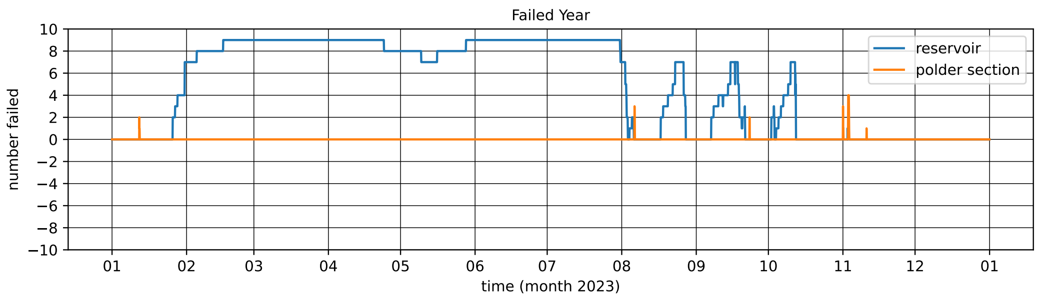


Figure 5.18: Threshold exceedance higher weighting for polder level deviations.

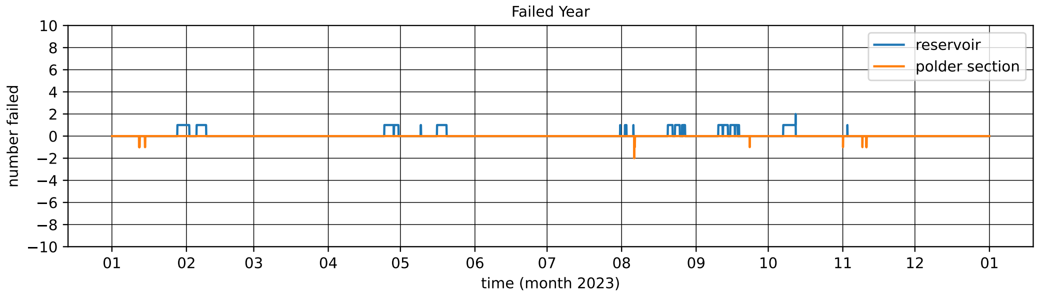


Figure 5.19: Net threshold exceedance higher weighting for polder level deviations with reference case.

Table 5.11: Hours failed higher weighting for polder level deviations compared to reference case.

Component	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Polder sections failed	0	0	0	0	0	0	0	0	0	0	0	0
Polder sections saved	-8	0	0	0	0	0	0	-4	-1	0	-5	0
Reservoirs failed	91	125	0	139	100	0	2	126	166	126	1	0

The simulation shows that fewer polder sections fail at a cost of reservoir threshold exceedances if the weights for the polder sections are increased and reservoir weights are decreased.

5.5. Less accurate weather prediction

This simulation sets the polder weight to 0.7 and the reservoir weight to 0.3. The number of valve realizations is 100. The calculation uses a 24 hour prediction of the rainfall, which is updated every six hours. The number of Rainlevelr participants is nine. For the precipitation forecast, weather data measurements at KNMI weather station Rotterdam are used.

Based on the weather forecast and the selected valve settings, a prediction of the reservoir water levels and the polder section water levels is made. Since this prediction differs from the actual measurement data, measurements can be used to correct the prediction when they become available. Water level measurements that are used in the feedback loop are generated out of rain gauge measurements. The controller corrects the predicted water levels with the measured water levels at the end of an feedback window. This enables the controller to construct a better valve setting for the next feedback window. In this simulation the feedback window is set to 24 hours and the correction of the predicted water level takes place at the start of each day. In this section water levels are presented for a single reservoir and a single polder section in November, Appendix I presents the results for all polder sections and all reservoirs.

Reservoir response

In Figure 5.20 the results for the reservoir Kwekerij Bergcamp are given. The difference between the water level of the actual and predicted weather forecast is relatively small. Figure 5.21 indicates that the draw down due to Rainlevelr actions is 86 mm. In the first MPC simulation that applied a perfect forecast the maximum draw down was 140 mm. Reason for this can be found in the duration of the rainfall event; the actual rainfall events in the polder have a longer duration than the predicted rain fall events based on the Rotterdam measurements. The controller therefore discharges less water than required.

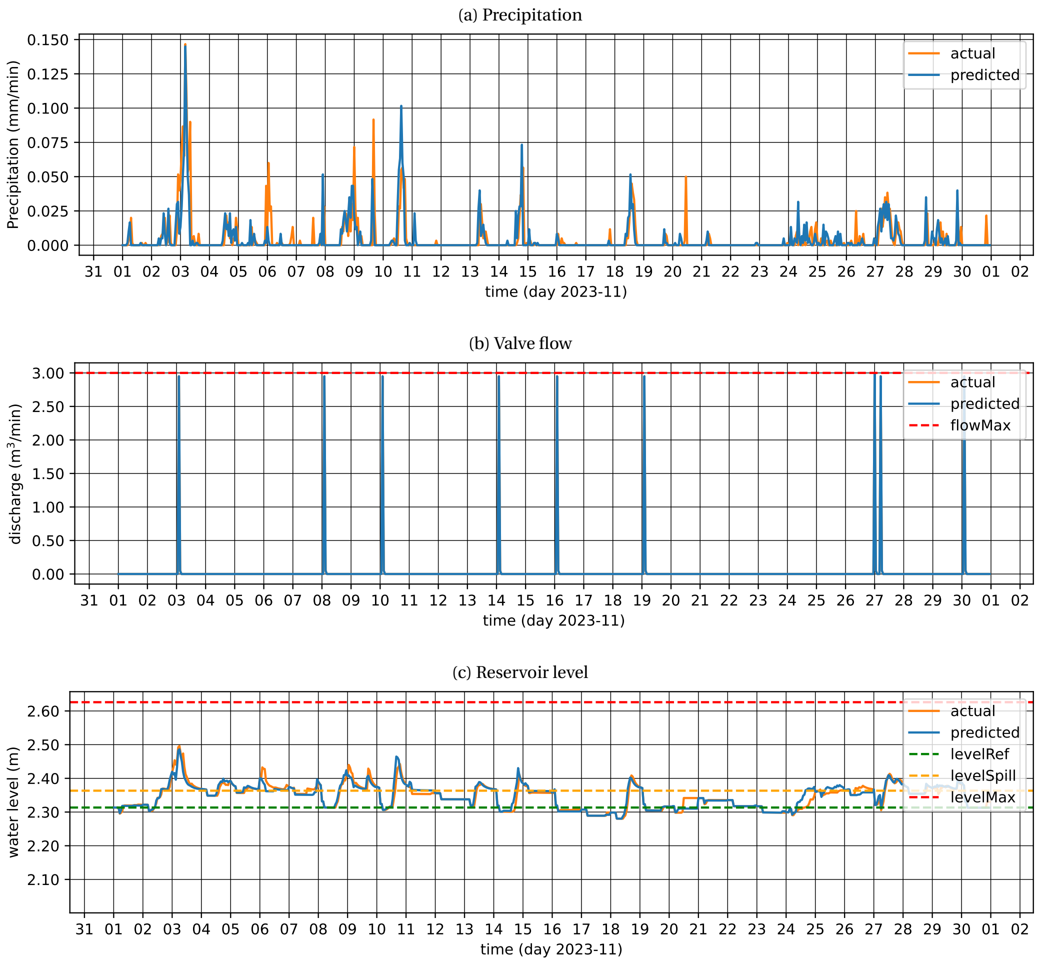


Figure 5.20: Reservoir Kwekerij Bergcamp, less accurate weather prediction.

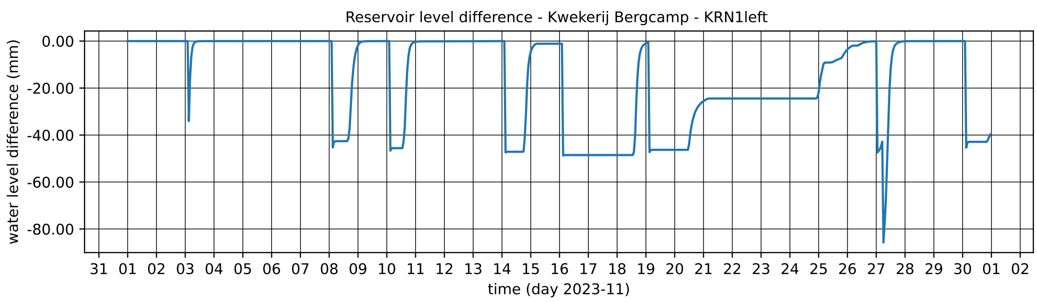


Figure 5.21: Reservoir Kwekerij Bergcamp, less accurate weather prediction compared to reference case.

Polder section response

In Figure 5.22 the water level in polder section KRN1 left is given. The orange line depicts (actual) generated water level measurements that follow from the optimized valve settings and are based on rain gauge measurements from Kerkpolder-Zuid. The blue line follows from a MPC forecast based on KNMI weather measurements in Rotterdam. The difference between the reference case from Chapter 4 and the MPC calculation (actual) is shown in Figure 5.23. The figure indicates that the increase in polder water level is 31 mm prior to a rain event and the decrease is 11 mm during the rain fall event relative to the simulation without Rainlevelr actions (Figure 4.16). The reduction of the polder water levels by this MPC strategy is small. In the first MPC simulation the increase was 40 mm and the decrease was 20 mm (Figure 5.5). Both the increase and decrease of water level are less than in the first MPC simulation.

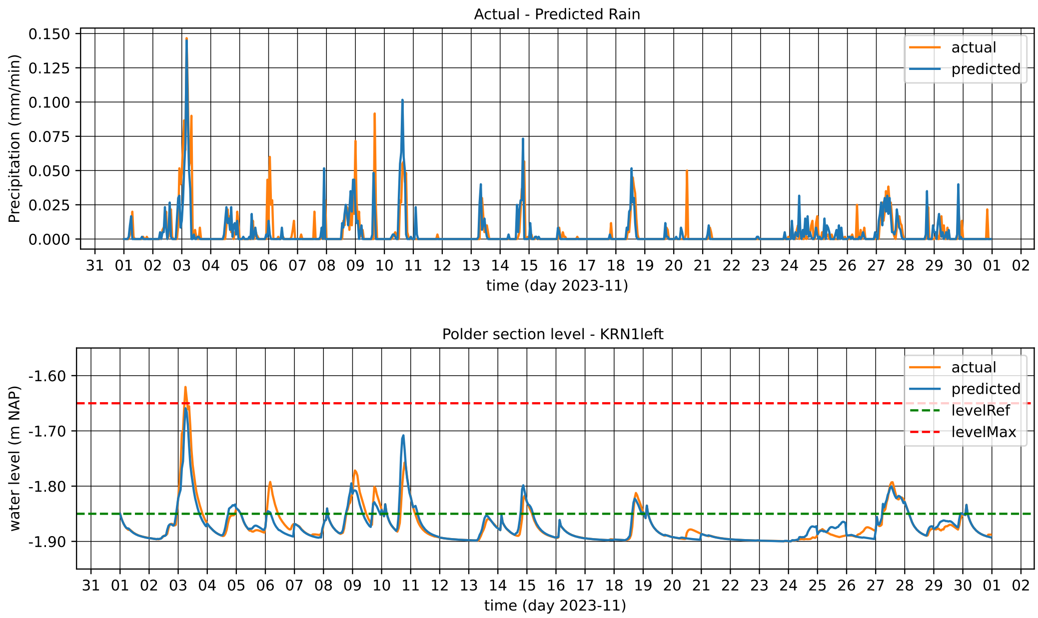


Figure 5.22: KRN1 left, less accurate weather prediction.

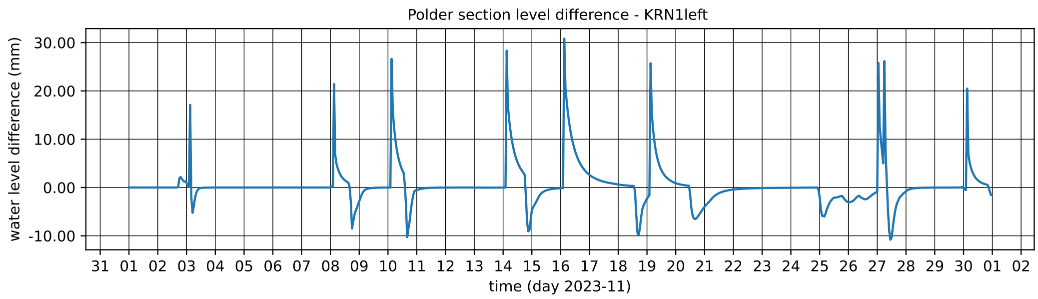


Figure 5.23: KRN1 left, less accurate weather prediction compared to reference case.

Polder response

Table 5.12 gathers the maximum decrease in reservoir water levels for this MPC simulation. In Table 5.13 the maximum decrease and the maximum increase in polder section water levels are collected. All extreme values are calculated over a year. The tables indicate that not all reservoirs have a smaller decrease in water level. Both the increase and decrease of polder section water levels are less then the first MPC simulation except for KRZ1.

Table 5.12: Maximum reservoir water level decrease less accurate weather prediction, feedback time 24 hours.

Name	Less accurate prediction Decrease (mm)	Perfect Prediction Decrease (mm)
Kwekerij Bergcamp	86	150
Van Dijk Flowers	76	153
Rijk Zwaan	51	50
Greenvalley		
Ammerlaan Growers		
SVco Kreekrug		
Lans Scheeweg	111	81
U Grand	170	117
Lans Burgerweg	89	153

Table 5.13: Maximum polder section water level change weather prediction, less accurate weather prediction.

	Less accurate weather prediction		Perfect prediction	
Name	Decrease (mm)	Increase (mm)	Decrease (mm)	Increase (mm)
KRN1 left	14	31	31	40
KRN1 right	8	9	5	14
KRZ1	10	7	5	8
KRZ5	14	24	20	33
KRZ4	97	101	101	97

Figure 5.24 presents the number of threshold exceedances when the reservoir level gets below or the polder level gets above a threshold. Figure 5.25 compares the graph with results found for the reference computation (Figure 4.17).

Table 5.14 shows the total threshold exceedance time per month. The table indicates that polder sections do not fail because of Rainlevelr actions for 6 hours (14 hours for the Rainlevelr MPC setup simulation). As a consequence the water level in the reservoirs gets less than 20 cm below reference level over 4508 hours (805 hours for the rain gauge simulation).

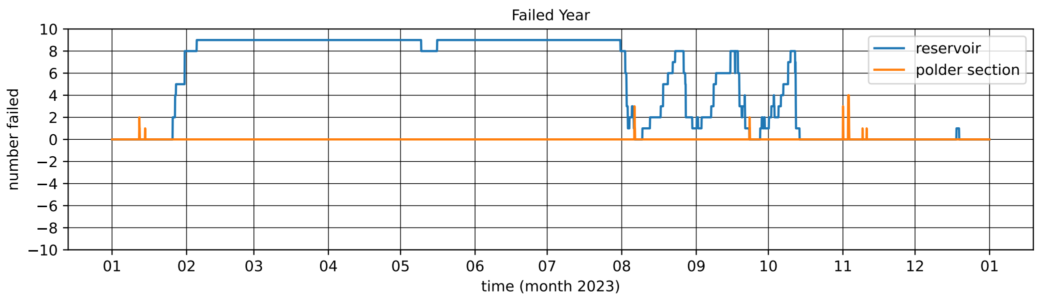


Figure 5.24: Threshold exceedance less accurate weather prediction, feedback time 24 hours.

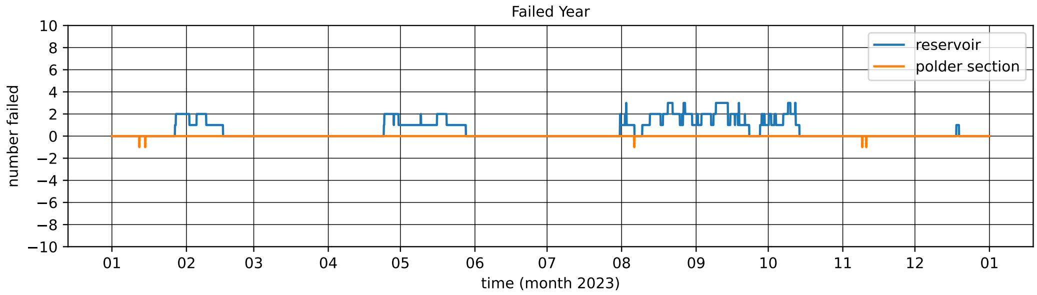


Figure 5.25: Net threshold exceedance less accurate weather prediction, feedback time 24 hours with reference case.

Table 5.14: Hours failed less accurate weather prediction, feedback time 24 hours.

Component	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Polder sections failed	0	0	0	0	0	0	0	0	0	0	0	0
Polder sections saved	-2	0	0	0	0	0	0	-2	0	0	-2	0
Reservoirs failed	221	490	0	305	753	0	19	1106	1084	503	0	27

It is concluded that the controller performs less well if the predicted weather condition deviates from the measured water level at the polder location.

5.6. Less accurate forecast, but more frequent feedback

For the simulation that is presented in this section the polder weight is set to 0.7 and the reservoir weight is 0.3. The number of valve setting realizations is 100. Precipitation was predicted base on measurements at the KNMI weather station in Rotterdam. The calculation used a 24 hour prediction of the rainfall, which was updated every six hours. The number of Rainlevelr participants is nine. In the simulation water levels are corrected with measured water levels every 6 hours (in the previous simulation this feed back loop was performed every 24 hours) as indicated in Figure 3.24 from Chapter 3. Water levels are given for November, Appendix J presents the results for all polder sections and all reservoirs.

Reservoir response

In Figure 5.26 simulation results are given for the reservoir Kwekerij Bergcamp. The difference between the water level in the actual and predicted weather forecast is small. It must be noted however the predicted values and actual values that are presented in the graph are both generated with the same valve settings. The predicted signal was calculated with data from KNMI weather station Rotterdam and the actual water levels follow from a calculation with rain gauge data. Figure 5.27 indicates that the maximum decrease of the reservoir water level is 127 mm just before a rain fall event. This value follows from the comparison of the actual water levels that were generated with the optimal valve settings (orange line in Figure 5.26) and the calculated water levels for the reference case (blue line in Figure 5.27). The calculation in Section 5.5 gave a decrease of 86 mm.

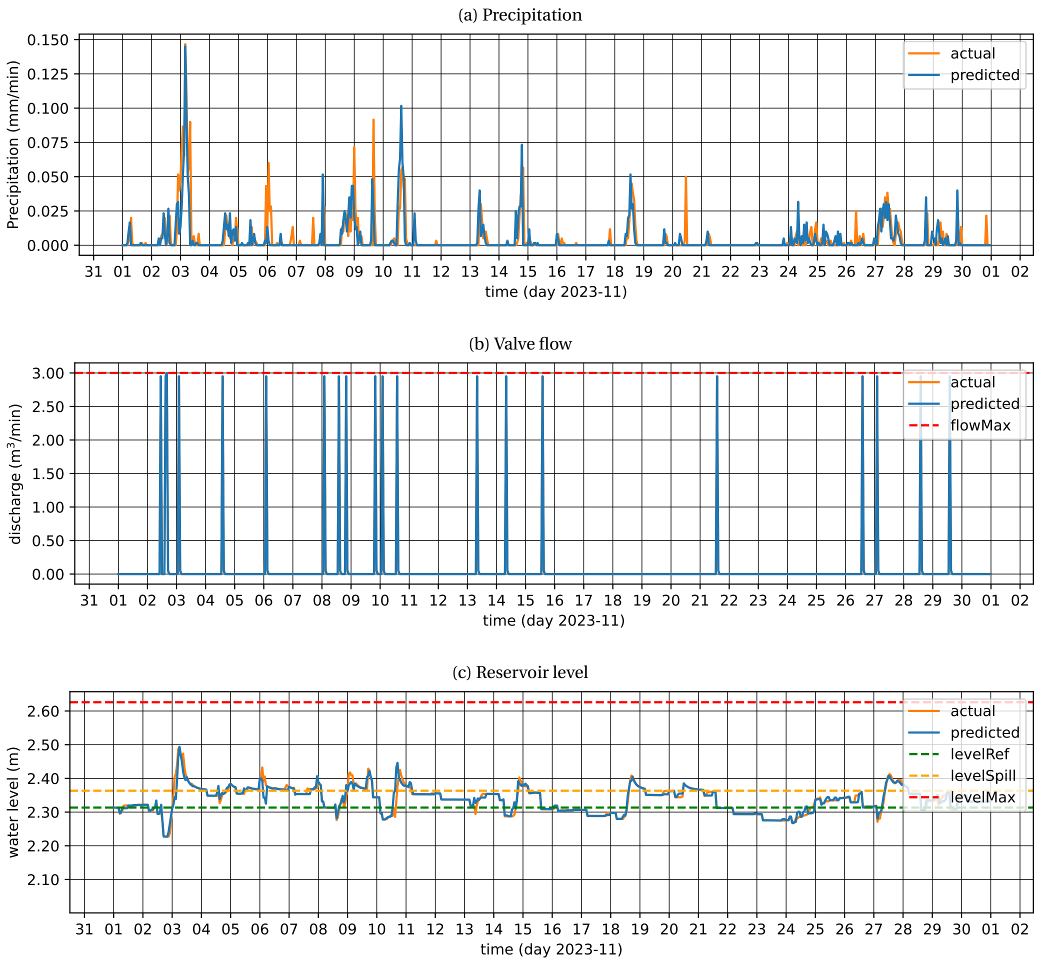


Figure 5.26: Reservoir Kwekerij Bergcamp, less accurate forecast, but more frequent feedback.

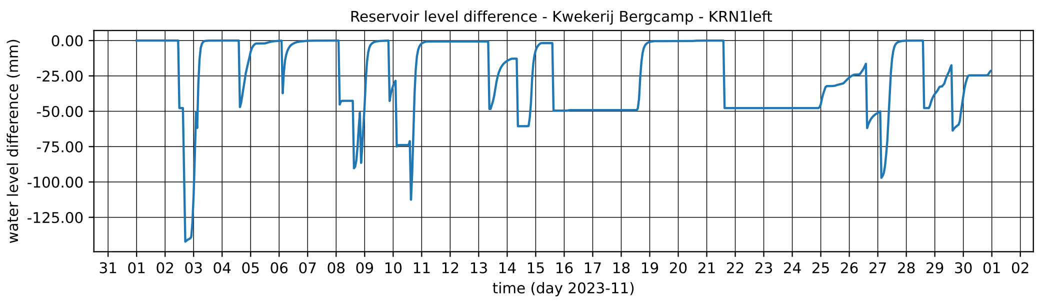


Figure 5.27: Reservoir Kwekerij Bergcamp, less accurate forecast, but more frequent feedback compared to reference case.

Polder section response

In Figure 5.28 the water level in polder section KRN1 left is given. The predicted water level in this feedback update simulation compares well with the first MPC calculation where rain gauge data was used. According to Figure 5.29 the water level increase before the rain fall event is 43 mm (40 mm in the first MPC calculation) and the maximum decrease during the event is 19 mm (20 mm in the first MPC calculation).

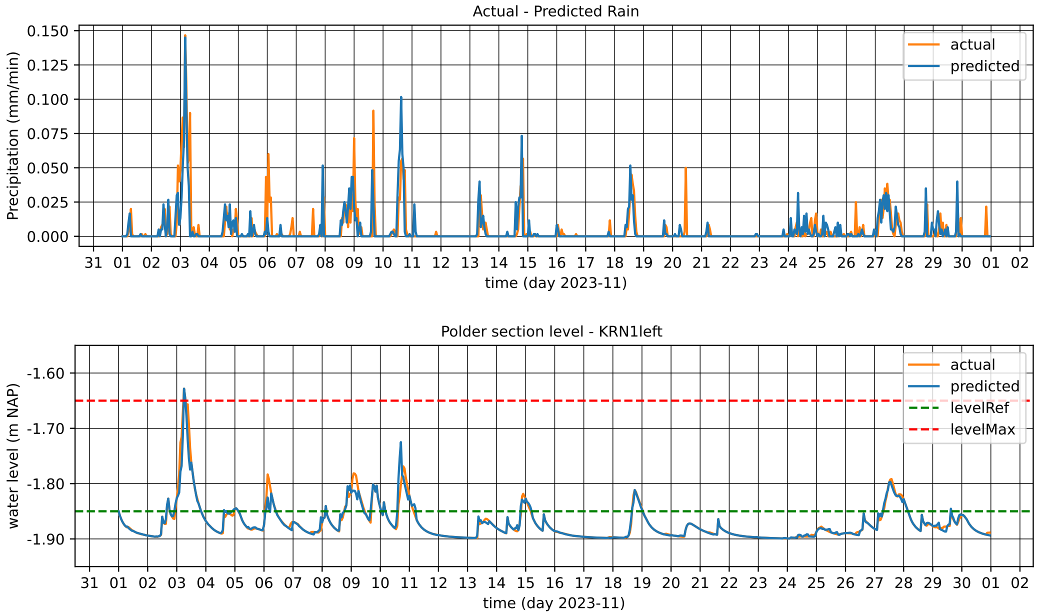


Figure 5.28: KRN1 left, less accurate forecast, but more frequent feedback.

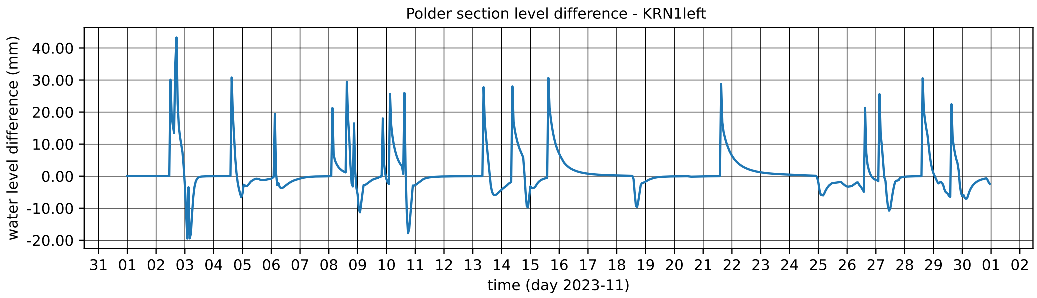


Figure 5.29: KRN1 left, less accurate forecast, but more frequent feedback compared to reference case.

Polder response

Table 5.15 gathers the maximum decrease in reservoir water levels for this MPC simulation. In Table 5.16 the maximum decrease and the maximum increase in polder section water level are collected. All extreme values are calculated over the year 2023. The results show that the maximum decrease and increase in water level agree well with the first MPC computation where rain gauge data was used to optimize the controller except for polder section KRZ1. Reason for this is that the reservoirs: Greenvalley, Ammerlaan Growers and SVco Kreekrug where not active in the first MPC computation.

Table 5.15: Maximum reservoir water level decrease, less accurate forecast, but more frequent feedback.

Name	Feedback update Decrease (mm)	Perfect prediction Decrease (mm)
Kwekerij Bergcamp	171	150
Van Dijk Flowers	151	133
Rijk Zwaan	46	50
Greenvalley	97	
Ammerlaan Growers	163	
SVco Kreekrug	116	
Lans Scheeweg	44	81
U Grand	71	117
Lans Burgerweg	155	153

Table 5.16: Maximum polder section water level change, less accurate forecast, but more frequent feedback.

	Feedback update		Perfect prediction	
Name	Decrease (mm)	Increase (mm)	Decrease (mm)	Increase (mm)
KRN1 left	31	41	31	40
KRN1 right	5	10	5	14
KRZ1	8	30	5	8
KRZ5	23	38	20	33
KRZ4	98	98	101	97

Figure 5.30 presents the number of threshold exceedances in 2023 under the assumption that polder sections fail when the water level get above a threshold and the water levels in the reservoirs get below a threshold. Figure 5.31 compares the graph with the results found of the reference computation (Figure 4.17).

Table 5.17 indicates that polder sections do not fail because of Rainlevelr actions for 13 hours (14 hours for the first MPC computation). In order to achieve this the water level in the reservoirs gets less than 20 cm below reference level over 908 hours (805 hours for the first MPC computation).

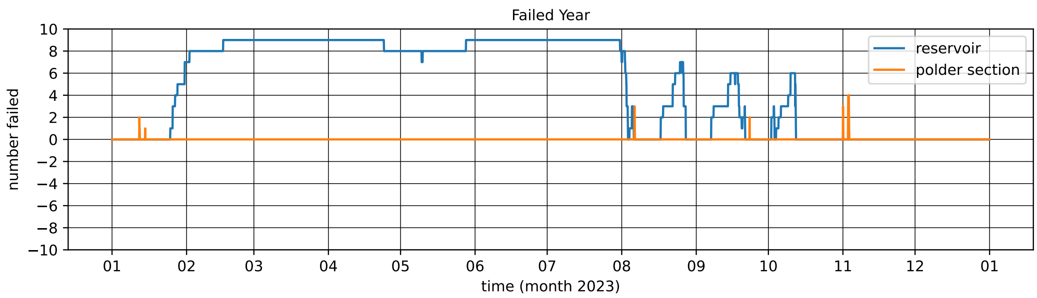


Figure 5.30: Threshold exceedance, less accurate forecast, but more frequent feedback.

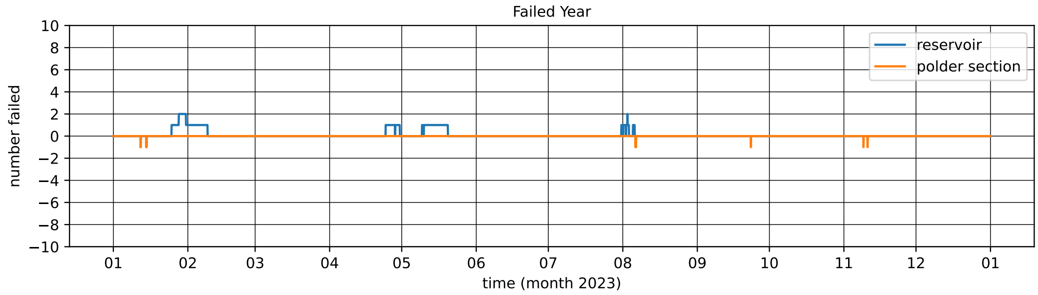


Figure 5.31: Net threshold exceedances less accurate forecast, but more frequent feedback with reference case.

Table 5.17: Hours failed less accurate forecast, but more frequent feedback.

Component	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Polder sections failed	0	0	0	0	0	0	0	0	0	0	0	0
Polder sections saved	-4	0	0	0	0	0	0	-3	-1	0	-5	0
Reservoirs failed	235	197	0	139	248	0	13	76	0	0	0	0

From the feedback simulation is concluded that a smaller feedback interval gives a more reliable estimation of the valve settings.

5.7. Increased number of participants

In order to investigate if the reservoirs that currently do not participate in the Rainlevelr project could contribute to the mitigation for flooding, a new simulation was set up. The polder weight is set to 0.7 and the reservoir weight is set to 0.3. The number of valve setting realizations is 100. Precipitation was predicted based on rain gauge measurements close to the polder. The calculation used a 24 hour prediction of the rainfall, which was updated every six hours. The number of Rainlevelr participants is 14. In this section water levels are given for a single polder in November, Appendix K presents the results for all polder sections and all reservoirs.

The valve height for the currently not-participating reservoirs is set to 50 % of the maximum height (de Vette and Berkhout, 2020). In Table 5.18 the valve dimensions of the non-Rainlevelr participants are given. The maximum valve dimension is set at 100 % and the valve flow is not maximized.

Table 5.18: Set valve dimensions in non-Rainlevelr reservoirs.

Name	Valve diameter (m)
otherKRN1 left	0.25
otherKRN1 right	0.50
otherKRZ1	0.50
otherKRZ5	0.25
otherKRZ4	0.16

Reservoir response

In Figure 5.32 the effect of the controller actions on the Kwekerij Bergcamp reservoir level is shown. Figure 5.33 compares the results with the reference simulation that was presented in Chapter 4. A maximum decrease of the water level of 110 mm was found for this simulation. In the first MPC simulation this decrease was 140 mm. The difference can be explained by the increase storage capacity as more reservoirs participate.

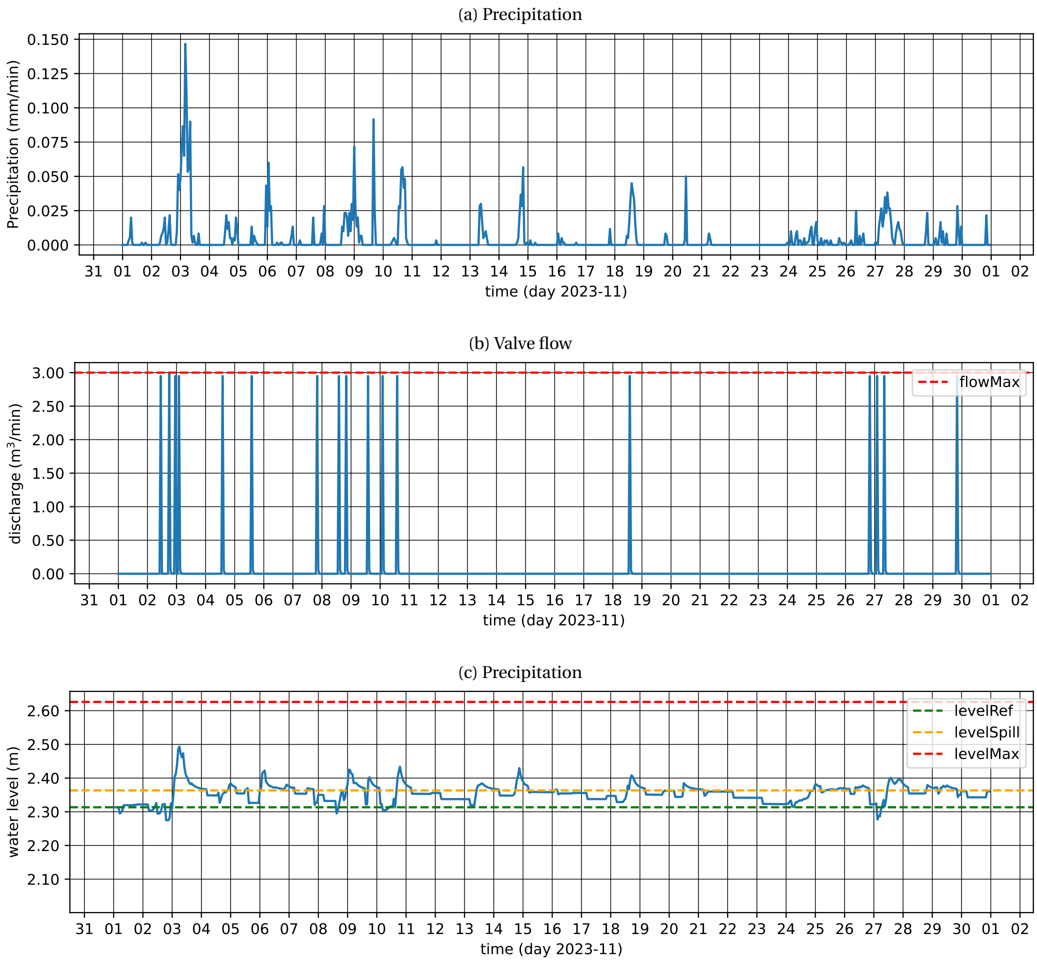


Figure 5.32: Reservoir Kwekerij Bergcamp, increased number of participants.

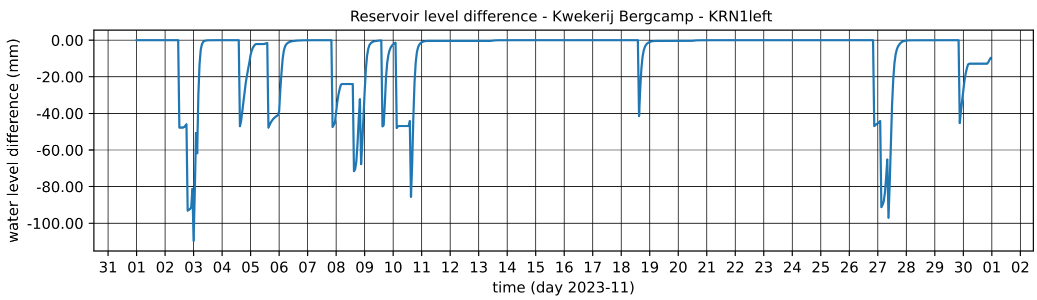


Figure 5.33: Reservoir Kwekerij Bergcamp, increased number of participants compared to reference case.

Polder section response

In Figure 5.34 the effect of the controller system on the polder section level in KRN1 left is shown if every reservoir in the Kralingerpolder participates in the Rainlevelr project. According to Figure 5.35 the water level increase is 82 mm (40 mm in the first MPC calculation) and the maximum decrease is 41 mm (20 mm in the first MPC calculation). Increasing the Rainlevelr capacity has a large effect on its performance.

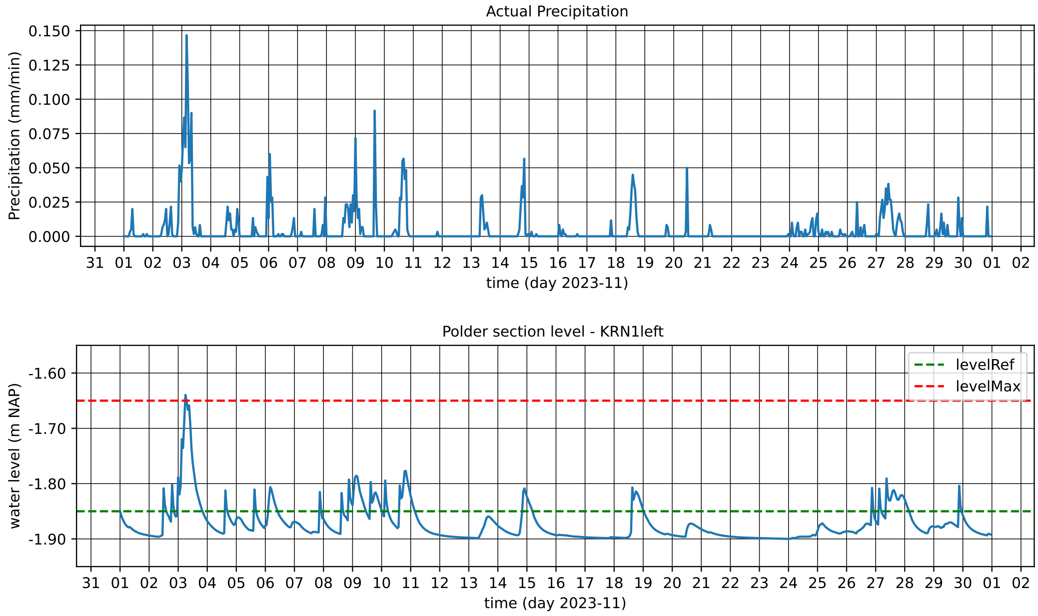


Figure 5.34: KRN1 left, increased number of participants.

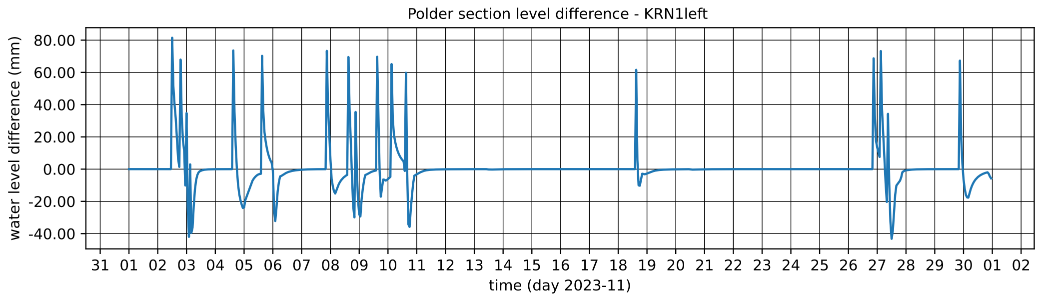


Figure 5.35: KRN1 left, increased number of participants compared to reference case.

Polder response

Table 5.19 gathers the maximum decrease in reservoir water levels for this MPC simulation. In Table 5.20 the maximum decrease and the maximum increase in polder section water level are collected. All extreme values are calculated over the year 2023. From both tables it can be concluded that currently participating reservoirs do not need to decrease their water level that much if all reservoirs participate in the Rainlevelr project. In the latter case the polder section levels, before a rain fall event takes place, can be reduced more.

Table 5.19: Maximum reservoir water level decrease, increased number of participants.

Name	14 participants Decrease (mm)	9 participants Decrease (mm)
Kwekerij Bergcamp	130	150
Van Dijk Flowers	120	133
otherKRN1left	290	
Rijk Zwaan	27	50
otherKRN1right	136	
Greenvalley	86	
Ammerlaan Growers	148	
SVco Kreekrug	108	
otherKRZ1	52	
Lans Scheeweg	45	81
U Grand	76	117
otherKRZ4	50	
Lans Burgerweg	122	153
otherKRZ5	187	

Table 5.20: Maximum polder section water level change, increased number of participants.

	14 participants		9 participants	
Name	Decrease (mm)	Increase (mm)	Decrease (mm)	Increase (mm)
KRN1 left	79	98	31	40
KRN1 right	22	65	5	14
KRZ1	22	106	5	8
KRZ5	37	75	20	33
KRZ4	95	100	101	97

Figure 5.36 presents the number of threshold exceedances in 2023. Figure 5.37 compares the graph with the results that were found for the reference computation (Figure 4.17).

Table 5.21 gathers the total threshold exceedance time per month. The table indicates that polder sections do not fail because of Rainlevelr actions over 26 hours (14 hours in the current situation where nine reservoirs participate). As a consequence the water level in the reservoirs never gets less than 20 cm below reference level (805 hours in the current situation). The table also shows that one false-negative event takes place where to polder exceeds the threshold. This happens in polder section KRZ5.

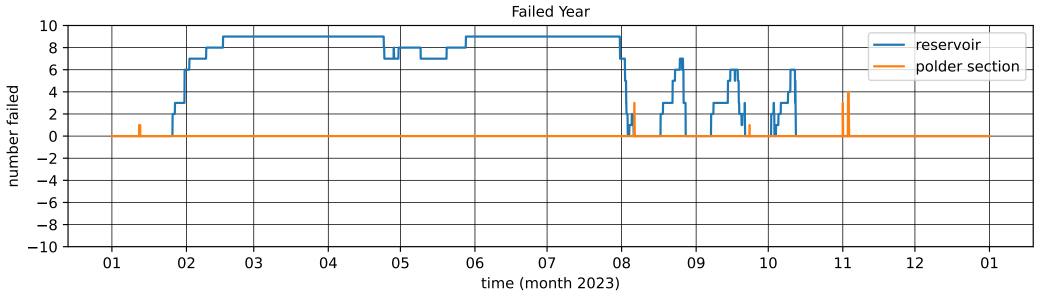


Figure 5.36: Threshold exceedance increased number of participants.

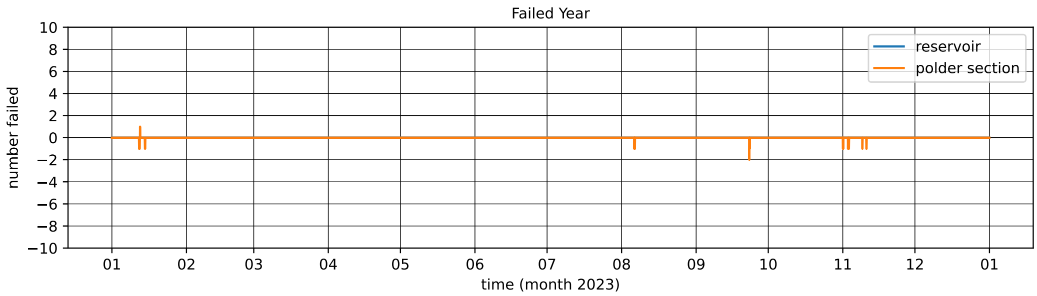


Figure 5.37: Net threshold exceedances increased number of participants with reference case.

Table 5.21: Hours failed increased number of participants.

Component	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Polder sections failed	1	0	0	0	0	0	0	0	0	0	0	0
Polder sections saved	-9	0	0	0	0	0	0	-2	-5	0	-10	0
Reservoirs failed	0	0	0	0	0	0	0	0	0	0	0	0

Increasing the Rainlevelr capacity has a large effect on its performance; currently participating reservoirs do not need to decrease their water level that much if all reservoirs participate in the Rainlevelr project and the polder section levels, before a rain fall event takes place, can be reduced more. The simulation showed that the controller was almost able to mitigate the flooding of the polder during the heavy rain event at the beginning of November.

6

Conclusions

This research focused on the coordinated management of reservoirs for a polder in Delfland. The goal of the research was to set up a Model Predictive Control strategy that optimizes valve settings of the Rainlevelr reservoirs to mitigate flooding in Westland. Rainlevelr uses storage space in irrigation water reservoirs to mitigate flooding while minimizing the loss of potential irrigation capacity.

Such a controller was designed and its performance was tested using a numerical model to represent the polder system being studied. The model run results showed that with the proposed strategy the risks can be reduced, and possible trade-offs were identified related to false positive or false negative errors due to inaccurate weather predictions. Risks were quantified by the exceedance of a threshold water level. Table 6.1 gives an overview of the simulations and the settings used for the Model Predictive Control.

Table 6.1: Scenarios settings

Scenario	Polder weight	Reservoir weight	Realizations	Weather	Feedback time (h)	Participants
Rainlevelr MPC	0.7	0.3	100	actual	-	9
Realizations	0.7	0.3	1000	actual	-	9
Weights	0.95	0.05	100	actual	-	9
Weather	0.7	0.3	100	predicted	24	9
Feedback	0.7	0.3	100	predicted	6	9
Participants	0.7	0.3	100	actual	-	14

In Table 6.2 the increase and decrease of the water levels are gathered together with the net threshold exceedances. These numbers represent the difference between the simulation outcome and the reference case result where no Rainlevelr actions were considered. Polder sections fail under the assumption that their water level gets above a threshold and the reservoirs fail when their water level gets below a threshold. The threshold for the polder sections is chosen at 10 cm below ground level and the threshold for the reservoirs is set to 20 cm below the reference level of the reservoirs.

Table 6.2: Threshold exceedance time and maximum water level changes per year for all scenarios

Scenario	Max polder decrease (mm)	Max polder increase (mm)	Polder failed (h)	Polder saved (h)	Max reservoir decrease (mm)	Reservoir failed (h)
Rainlevelr MPC	31	40	0	14	153	805
Realizations	25	38	1	9	196	626
Weights	37	49	0	18	316	876
Weather	14	31	0	6	501	4508
Feedback	31	41	0	13	171	908
Participants	79	106	1	26	290	0

The simulation showed that the Model Predictive Controller is able to reduce the number of polder section threshold exceedances at the expense of the reservoir threshold exceedances. However, the controller was not able to mitigate the flooding of the polder during the heavy rain event at the beginning of November.

It is concluded that the difference in predicted water levels with 1000 realizations and 100 realizations is small. However, the computation time increases with a factor 10. A computation over a period of a year takes about 2 hours for 100 realizations and about 20 hours for a 1000 realization simulation. For this reason it was decided that further computations would use 100 realizations.

The simulation showed that fewer polder sections fail at a cost of reservoir threshold exceedances if the weights for the polder sections are increased and reservoir weights are decreased.

The results show that controller performance decreases with decreasing accuracy of the weather forecast.

From the feedback simulation it followed that a smaller feedback interval of 6 hours gives a more reliable estimation of the valve settings than a water level update interval of 24 hours.

Increasing the potential storage capacity available to Rainlevelr has a large effect on its performance. Currently participating reservoirs do not need to decrease their water level that much if all reservoirs participate in the Rainlevelr project. The polder section levels, before a rain fall event takes place, can be reduced more. The simulation showed that the controller came very close to completely preventing a level exceedance of the polder during the heavy rain event at the beginning of November.

7

Discussion and recommendations

In this chapter alternative ways to mitigate polder flooding are discussed, aspects of the performance MPC algorithm presented here that may be improved by changes to the algorithm are discussed and recommendations to improve the model are given.

This research aimed at creating storage in greenhouse reservoirs before heavy rain fall events take place and did not focus on the storage in polder ditches and retention areas. Additional storage in the ditches can be created by lowering the weir heights in ditches before the rainfall event. This can be done manually or automatically and can also be supported by Model Predictive Control. Retention areas can be operated in the same way. The recharge from reservoirs and polder ditches prior to a rain event has to be pumped out of the polder into the boezem. This assumes the sufficient storage capacity is available in the boezem. A combination of Rainlevelr reservoirs, automatic weirs and retention areas will be most effective in preventing flooding in the polder.

The study indicated that the dewatering system of the polder could be improved by widening the ditch that transports the recharge out of the reservoirs of Kwekerij Bergcamp and van Dijk Flowers. The valve diameters of both reservoirs can then be enlarged.

The model that was set up does not consider time dependent flow of water through polder ditches. In order to inspect bottlenecks in the dewatering system of the polder a Sobek model could be set up. Sobek could potentially be integrated with the existing POKKA code.

The model only considers polder sections where Rainlevelr reservoirs are located. Adding all polder sections with their connecting weirs and culverts will make the outcome of the model more accurate. The water retention area Kraaiennest northeast of the Kralingerpolder should also be included in the model if the retention area will be part of the flood mitigating measures that need to be investigated. The model considers a static water level in the boezem. In an extension of the model this water level could be regulated. When the model has been adapted in this way, the model could be calibrated on field measurements.

The reservoirs of each greenhouse were assembled into one reservoir. However, each reservoir can be equipped with its own Rainlevelr valve. This will in practice create different dynamic behaviour of the water in the reservoirs and the polder ditches. Modeling all reservoirs of the greenhouses individually will make model predictions more accurate.

A generic irrigation schedule was proposed in the model. Irrigation schedules differ for all greenhouses because of difference in cultivation and different conditions over the year. Implementing the specific irrigation schedules for each greenhouse improves the model.

If the reservoir water levels get below a certain level, greenhouse owners will add water to the reservoir from other sources than rain. This ensures that there will be a sufficient amount of water available for irrigation. It also guarantees that the quality of the water is high. However, rain provides the best source for the plants. Adding this as a condition in the model will improve the model.

The model does not consider side friction or bend friction in the Rainlevelr pipe and the spill pipe. As both pipes need to overcome the distance between the reservoir and the ditch, the bends and side friction might be important. For the culvert side friction is not considered, however the culvert width is only two meters. The relevance could be investigated further.

A simulation in which all reservoir owners participate in the Rainlevelr project showed that the risk of flooding is further reduced and the reservoirs of the current participants lose less water. It is therefore recommended that all reservoirs should be equipped with a Rainlevelr pipe.

The current Rainlevelr actions are based on weather predictions. The actual precipitation is measured with a rain gauge. In order to facilitate future research both predictions and measurements should be stored.

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A

Elaborate calculation steps

A.1. Evaporation

Vapor pressures

The saturated vapor pressure e_s [kPa] (Food and Agricultural Organization of the United Nations, nd) is derived as:

$$e_s = 0.61 \exp\left(\frac{17.27\,T}{T + 273.30}\right), \tag{A.1}$$

where:

T	Temperature	[°C]

The temperature is measured at a KNMI weather station (KNMI, 2024). The change in saturated vapor pressure on temperature s [kPa/°C] is expressed as:

$$s = \frac{de_s}{dT} = \frac{4719.89\,e_s}{(T + 273.30)^2}. \tag{A.2}$$

The actual vapor pressure e_a [kPa] is derived as follows:

$$e_a = \frac{U}{100} e_s. \tag{A.3}$$

where:

U	Relative humidity	[%]

This relative humidity is obtained from weather station data.

Radiation

The net short-wave radiation R_n [J/m^{2}s] is expressed as:

$$R_n = (1 - \alpha) R_c - R_B. \tag{A.4}$$

where:

α	Albedo reflection coefficient	[−]
R_c	Incoming short wave radiation	[J/m^{2}s]
R_B	Outgoing long wave radiation	[J/m^{2}s]

The incoming short-wave radiation is derived from weather station data. The Albedo coefficient α for water varies between 5 and 22 %. For the calculation this value is set to 0.13.

The outgoing long-wave flux R_B [J/m^{2}s] is derived as:

$$R_B = \sigma (T + 273.15)^4 \left(0.47 - 0.24\sqrt{e_a}\right)(0.2 + 0.8\,\theta). \tag{A.5}$$

where:

σ	Stefan Bolzmann's constant, cloudiness factor	[$\approx 5.67510^{-8} \cdot$ J/m^{2}K^{4}s]
θ	Ratio of the actual sun hours and the theoretical maximum sun hours	[-]

The ratio of the actual sun hours and the theoretical maximum sun hours θ [-] for the Netherlands is expressed as:

$$\theta = \frac{(R_c/R_a - 0.2)}{0.48}. \tag{A.6}$$

where:

R_a	Short-wave radiation	[J/m^2/s]

The short-wave radiation R_a [J/m^{2}s] follows from Food and Agricultural Organization of the United Nations (nd):

$$R_a = \frac{G_{sc}}{\pi} d_r \left(\omega_s \sin(\phi)\sin(\delta) + \cos(\phi)\cos(\delta)\sin(\omega_s)\right). \tag{A.7}$$

where:

G_{sc}	Solar radiation flux	[$\approx$ 1367 J/m^2/s]
ω_s	Solar Hour Angle at Sunset	[rad]
ϕ	Angle of the latitude	[rad]
δ	Declination of Sun	[rad]

The inverse relative distance Earth-Sun d_r [-] is written as:

$$d_r = 1 + 0.033\cos\left(\frac{2\pi N}{365.25}\right). \tag{A.8}$$

where:

N	Day number in year	[-]

The sun declination angle δ [rad] is calculated as:

$$\delta = 0.409\sin\left(\frac{2\pi N}{365.25} - 1.39\right) \tag{A.9}$$

where:

N	Day number in year	[-]

The hour angle at sunset ω_s [rad] is calculated as:

$$\omega_s = \arccos(-\tan(\phi) * \tan(\delta)) \tag{A.10}$$

Aerodynamic Resistance
The aerodynamic resistance r_a [s/m] is expressed as:

$$r_a = \frac{245}{(0.54F + 0.5)} \frac{1}{86400} \tag{A.11}$$

where:

F	Wind speed	[m/s]

The wind speed is derived from the weather station.

A.2. Derivative of valve flow

The non-linear differential equation by the discharge of the valve Q_v [m^3/min] is derived from Equation 3.1 and Equation 3.11 and can be expressed as:

$$\frac{d\zeta}{dt} = -\frac{Q_v}{A_r} = -\frac{a\sqrt{b(\zeta(t) - c)}}{A_r} \tag{A.12}$$

$$a = \frac{1}{4}\pi(D_v v)^2 \mu_v \quad b = 2g \quad c = z_v + D_v v \quad \zeta(t) \geq c \quad \zeta(0) = z_s$$

Because c is a constant:

$$\frac{d(\zeta - c)}{dt} = \frac{d\zeta}{dt} \tag{A.13}$$

If y is defined as $y^2 = \zeta - c$, then:

$$\frac{dy^2}{dt} = -\frac{a\sqrt{b}}{A_r} y \tag{A.14}$$

so:

$$\frac{dy}{dt} = -\frac{a\sqrt{b}}{2A_r} \tag{A.15}$$

with $Q_v = ay\sqrt{b}$ then:

$$\frac{dQ_v}{dt} = a\sqrt{b}\frac{dy}{dt} = -a\sqrt{b}\frac{a\sqrt{b}}{2A_r} = -\frac{a^2 b}{2A_r} \tag{A.16}$$

Solving this differential equation with an initial level at spill height z_s yields:

$$Q_v(t) = Q_v(0) - \frac{a^2 b}{2A_r} t \tag{A.17}$$

$$Q_v(0) = a\sqrt{b(z_s - c)}$$

Resulting in:

$$Q_v(t) = a\sqrt{b(z_s - c)} - \frac{a^2 b}{2A_r} t \tag{A.18}$$

B

Input files

Table B.1: Dimensions of the culvert (Hoogheemraadschap van Delfland, 2024).

Code	Culvert width (m)	Ditch width (m)	Contraction coefficient (-)
Kralingerpad	3.10	3.85	1.00

Table B.2: Dimensions of the weirs (Hoogheemraadschap van Delfland, 2024).

Code	Weir width (m)	Max height (m NAP)	Min height (m NAP)	Regulation height (m NAP)
114201	1.00	-1.63	-2.34	-1.90
114205	1.00	-1.47	-2.47	-2.40
114206	1.00	-1.28	-2.23	-1.90
114209	1.50	-2.00	-2.60	-2.25
114210	2.00	-2.10	-3.00	-2.40
114211	0.60	-1.59	-2.28	-1.90
114413	0.50	-2.30	-2.30	-2.30
114416	4.00	-1.86	-1.86	-1.86
11480221	1.04	-1.31	-2.19	-1.82

Table B.3: Dimensions of the pumps (De Nederlandse Gemalen Stichting, 2024) (Hoogheemraadschap van Delfland, 2024).

Code	Min pump flow (m^3/min)	Max pump flow (m^3/min)	Pump amount (-)	Max level (m NAP)	Min level (m NAP)
114102	63	75	2	-2.55	-2.65

Table B.4: Overview of reservoirs in the Kralingerpolder (Hoogheemraadschap van Delfland, 2024)

Code	Name	Participant	Max volume (m^3)	Reservoir area (m^2)	Greenhouse area (m^2)	Plot area (m^2)	Spill diameter (m)	Valve diameter (m)	Max valve (%)	Max flow (m^3/hour)
DIG0017	Rijk Zwaan	True	10,000	5,700	50,000	50,000	1.00	0.16	100	180.0
DIG0155	Kwekerij Bergcamp	True	9,900	3,770	68,000	68,000	1.00	0.16	40	22.0
DIG0203	van Dijk Flowers	True	7,600	3,050	35,500	35,500	1.00	0.16	100	
DIG0061	Greenvalley	True	8,000	3,000	120,000	120,000	1.00	0.20	100	432.0
DIG0141	Ammerlaan Growers	True	6,000	1,500	51,000	51,000	1.00	0.20	100	468.0
DIG0146	SVco Kreekrug	True	4,000	1,600	33,500	33,500	1.00	0.16	100	252.0
DIG0113	Lans Scheeweg	True	20,000	5,660	125,000	125,000	1.00	0.20	100	468.0
DIG0158	Lans Burgerweg	True	20,000	5,660	128,550	128,550	1.00	0.20	80	270.0
DIG0117	U Grand	True	8,000	2,500	103,000	103,000	1.00	0.25	100	684.0
otherKRN1 left	otherKRN1 left	False	13,317	4,439	200,775	200,775	1.00			
otherKRN1 right	otherKRN1 right	False	62,564	15,641	467,913	467,913	1.00			
otherKRZ1	otherKRZ1	False	132,171	37,763	504,259	504,259	1.00			
otherKRZ5	otherKRZ5	False	15,030	5,010	148,640	148,640	1.00			
otherKRZ4	otherKRZ4	False	2,510	2,510	0	0	1.00			

Table B.5: Overview characteristics of the Kralingerpolder (Geofabrik, 2024) (Hoogheemraadschap van Delfland, 2024)

Code	Paved area (m^2)	Unpaved area (m^2)	Ditch area (m^2)	level Ref (m NAP)	Reservoir code	Weir contact	Weir code	Culvert contact	Culvert code	Pump code
KRN1left	8,677	24,573	8,117	-1.85	['DIG0155', 'DIG0203', 'oth-erKRN1left']	['KRZ5']	['114201']	['KRN1right']	['Kralingerpad']	
KRN1right	140,243	77,022	31,626	-1.85	['DIG0017', 'oth-erKRN1right']	['KRZ1', 'KRZ1', 'KRZ1', 'KRZ1']	['114206', '114211', '114416', '11480221']			
KRZ1	48,668	109,359	26,023	-2.35	['DIG0061', 'DIG0141', 'DIG0146', 'otherKRZ1']	['KRZ4', 'KRZ4']	['114205', '114210']			
KRZ5	24,992	72,925	17,733	-2.20	['DIG0113', 'otherKRZ5']	['KRZ4', 'KRZ4']	['114209', '114413']			
KRZ4	27,950	118,350	79,431	-2.60	['DIG0117', 'DIG0158', 'otherKRZ4']					['114102']

C
Reference simulation 2023

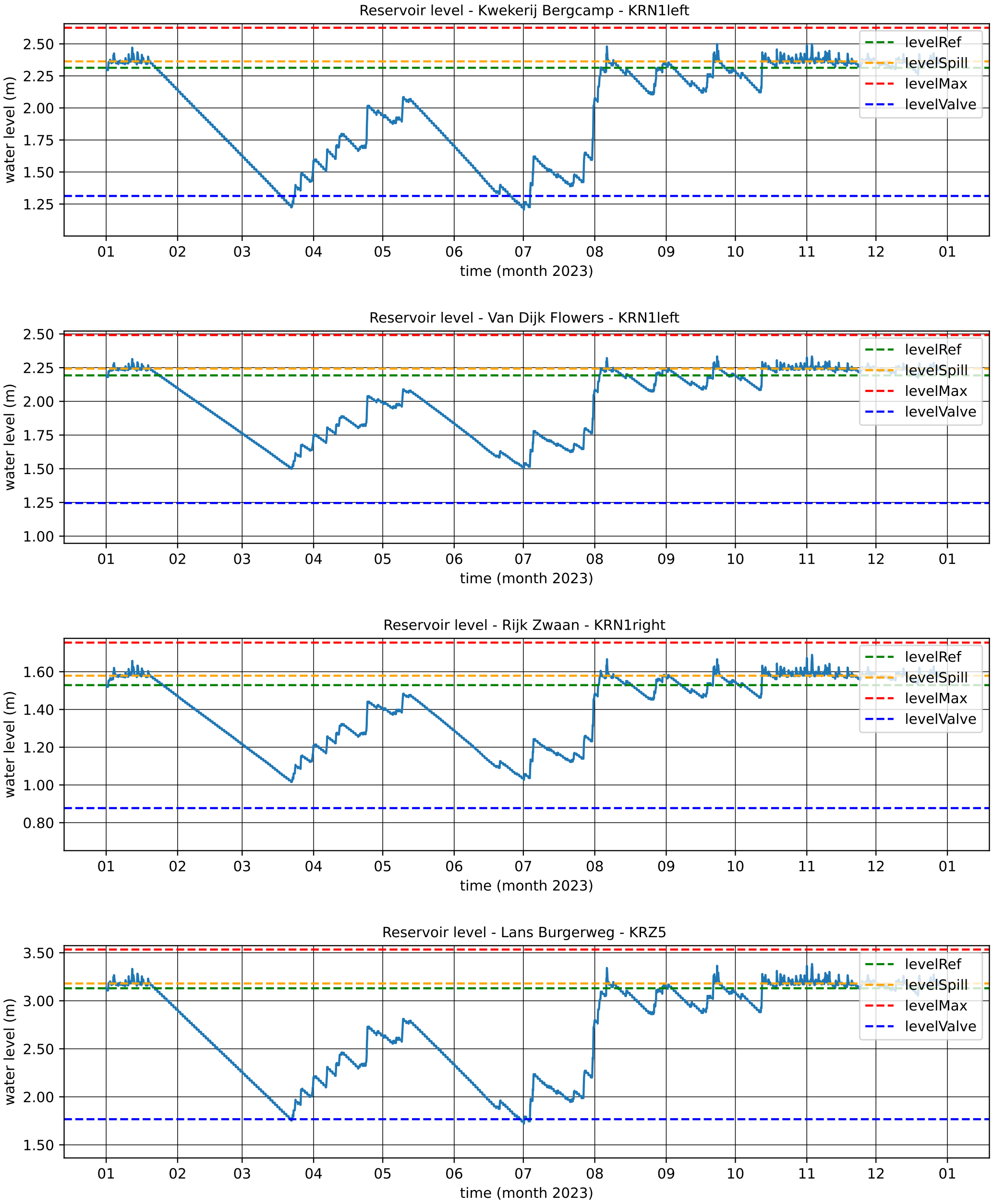

Figure C.1: Water level reservoirs part 1, 2023 without Rainlevelr.

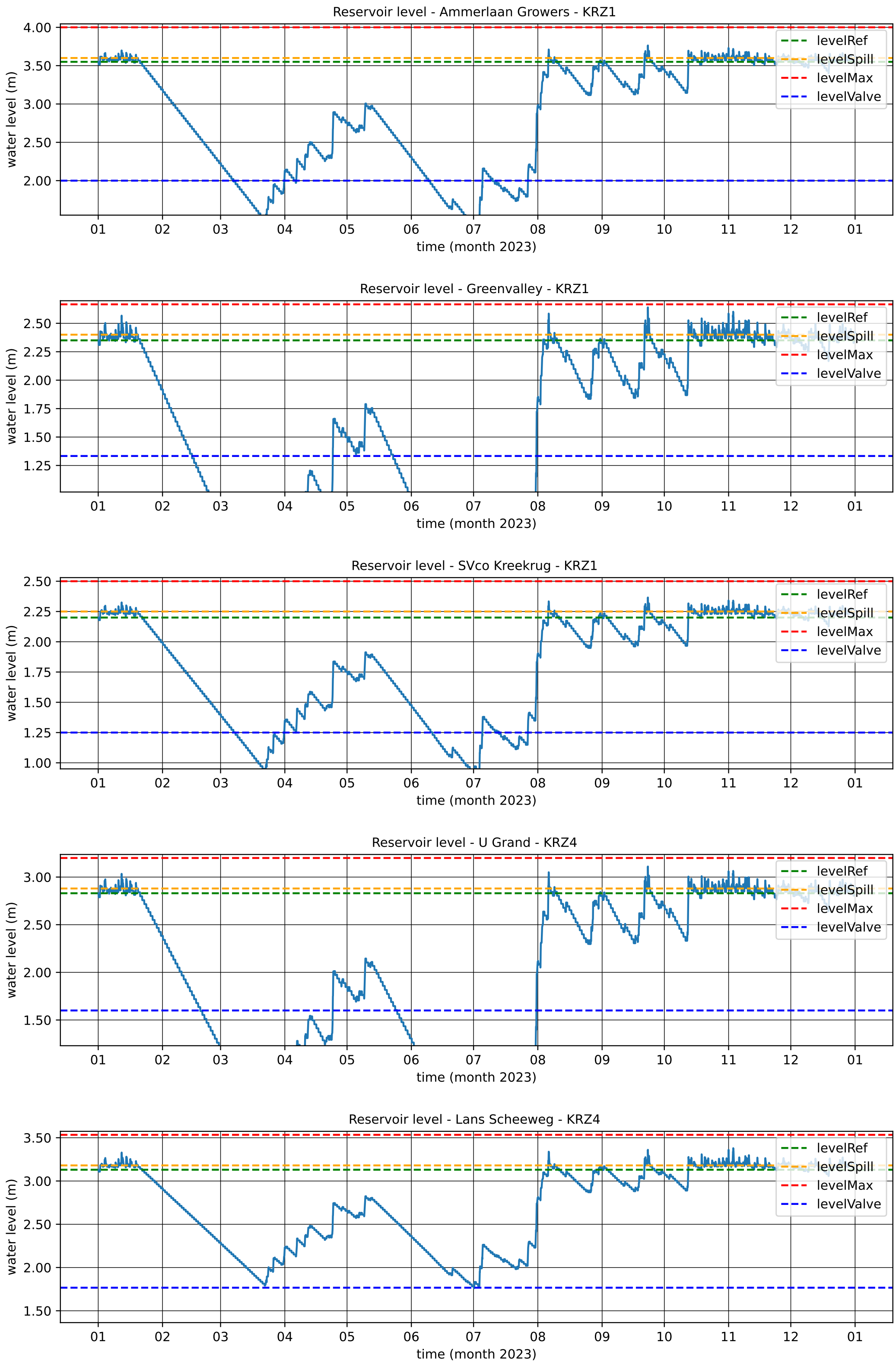

Figure C.2: Water level reservoirs part 2, 2023 without Rainlevelr.

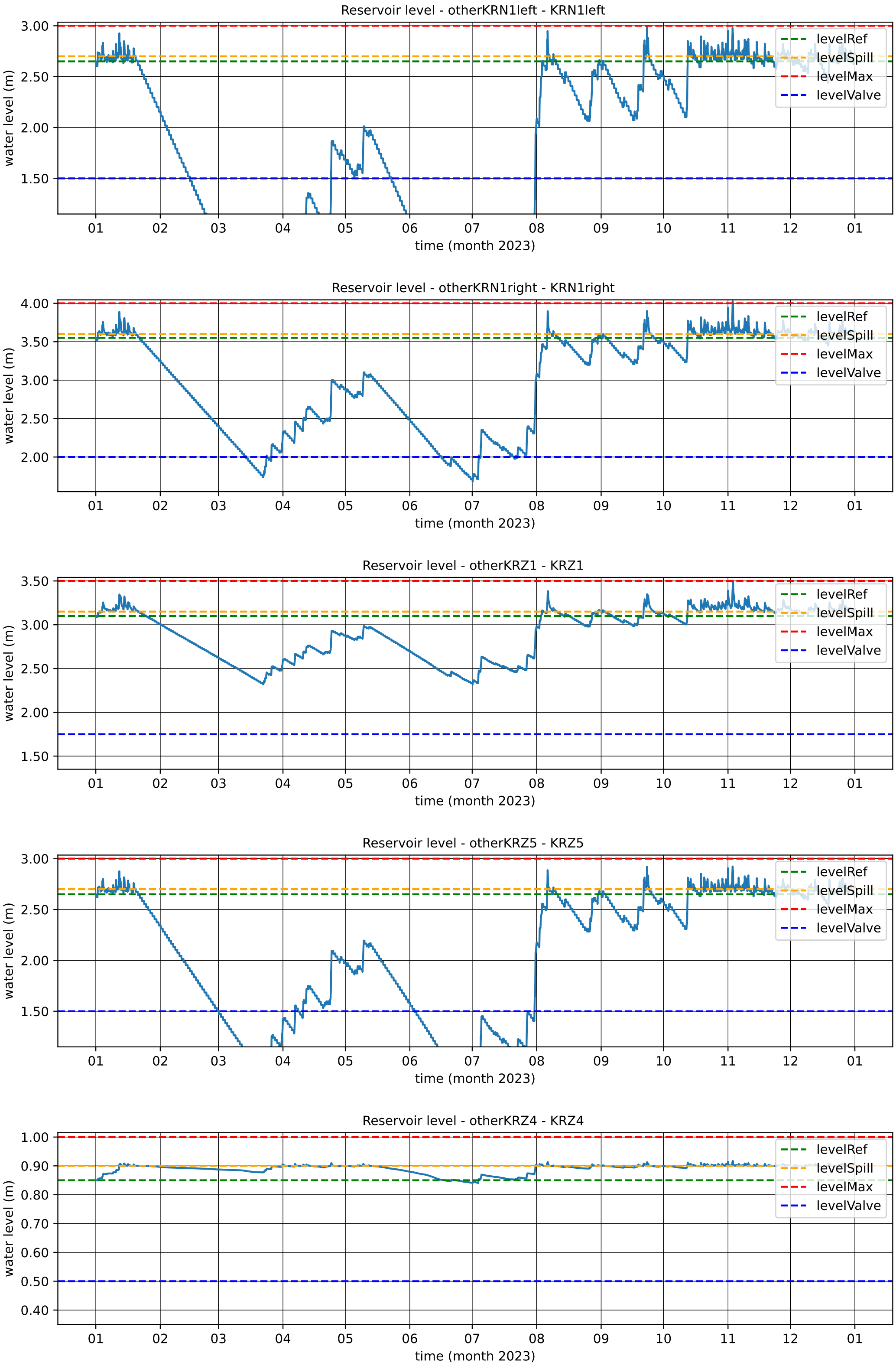

Figure C.3: Water level reservoirs part 3, 2023 without Rainlevelr.

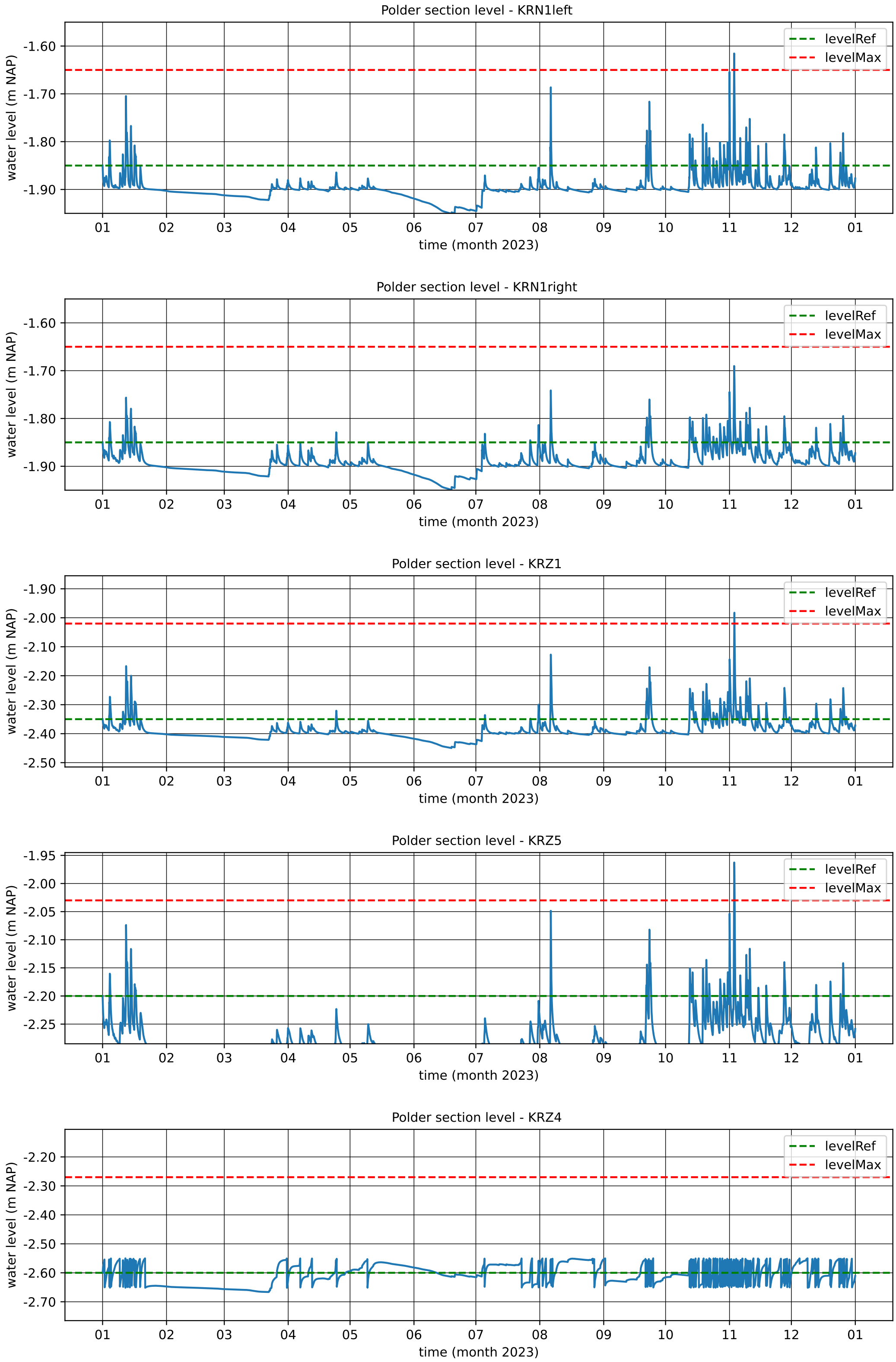

Figure C.4: Water level polder sections, 2023 without Rainlevelr.

D

Reference simulation November 2023

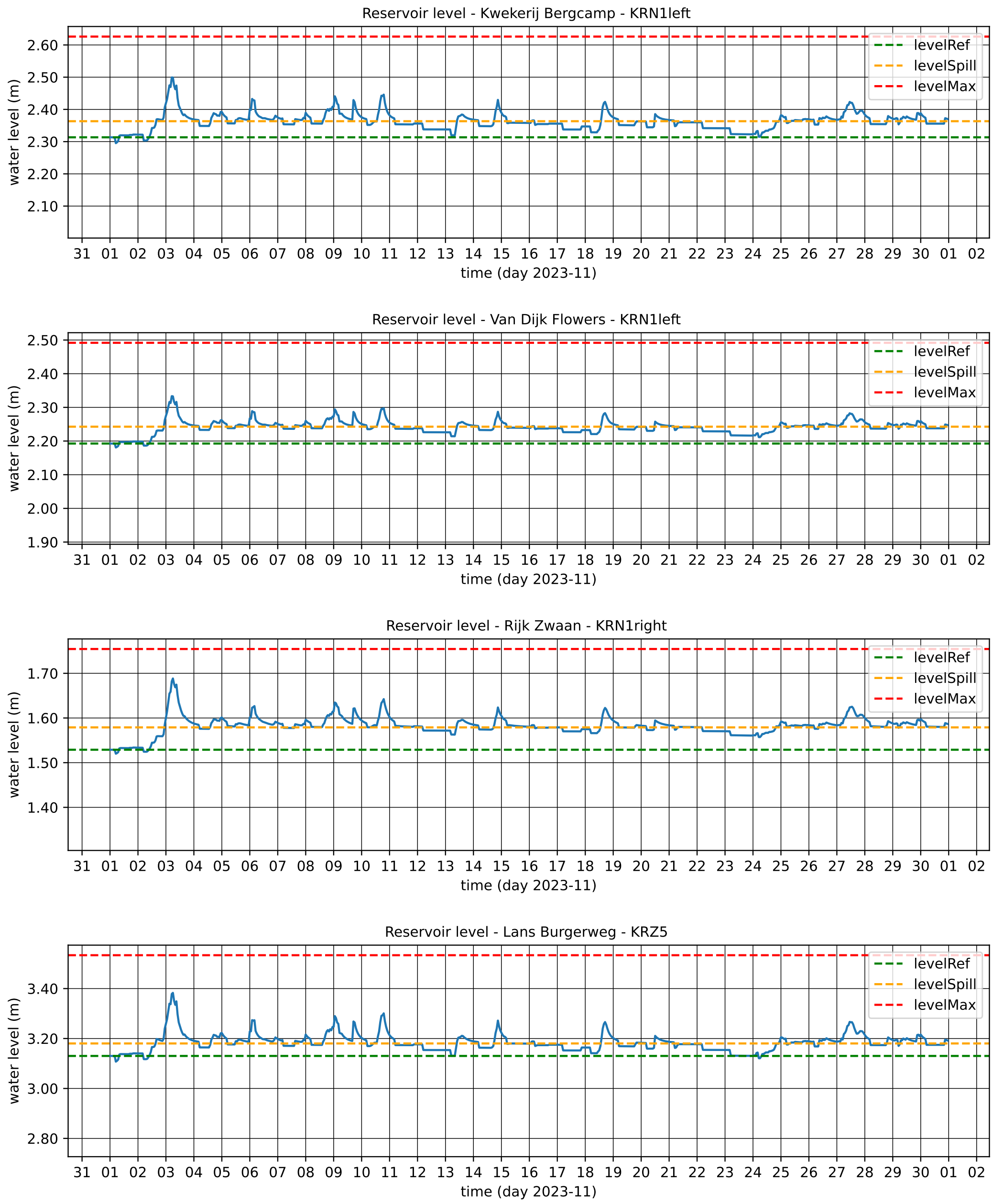

Figure D.1: Water level reservoirs part 1, November 2023 without Rainlevelr.

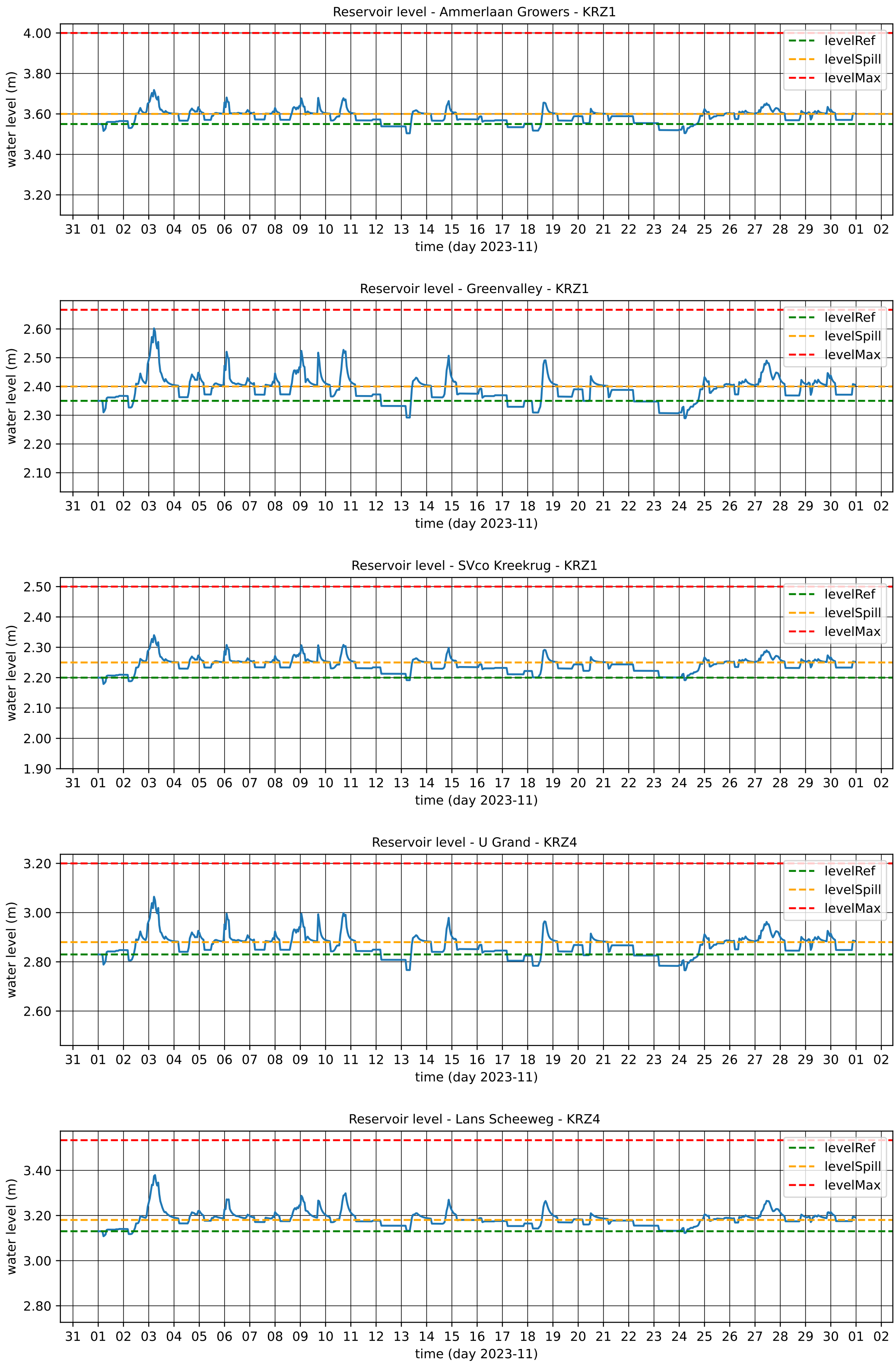

Figure D.2: Water level reservoirs part 2, November 2023 without Rainlevelr.

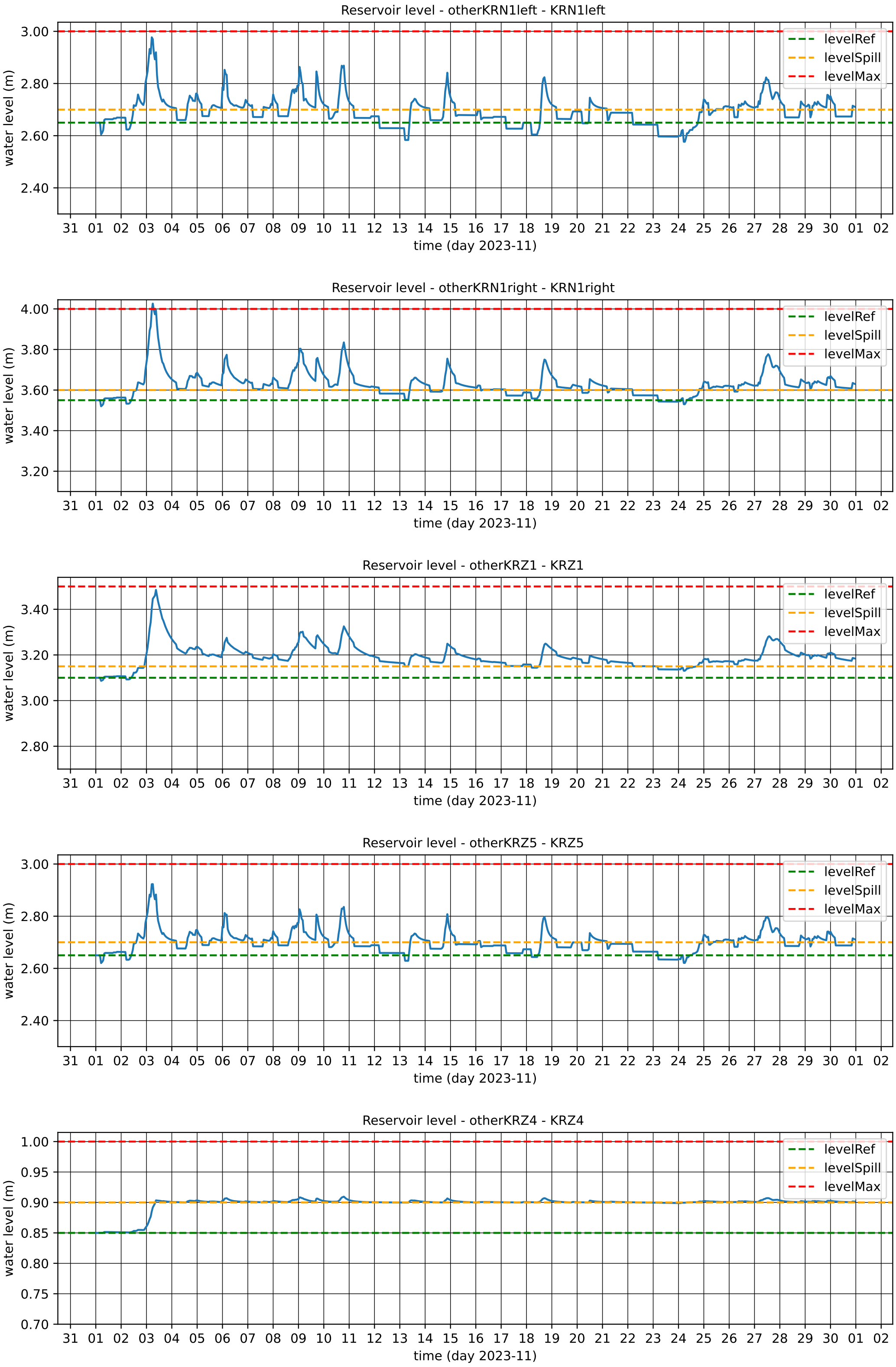

Figure D.3: Water level reservoirs part 3, November 2023 without Rainlevelr.

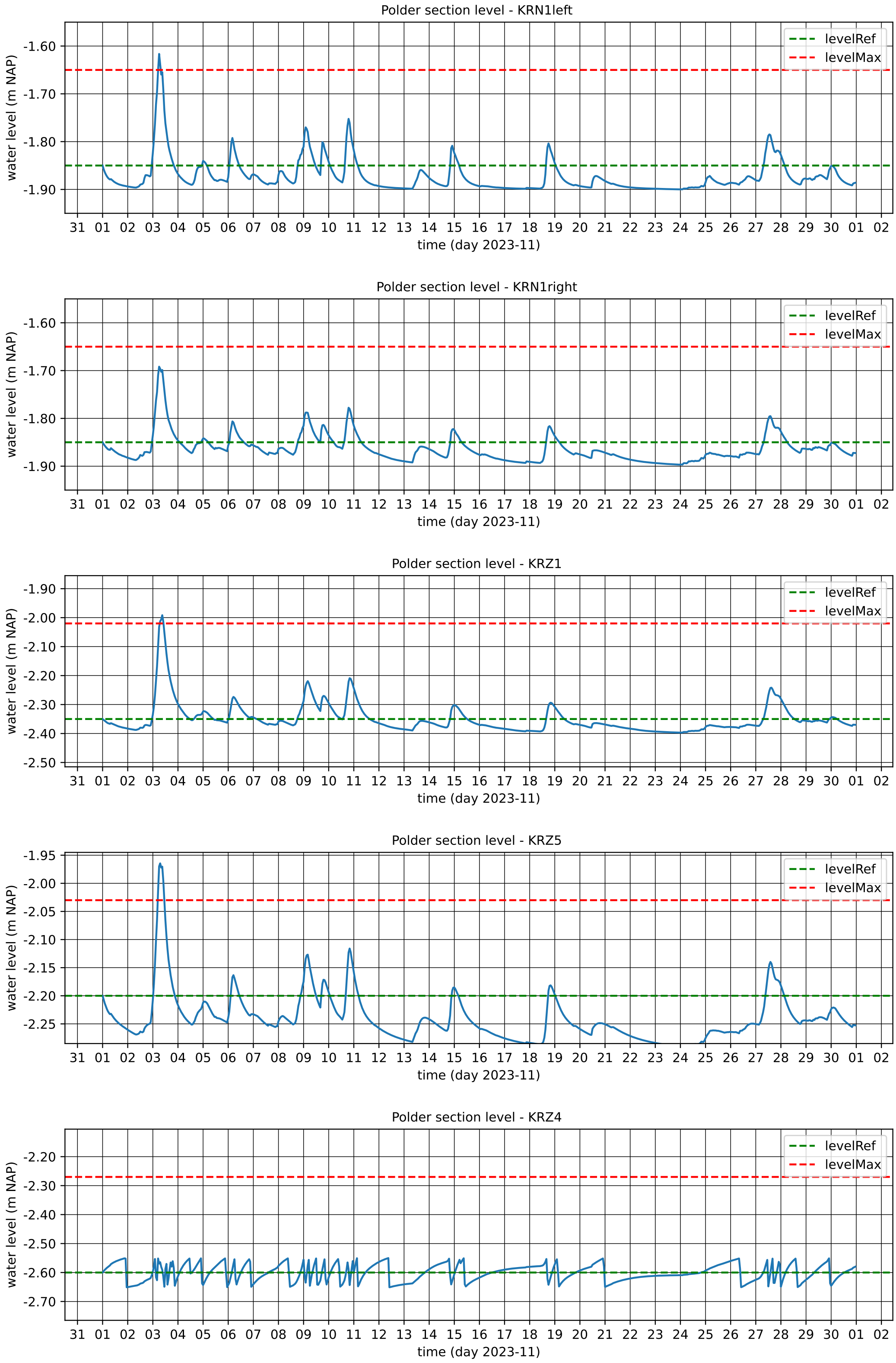

Figure D.4: Water level polder sections, November 2023 without Rainlevelr.

E
Valve dimension synchronization

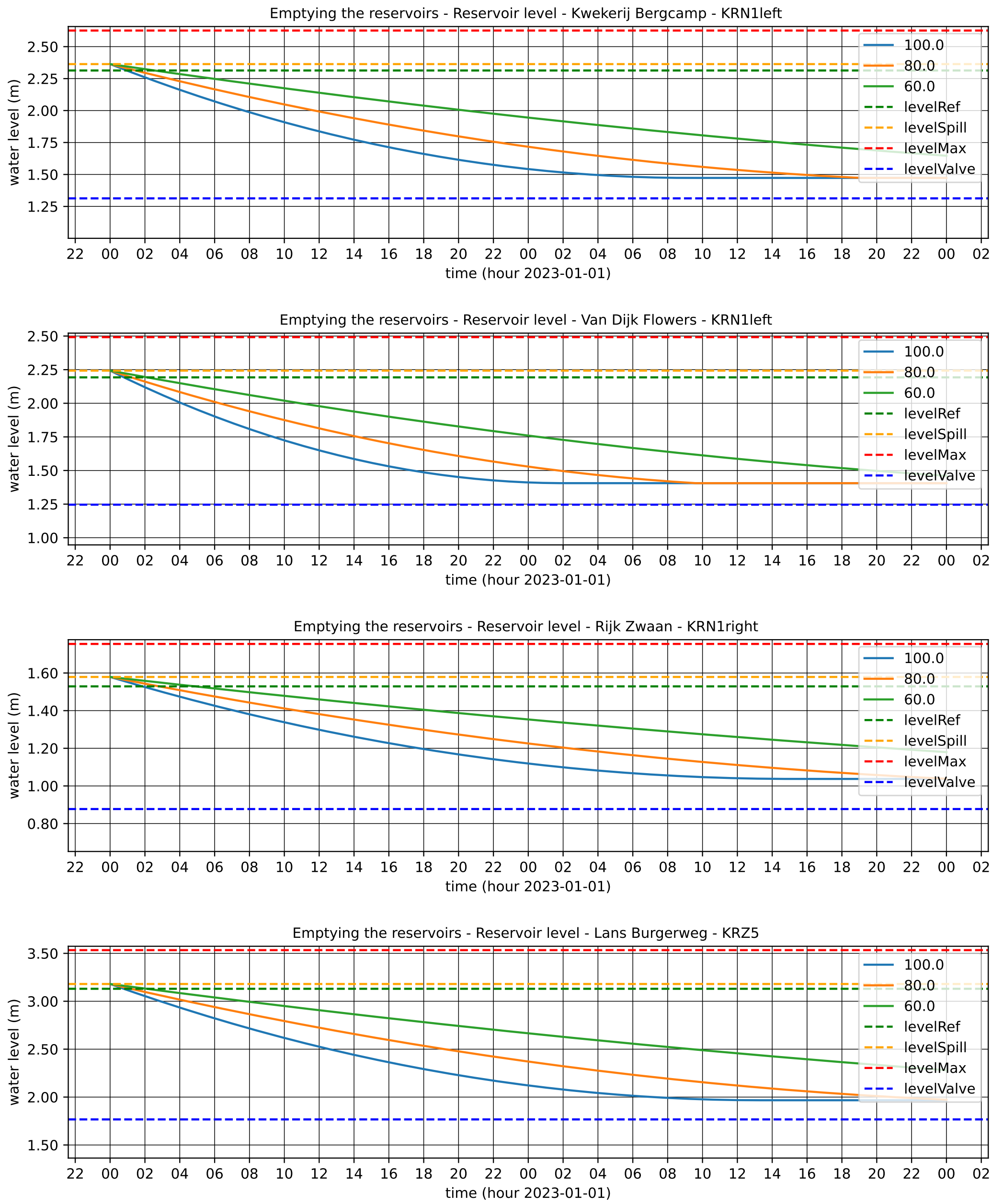

Figure E.1: Water level reservoirs part 1, valve dimension synchronization.

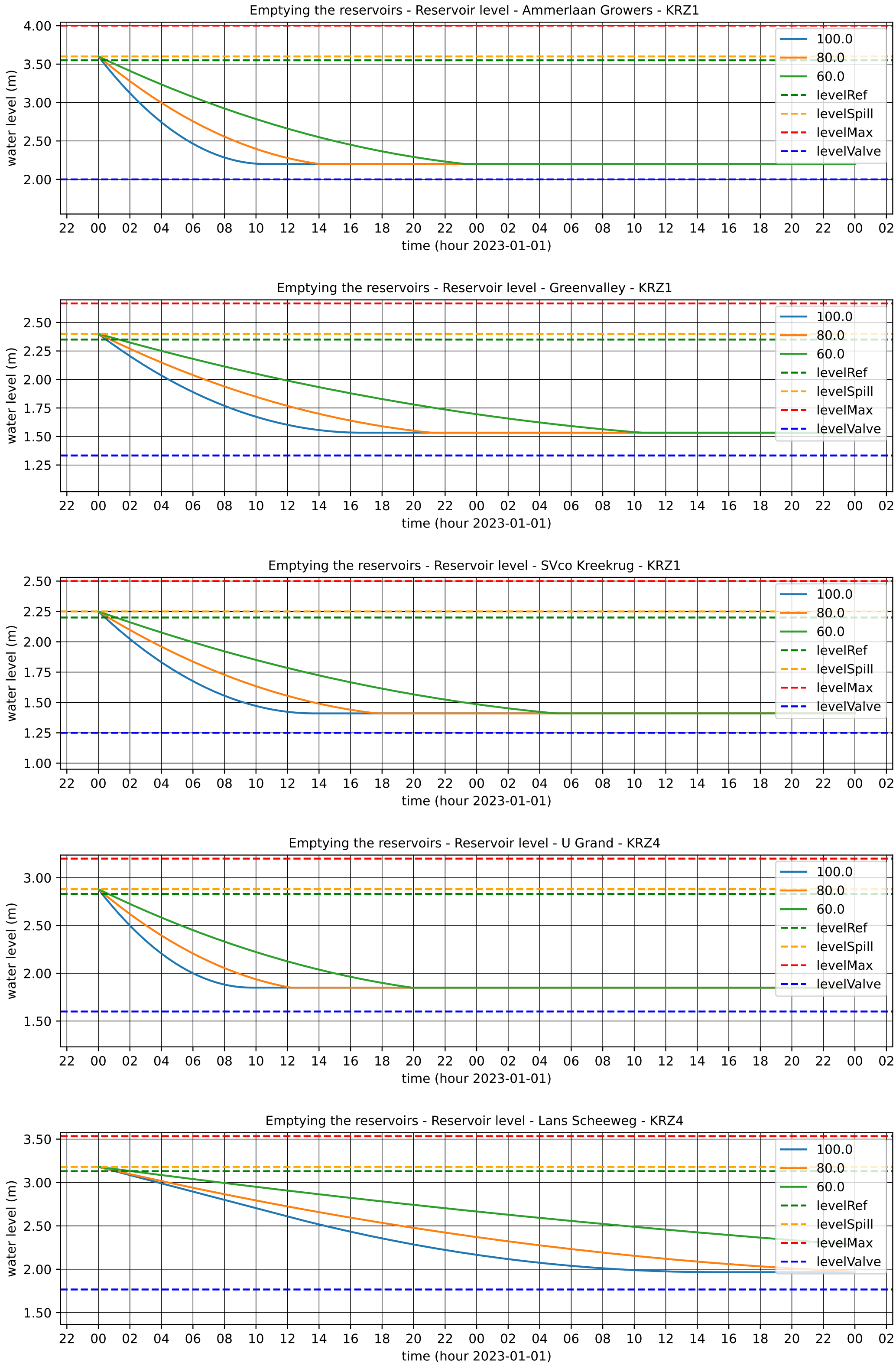

Figure E.2: Water level reservoirs part 2, valve dimension synchronization.

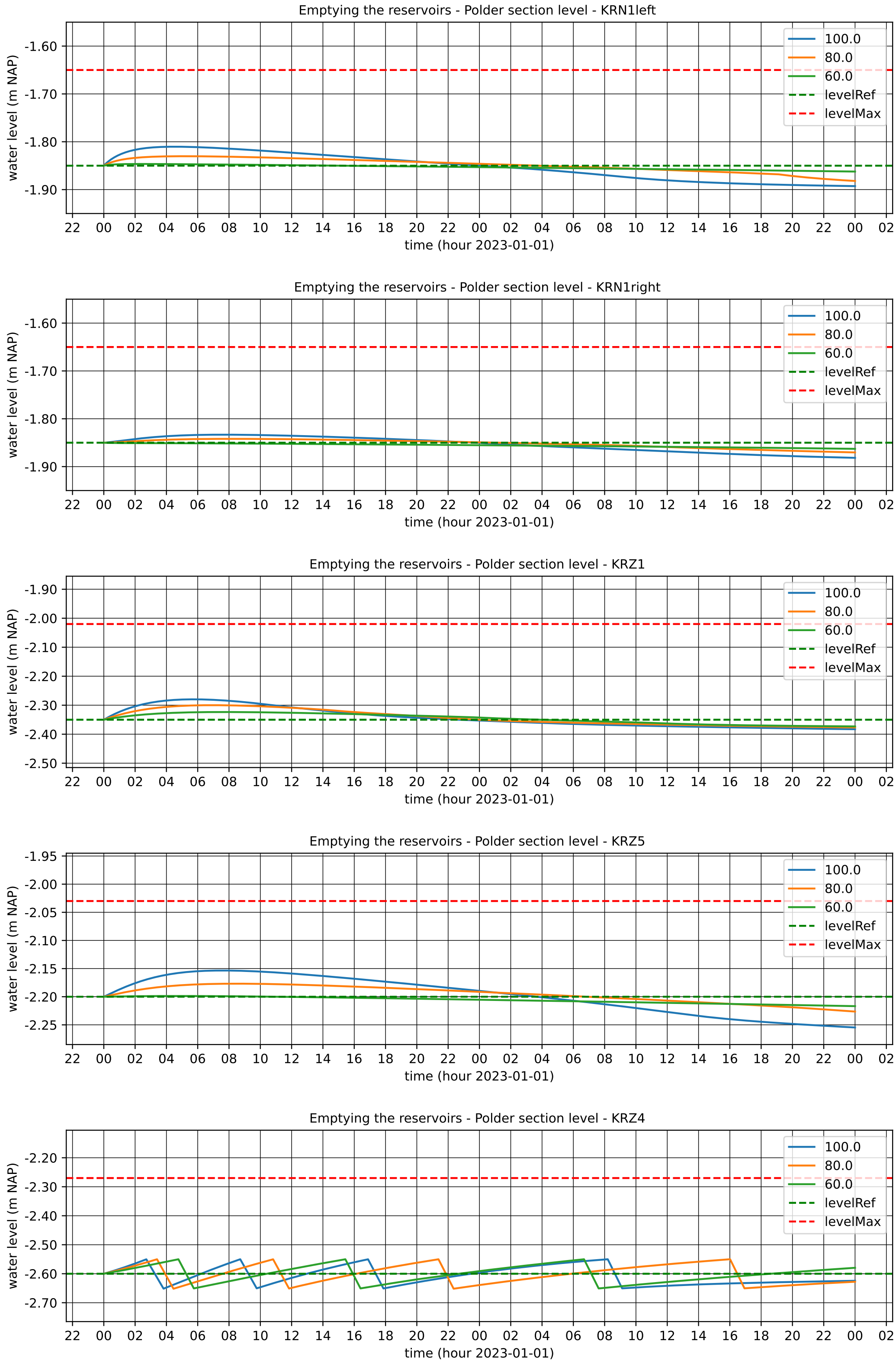

Figure E.3: Water level polder sections, valve dimension synchronization.

F

Rainlevelr MPC setup

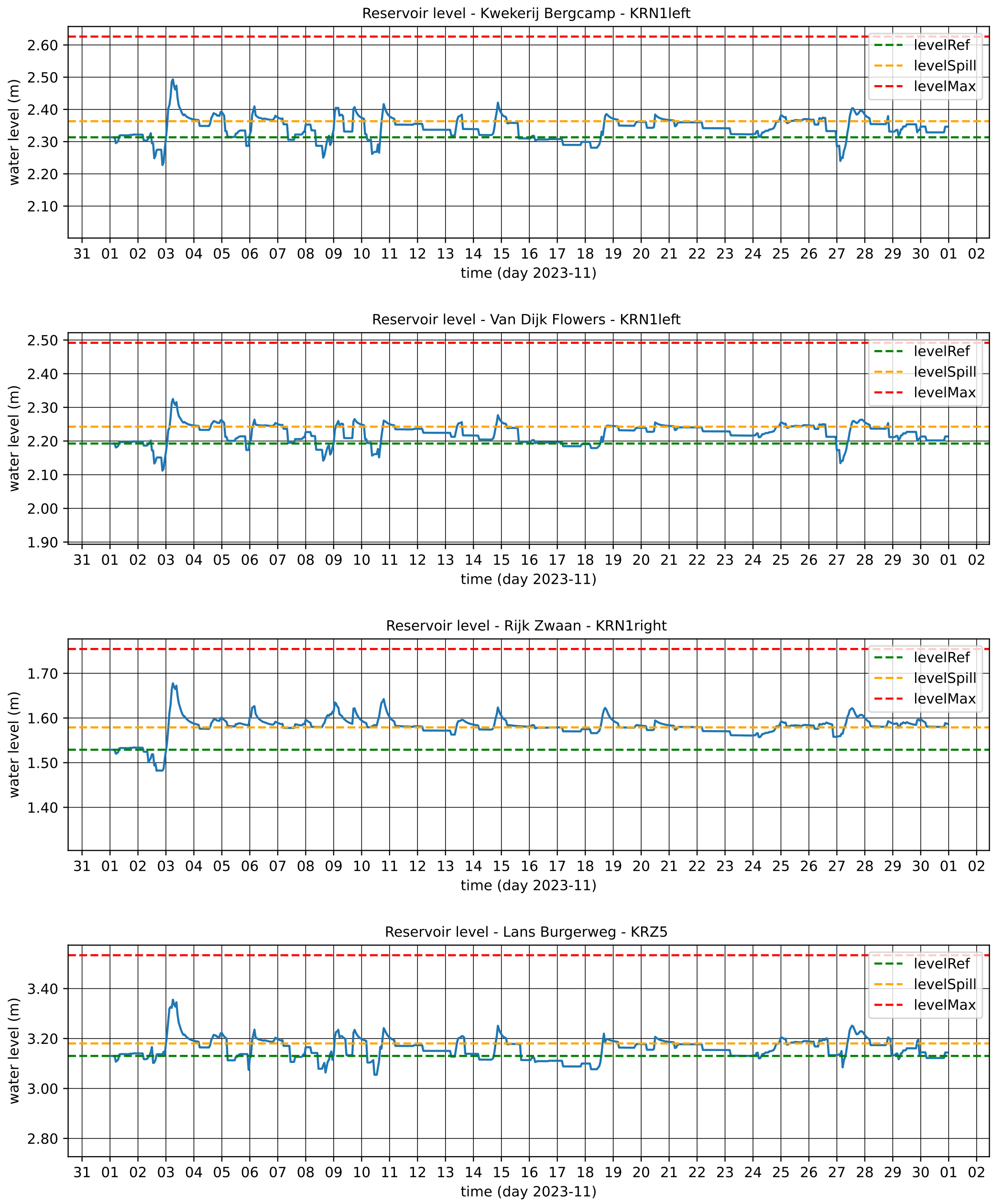

Figure F.1: Water level reservoirs part 1, Rainlevelr MPC setup.

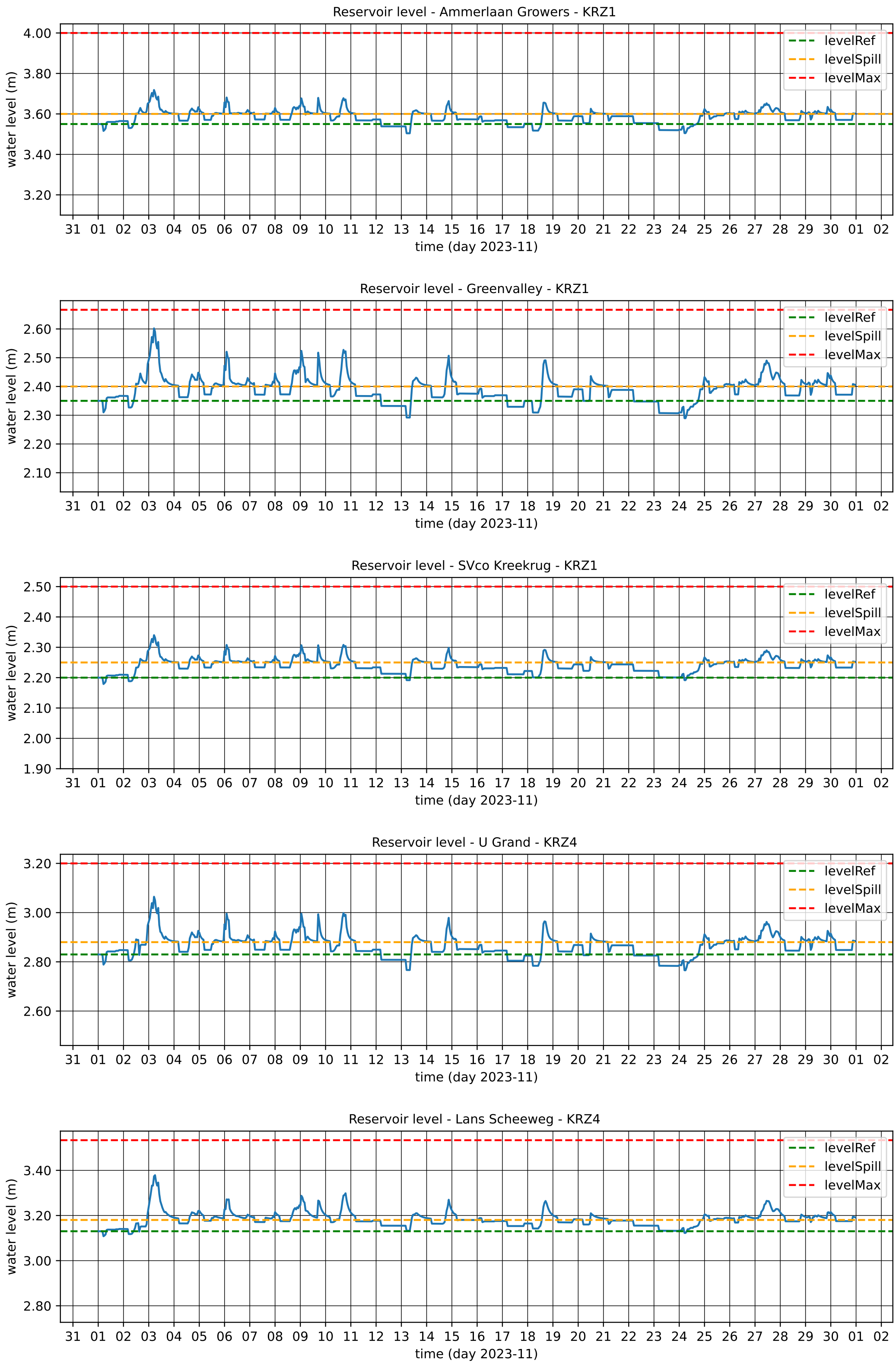

Figure F.2: Water level reservoirs part 2, Rainlevelr MPC setup.

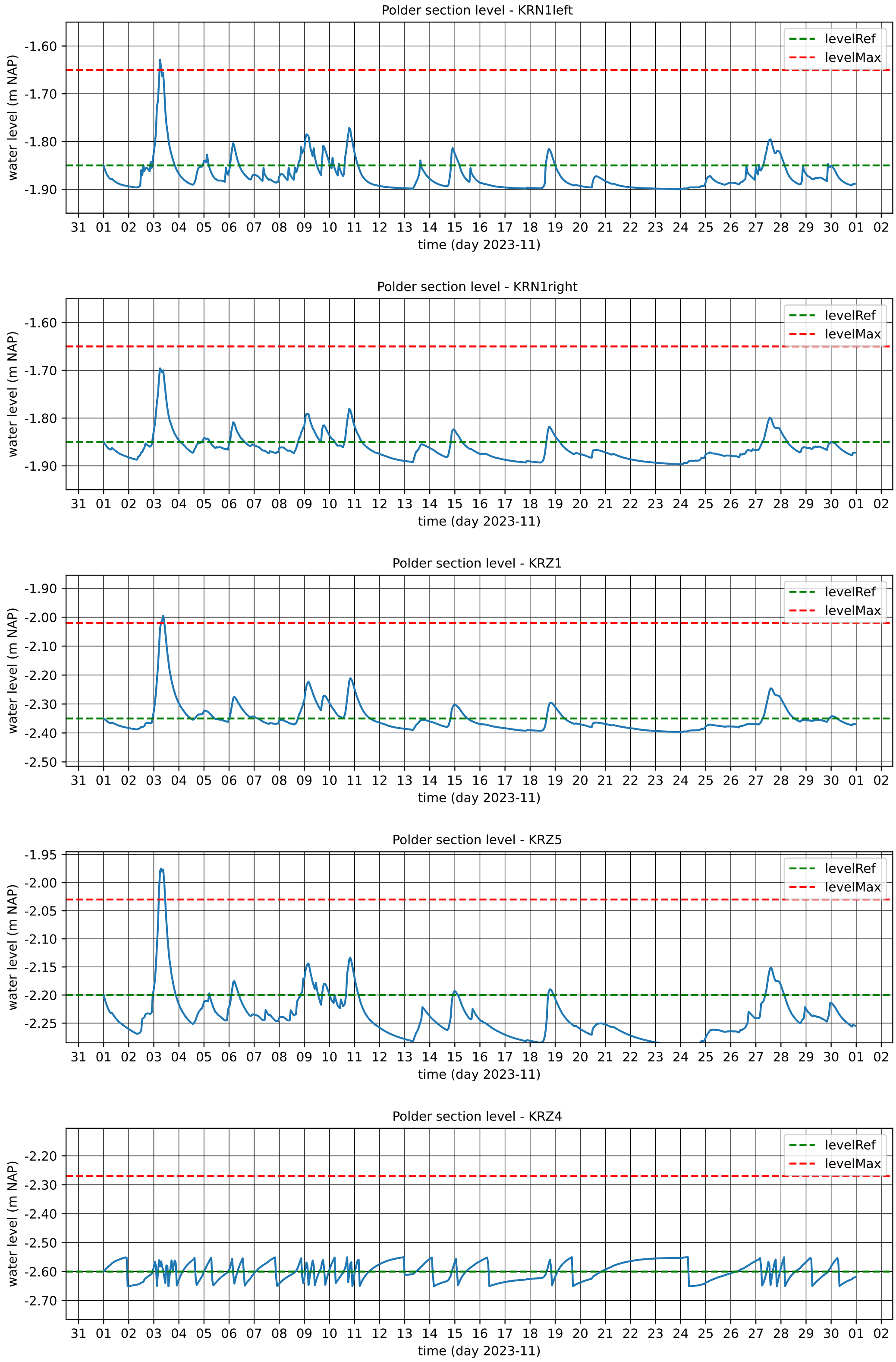

Figure F.3: Water level polder sections, Rainlevelr MPC setup.

G

Number of realizations in optimizer

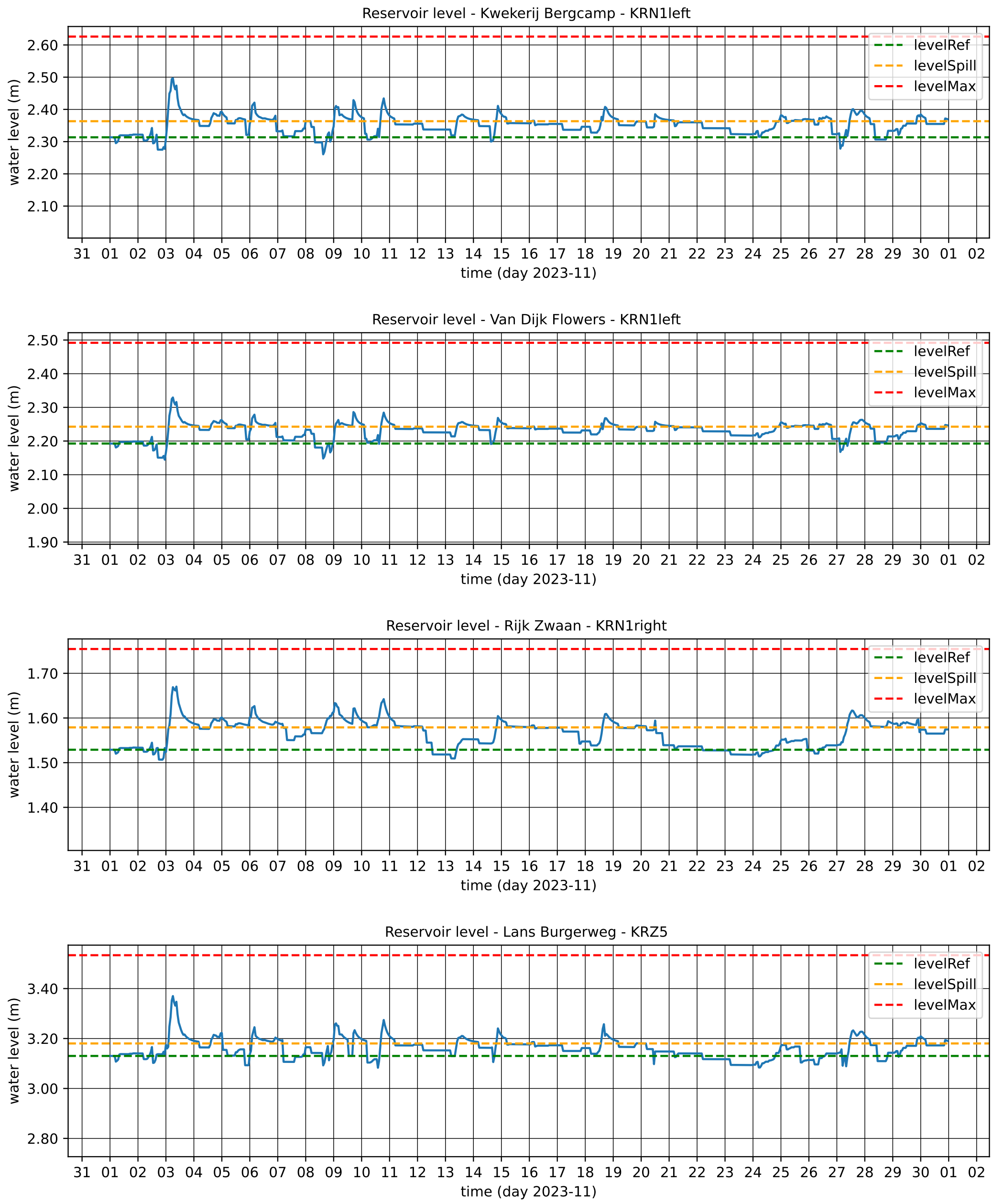

Figure G.1: Water level reservoirs part 1, increased number of realizations.

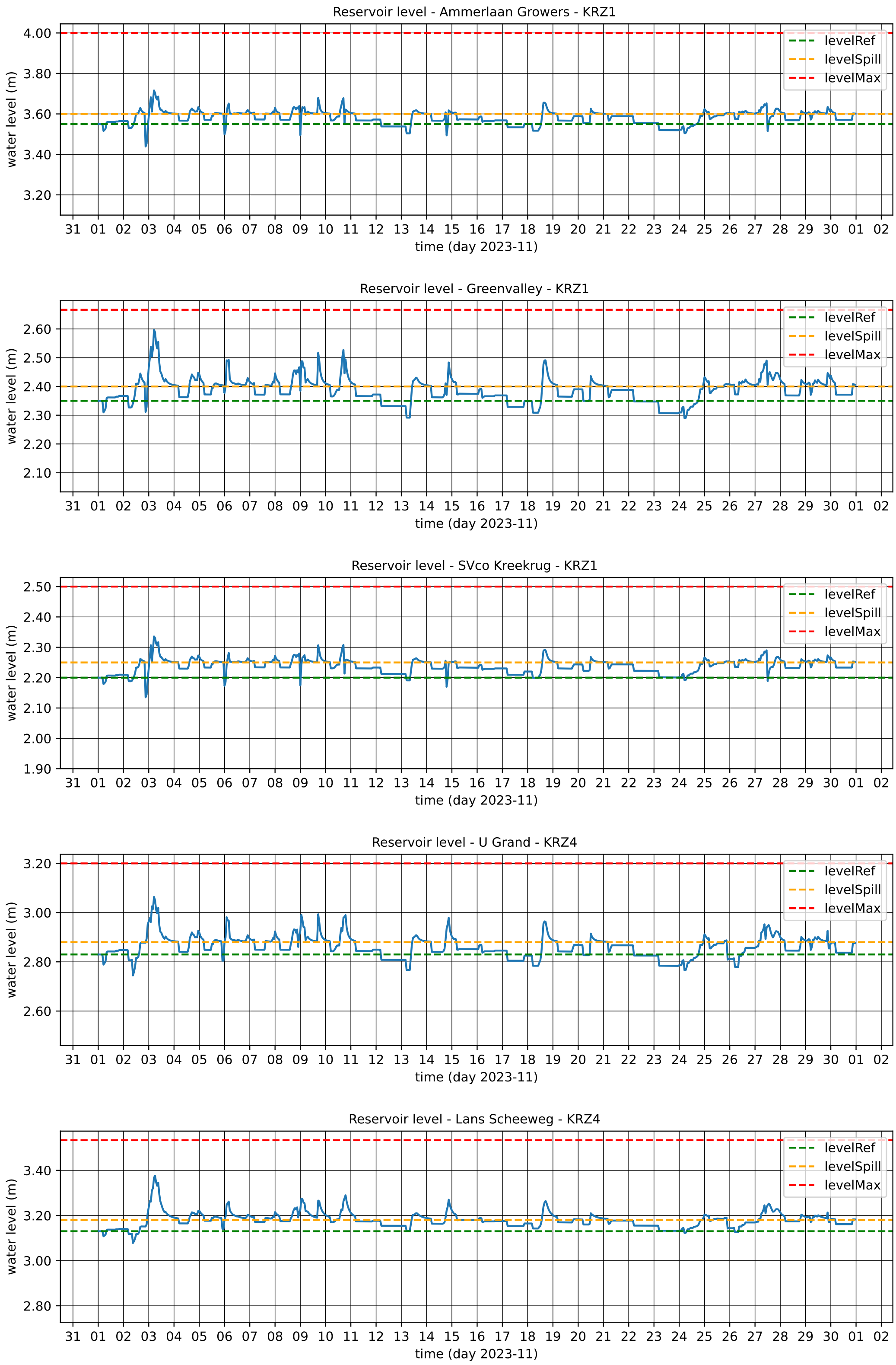

Figure G.2: Water level reservoirs part 2, increased number of realizations.

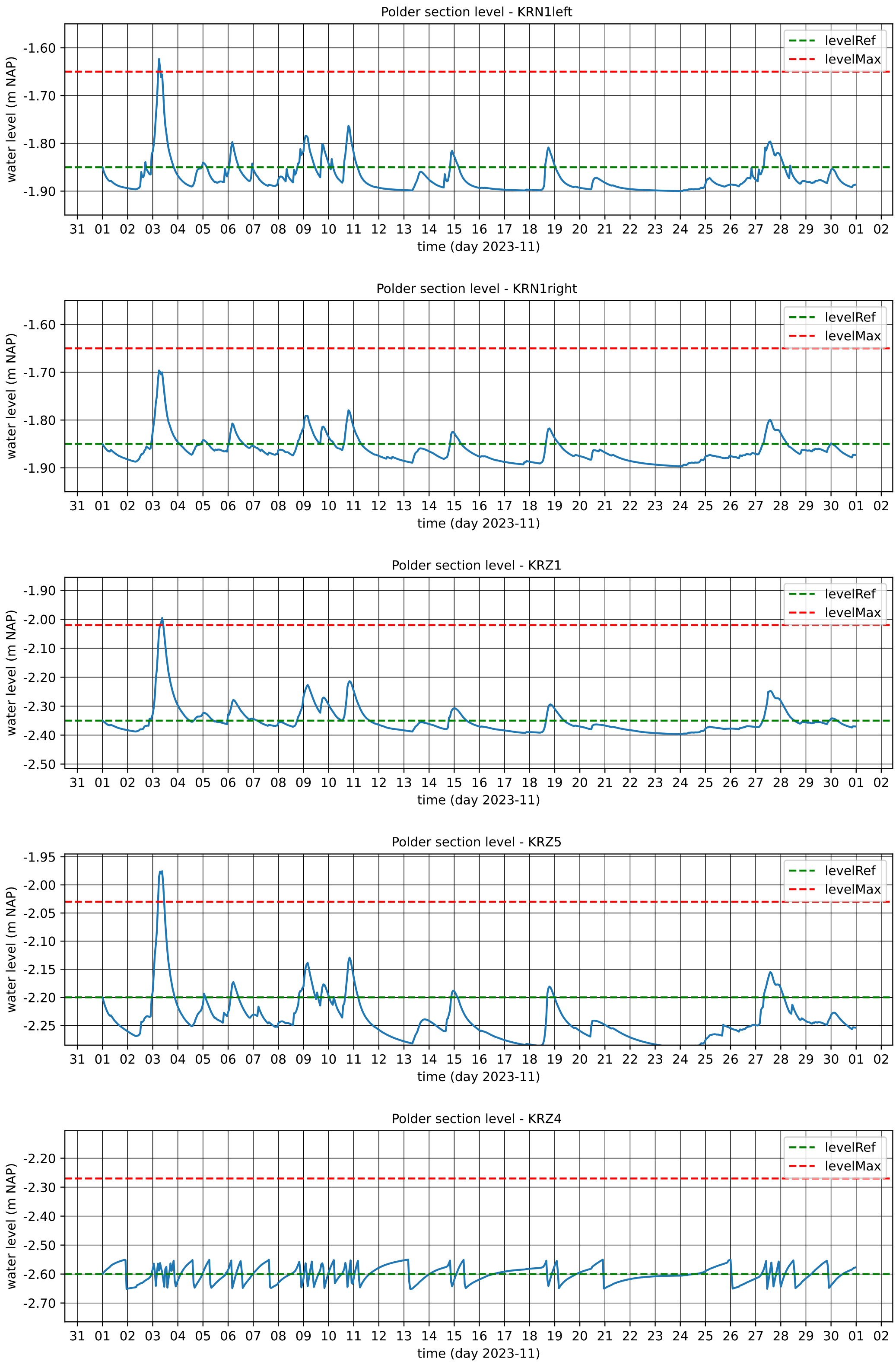

Figure G.3: Water level polder sections, increased number of realizations.

H

Higher weighting for polder level deviations

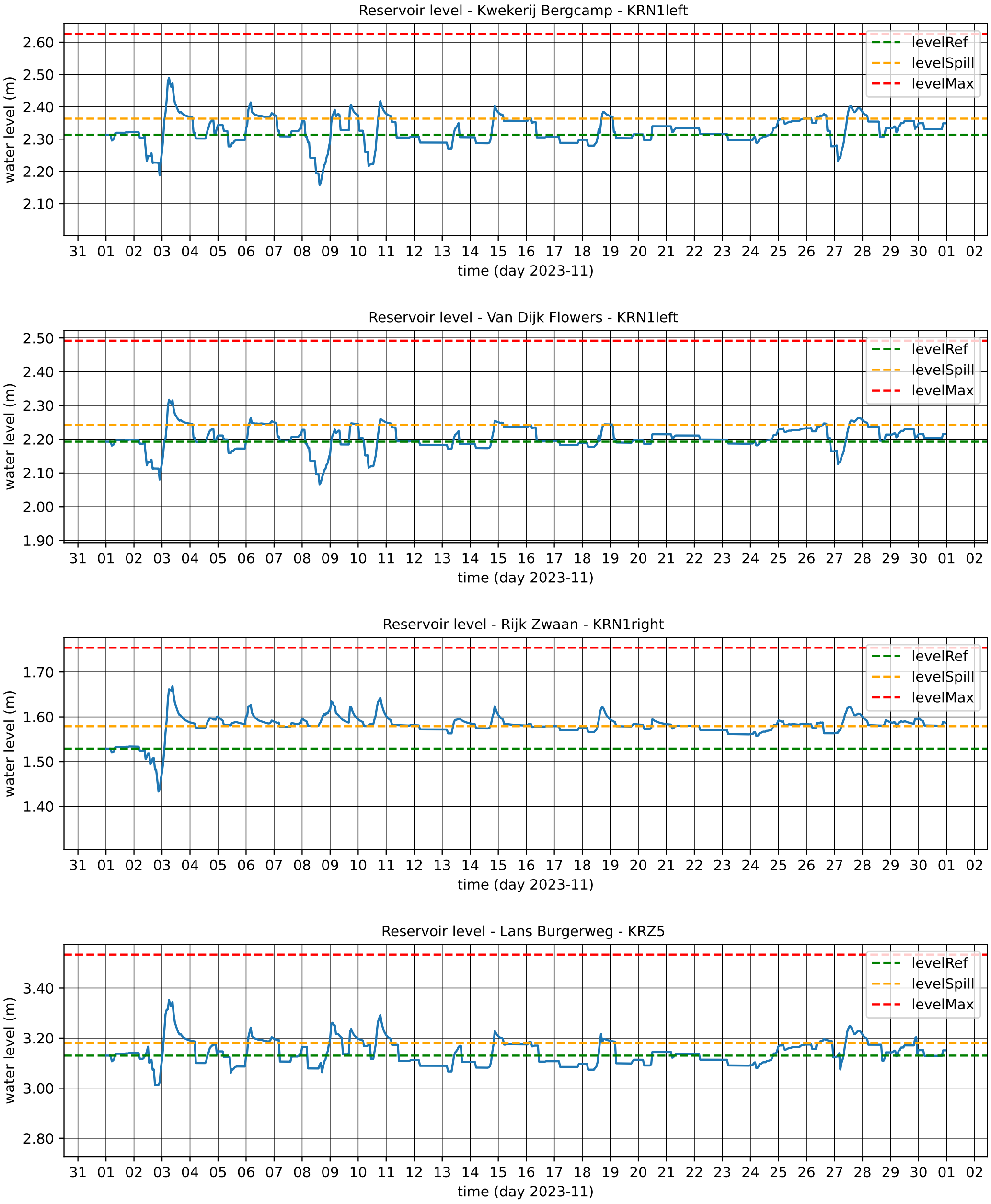

Figure H.1: Water level reservoirs part 1, higher weighting for polder level deviations.

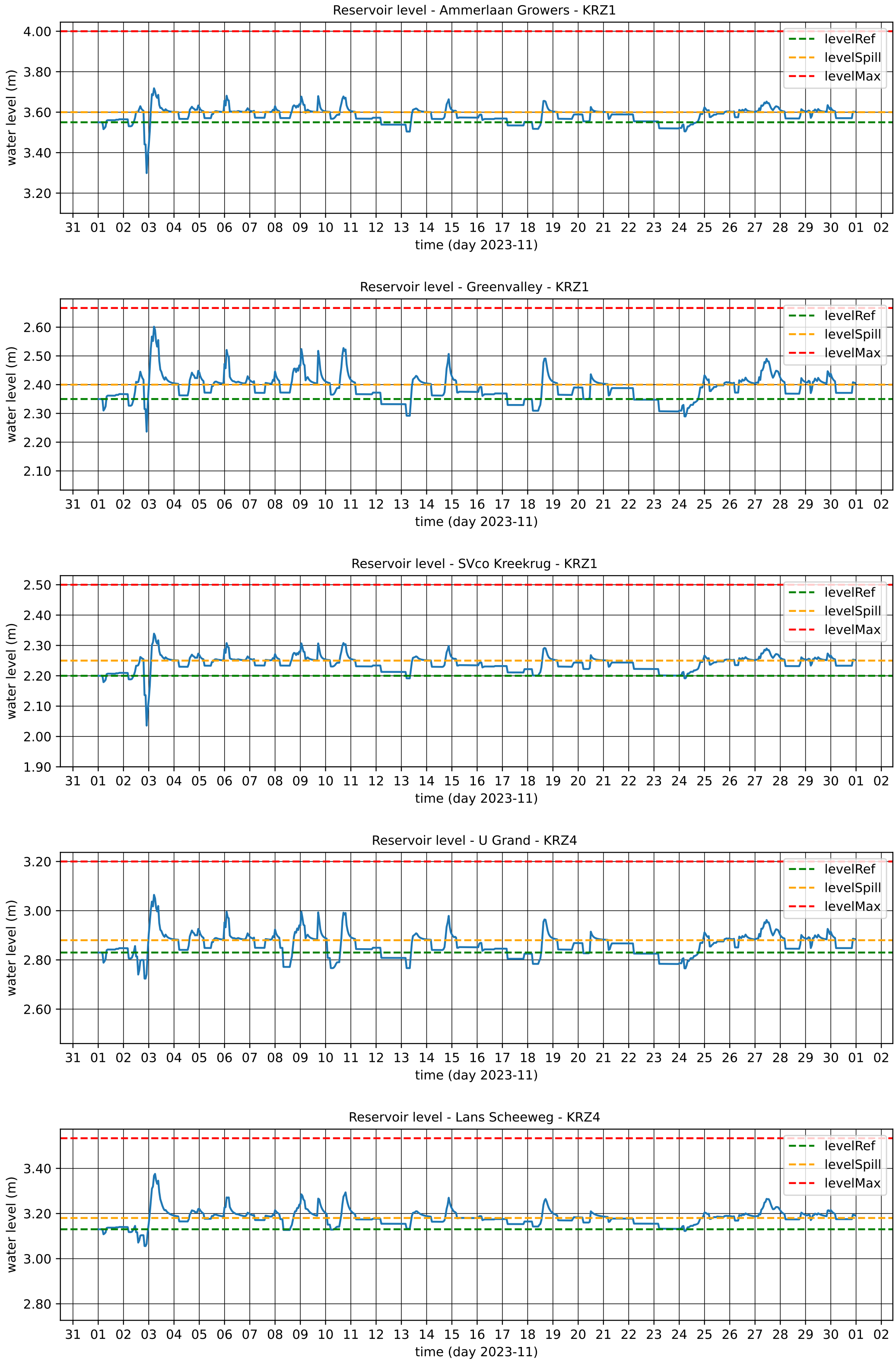

Figure H.2: Water level reservoirs part 2, higher weighting for polder level deviations.

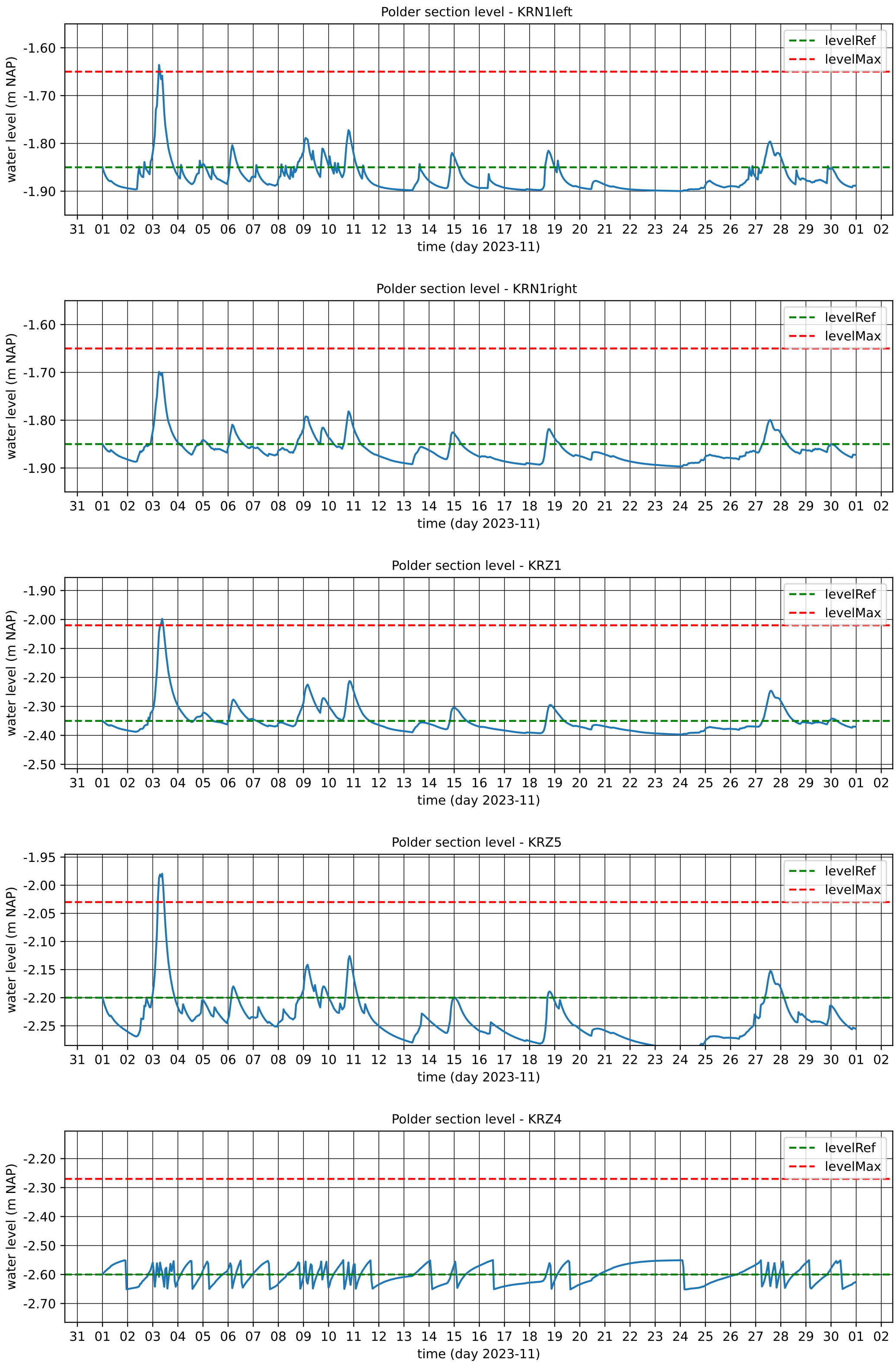

Figure H.3: Water level polder sections, higher weighting for polder level deviations.

I

Less accurate weather prediction

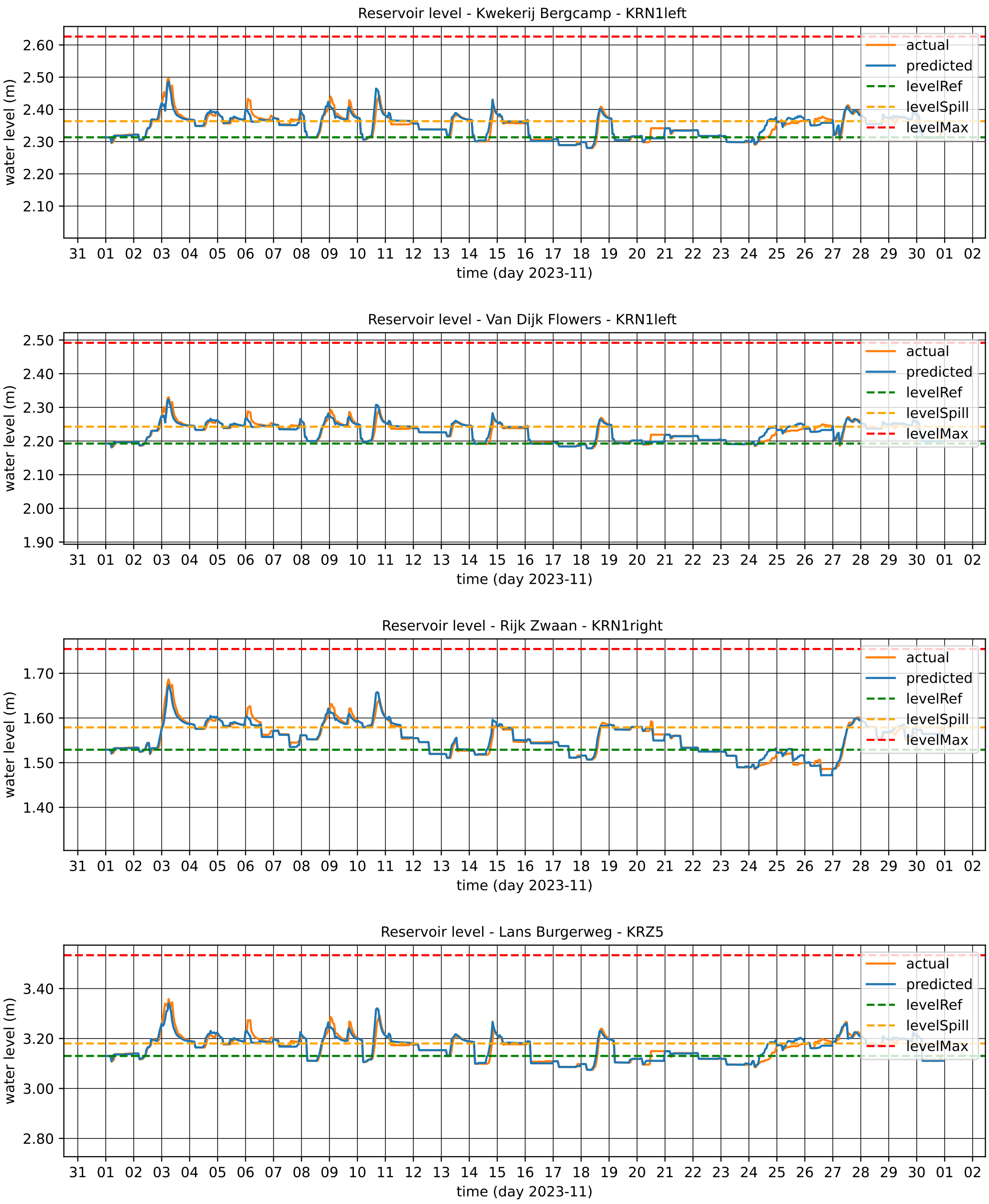

Figure I.1: Water level reservoirs part 1, less accurate weather prediction.

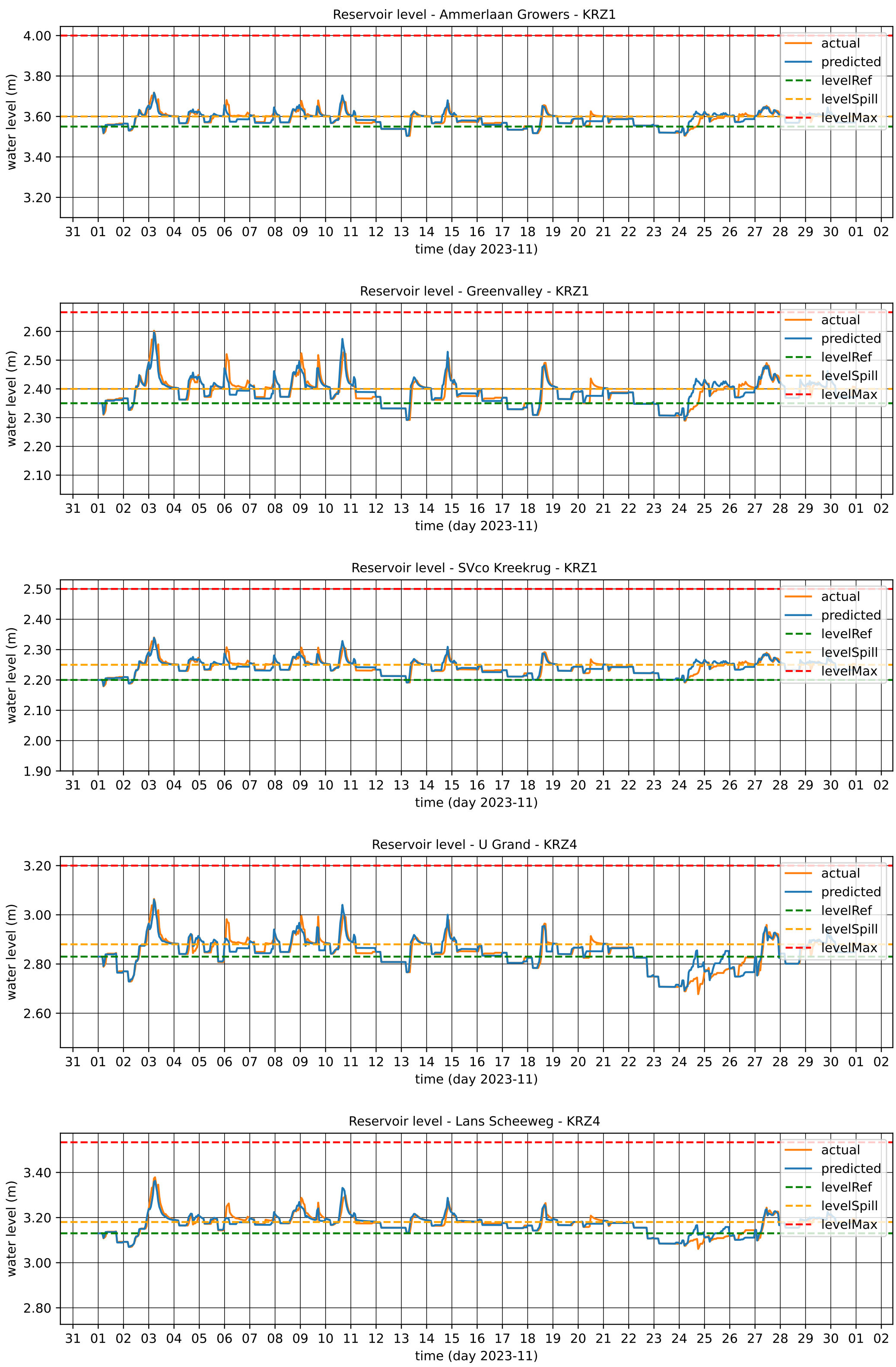

Figure I.2: Water level reservoirs part 2, less accurate weather prediction.

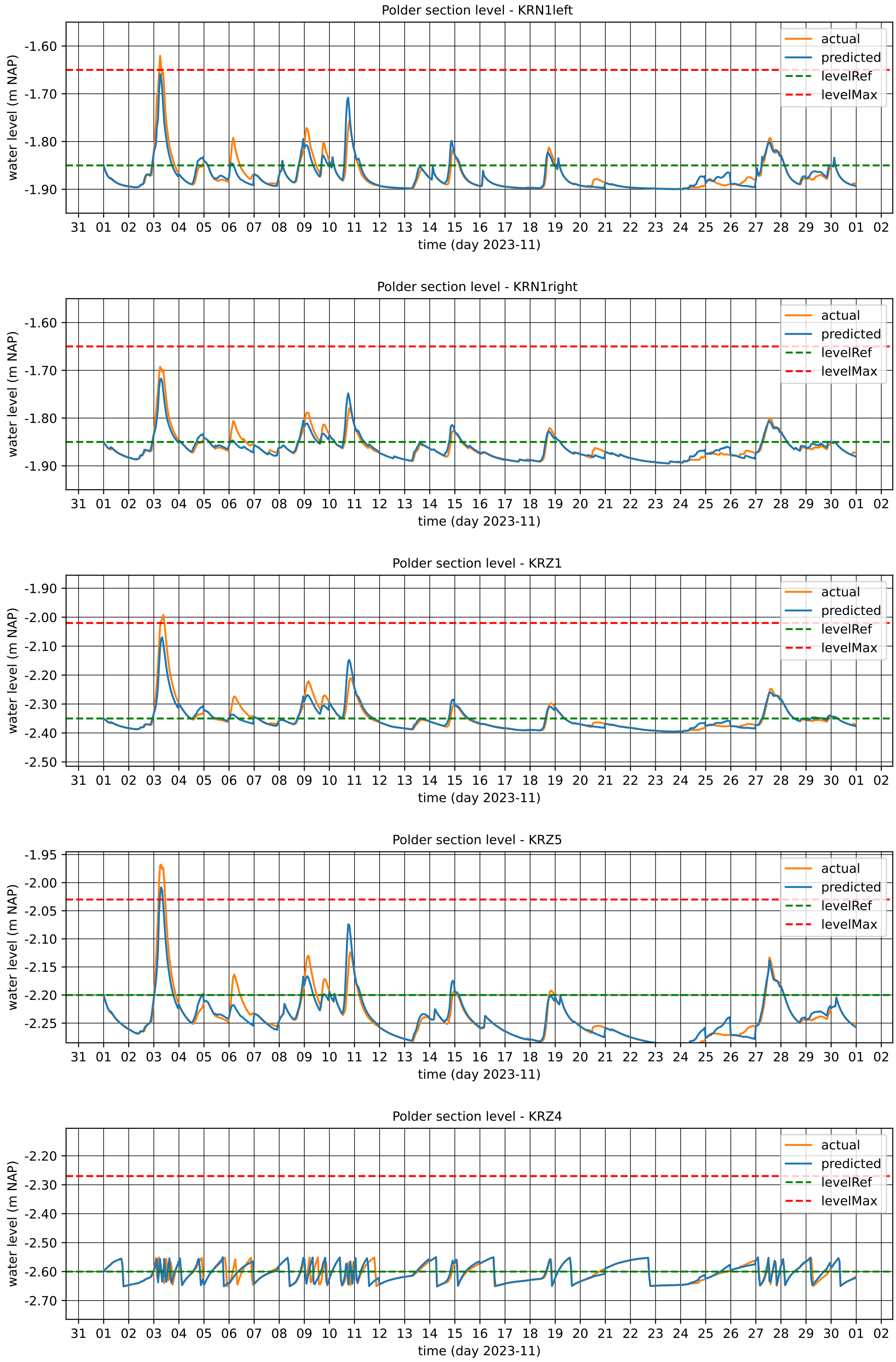

Figure I.3: Water level polder sections, less accurate weather prediction.

J

Less accurate forecast, but more frequent feedback

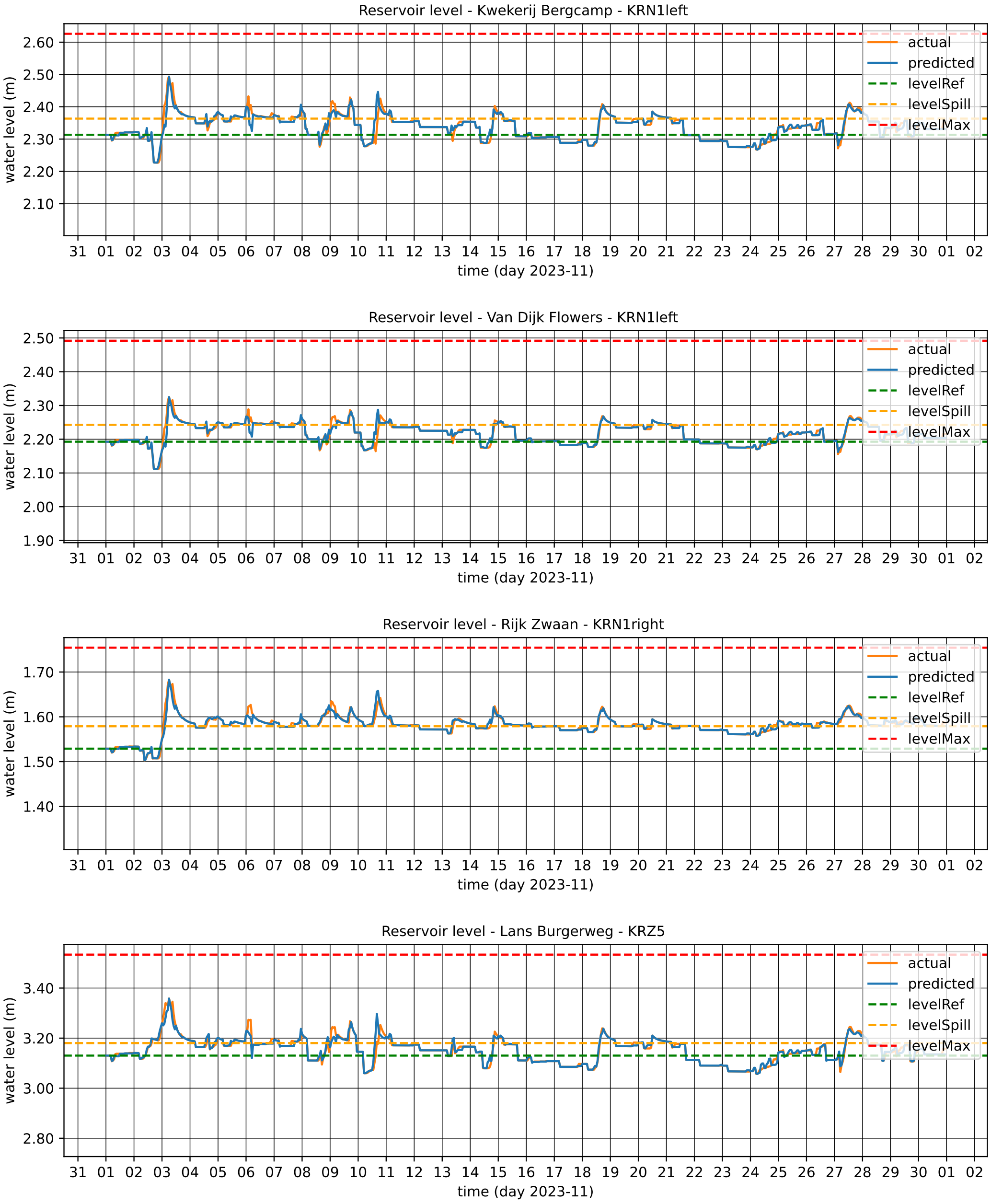

Figure J.1: Water level reservoirs part 1, less accurate forecast, but more frequent feedback.

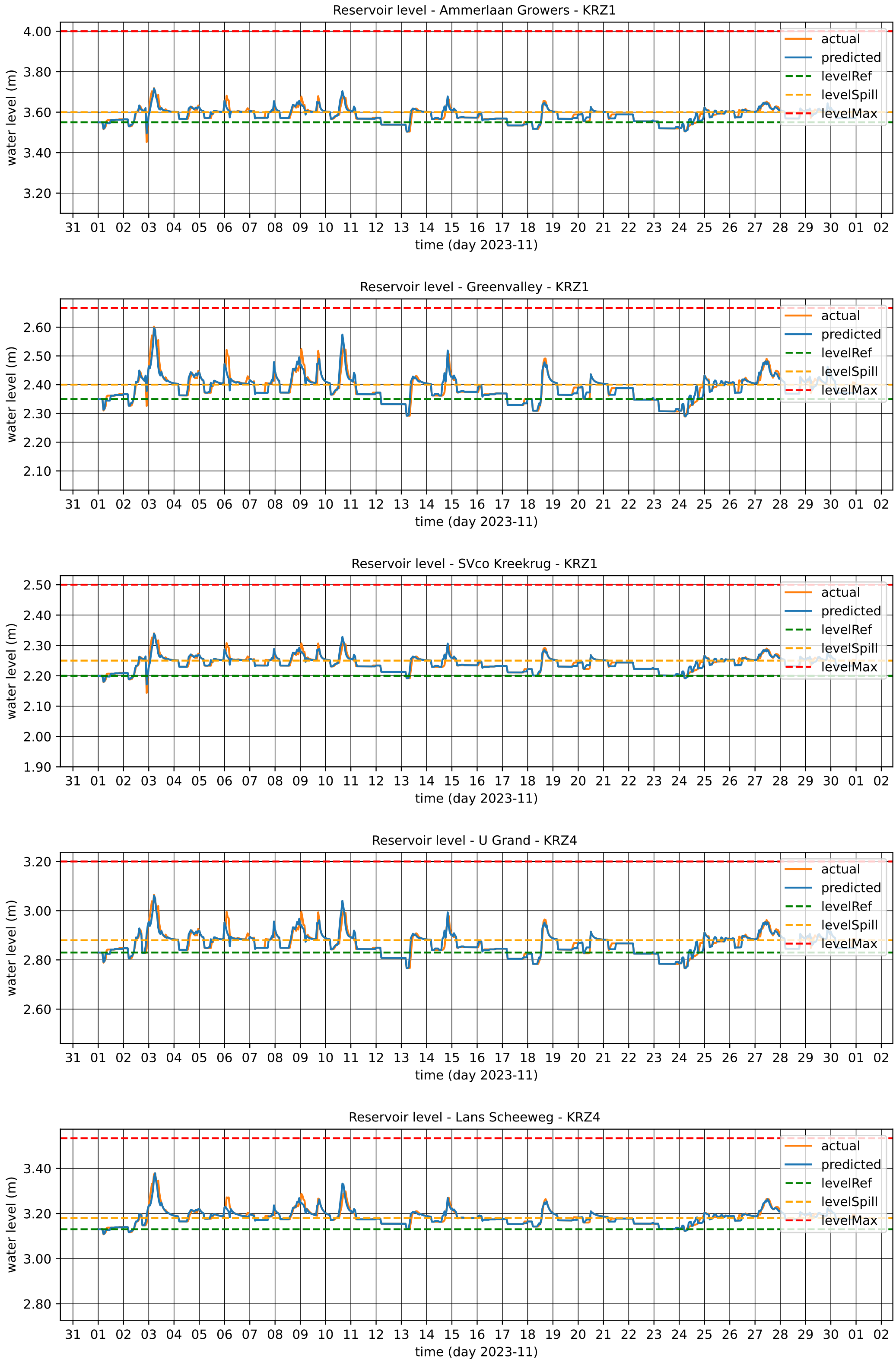

Figure J.2: Water level reservoirs part 2, less accurate forecast, but more frequent feedback.

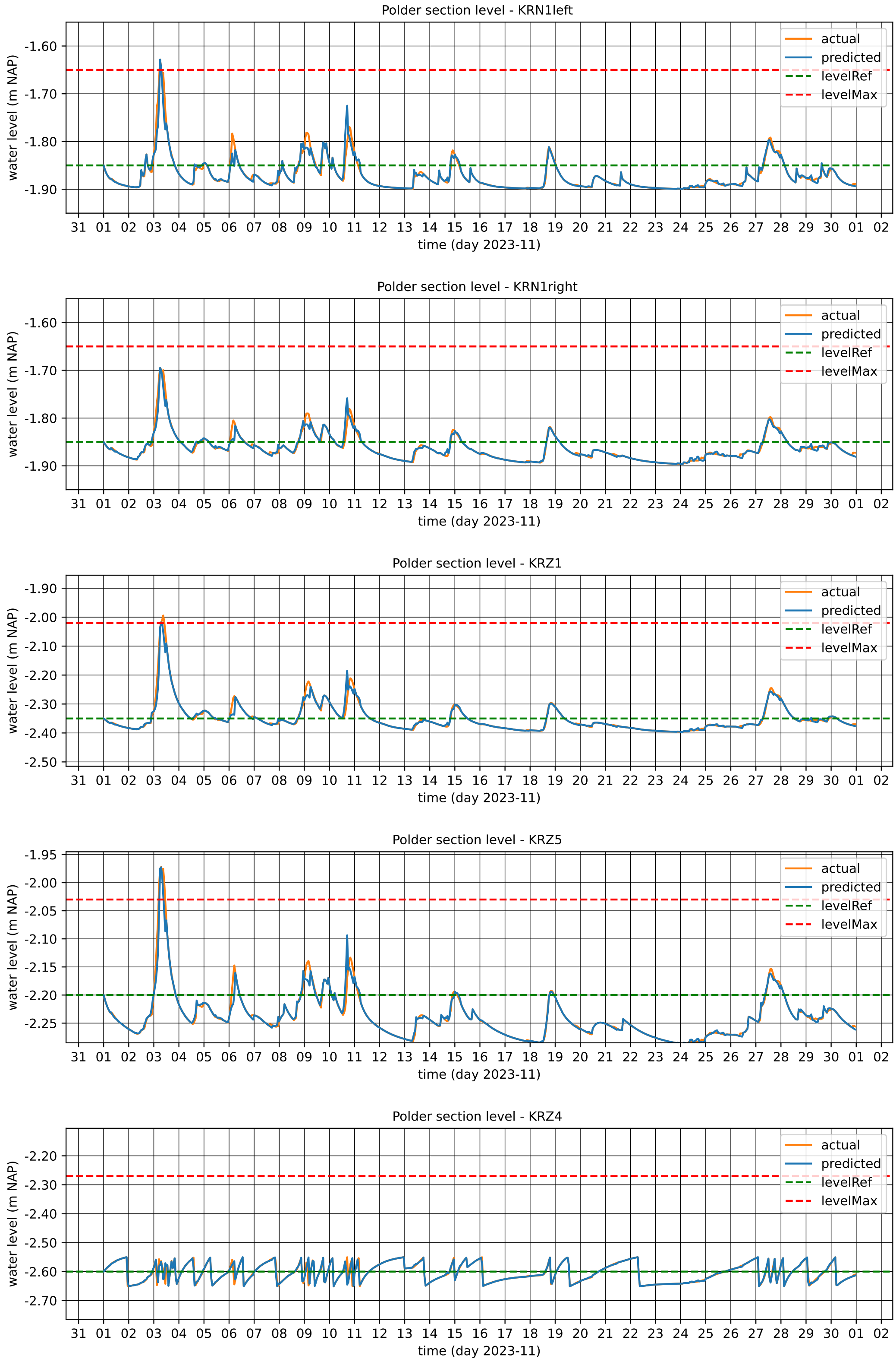

Figure J.3: Water level polder sections, less accurate forecast, but more frequent feedback.

K

Increased number of participants

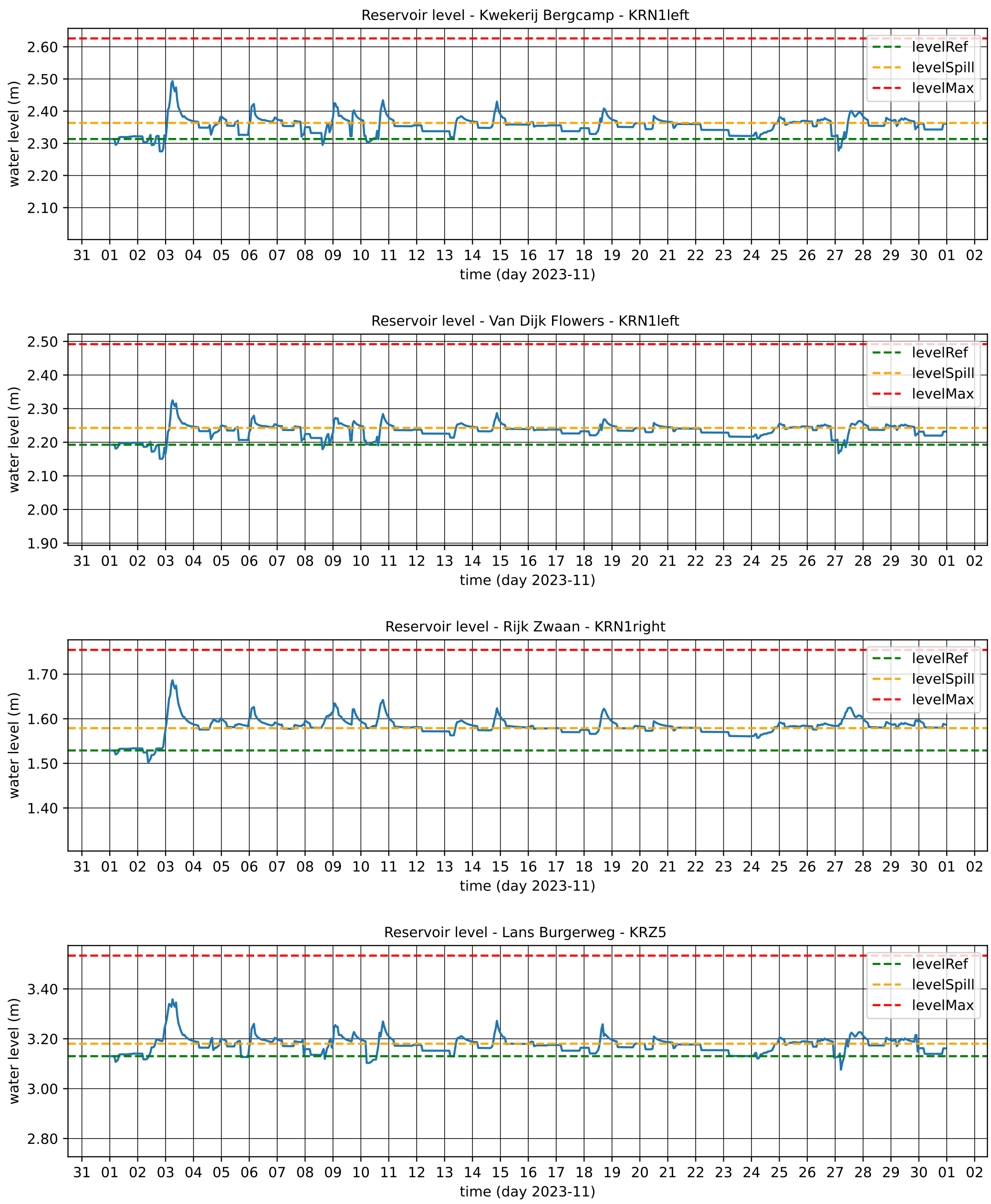

Figure K.1: Water level reservoirs part 1, increased number of participants.

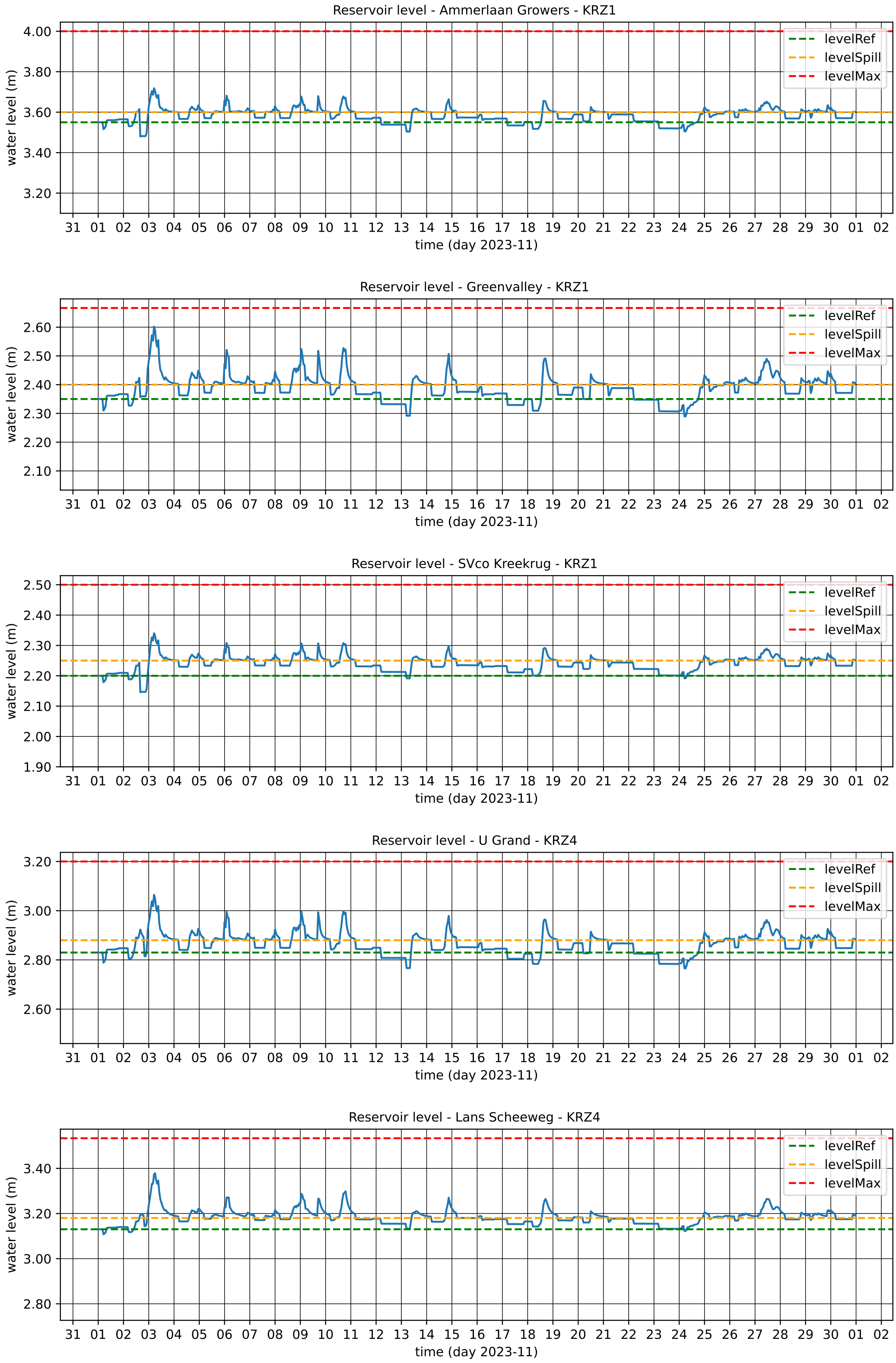

Figure K.2: Water level reservoirs part 2, increased number of participants.

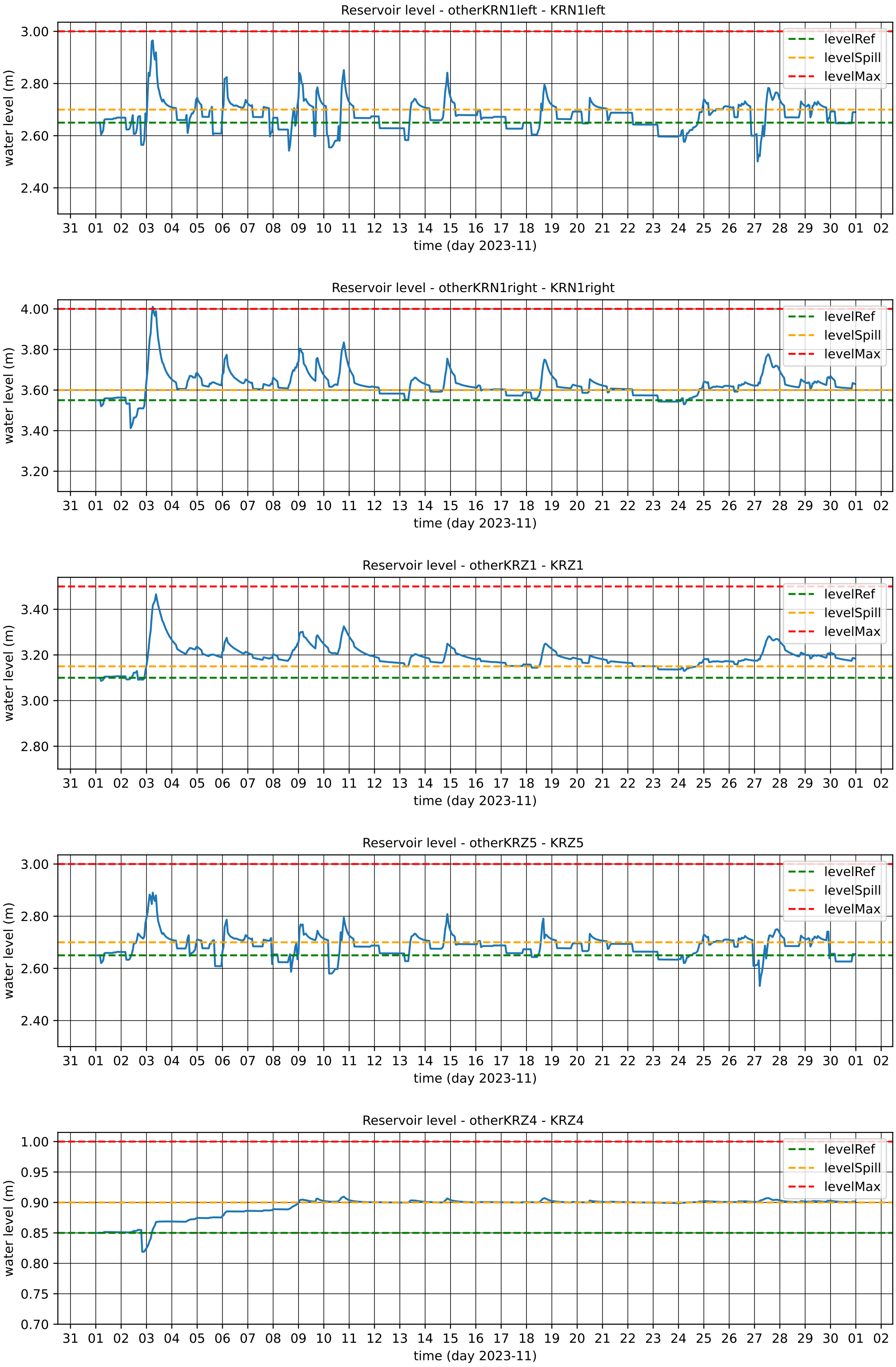

Figure K.3: Water level reservoirs part 3, increased number of participants.

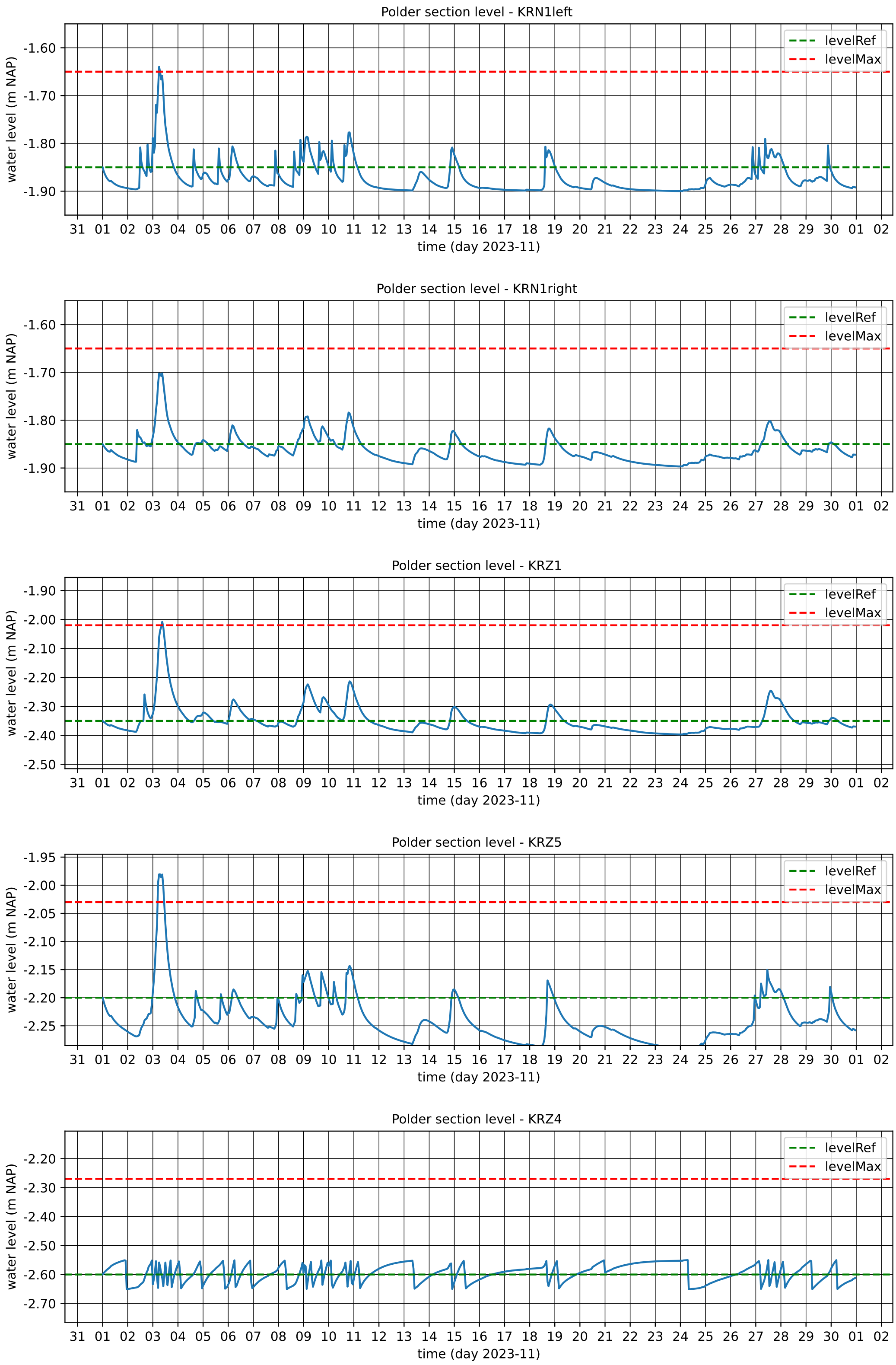

Figure K.4: Water level polder sections, increased number of participants.