Real-time Control of the South-North Water Transfer Project within Jiangsu Province in China: Development and Assessment of Model Predictive Control (MPC) as Operational Management System

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Summary

China is currently working on the construction of the massive South-North Water Transfer Project (SNWTP), the largest project of its kind ever undertaken. Planned to be completed ultimately by 2050, over 300 million people are expected to benefit from the transfer of 44.8 billion m^3 of water per year. The project corresponds to China's severe water scarcity and geographically uneven south-north distribution of water. The Jiangsu water transfer system is a 411 kilometers long section of this project and will divert as much as 8.9 billion $m^3/year$ (up to 500 m^3/s) from the lower Yangtze River reach uphill through an existing network of canals and lakes of Jiangsu province in the direction of the Yellow River and Beijing. The water system serves many functions such as drainage, flood control, navigation, water supply and from 2013 the new function of water transfer to the north is added.

In order to fulfill these functions, controllable structures, such as gates, weirs and pump stations are used. The daily operation of these structures is referred to as real-time control and is subject of this thesis. Real-time control of a complex water system as the Jiangsu water transfer system with different (sometimes conflicting) objectives preferably requires advanced control techniques in order to meet the desired system behavior. Model Predictive Control (MPC) is such an advanced controller that has shown good performance on a number of different water systems (Overloop [2005]). MPC is a control algorithm that makes explicit use of a simplified process model (internal model) of the real system to obtain control actions by minimizing an objective function over a prediction horizon. It has been suggested by Dutch experts that the Jiangsu water transfer system may be controlled by the advanced Model Predictive Controller. This might contribute to meet the desired system behavior and increase the water system's performance. This hypothesis is tested in this thesis by studying an idealized reflection (schematization) of the Jiangsu system.

In order to put the performance of MPC into perspective, classical feedback control [Proportional-Integral control (PI)] has been developed for comparison in the test scenarios. PI control is a simple, robust and common used control method. In order to assess the performance of the controllers a hydro-dynamic model of the water system has been developed in the unsteady-flow simulation software package SOBEK (WL|Delft Hydraulics). The controllers have been tested on simulations of various scenarios and conditions.

Model Predictive Control has not been applied to a water system as large as the Jiangsu water transfer system before. Analysis of the control problem has shown that the enormous size of the lakes play a determinative role in real-time control of this system. Due to the size real-time control depends on long-term decisions that have to be made on a tactical level (e.g. by water managers); not on the operational level on which a controller operates. With and only with up to date long-term decisions a controller can really adequately control the Jiangsu water transfer system. The system objectives are to keep all water levels close to target levels, supply local water demands within Jiangsu province, transfer

water quantities of the SNWTP, minimize the operational costs and limit the change and frequency of changes in structure settings.

This research showed that the complex Jiangsu water system can successfully be modeled using a 1D-hydrodynamic model and can be controlled using MPC. The results show that MPC outperforms classical PI control under all scenarios, however on some objectives the improvement is minor. It is concluded that MPC is especially effective in maintaining water levels in the various canals under all circumstances. PI control violates minimum water levels under high flow conditions, due to the inability to handle system constraints. The maximum water level deviations by MPC occur under high flow conditions and are limited to 0.16 meters. It is concluded that the performance on water levels degrades when the flows through the canals are higher. This degradation is the result of un-modeled dynamics in the underlying process model (internal model) and not by the MPC itself. Furthermore MPC has shown to be able to handle calamities and (unexpected) disturbances satisfactory. An unexpected (partial) failure of a pump station is handled with a maximum deviation of 0.36 meters; corrective actions are immediately executed throughout a large part of the system. This can be assigned to the ability of MPC to assess the hydraulic interactions within the whole water system at once. A comparison with PI control could not be made here. The results show also that unpredicted disturbances are handled comparable by both controllers. When disturbances are predicted, the MPC performs significantly better.

Regarding the goal of water delivering, the failure of PI control to maintain water levels also implies the failure of water delivery; MPC delivers always all required water quantities.

Regarding the operational costs, the results show that MPC is not able to significantly reduce the operational costs; MPC realizes a negligible reduction in operational costs (<1%) compared to PI control. The results show that significant reduction of operational costs is possible, though only by making large sacrifices on the performance on other goals (water levels and structure changes). A procentual cost reduction of 27% under low flow conditions and 7% under high flow conditions can be achieved when allowing daily water level deviations up to 0.30 meters in the largest canal pool. In a dry year with maximum supply, this results in an estimated maximum reduction of operational costs of 3 million Euro (30 million Yuan).

Due to the difference in control time step (20 min for feedback; 60 min for MPC) the feedback controller uses trice as many structure changes as the MPC to achieve the above described performance.

This research also shows that the limits of MPC are almost reached. The use of a commercial solver (TOMLAB) on a 64-bit computer is necessary to enable real-time application of MPC. The control time step has been chosen 1 hour and a prediction horizon 24 hours to make sure that the control actions can be calculated within one control time step. These cannot be lowered and increased much respectively. Moreover the internal model of the MPC needed to be a strong simplification of the water system in order to keep the optimization problem compact.

In conclusion, MPC is able to meet the system objectives under all circumstances. MPC keeps water levels within a bandwidth of 0.16 meters from target level under all circumstances and therefore never exceeds minimum or maximum allowed water levels. With good disturbance predictions the performance of MPC on water levels is further improved. The higher the flows through the canals, the larger the water level deviations. MPC is not able to significantly reduce operational costs without making sacrifices on other objectives. The limits of MPC have been reached; a large time step (1 hour) and a short prediction horizon (1-2 days) are required to enable MPC on a system this large. Almost perfect disturbance predictions have been used, thus performance on the real system might be lower. On the other hand the quality of the process model can be improved to improve the performance

It is recommended to test the MPC parallel with the real system in order to make a comparison with the current form of real-time control, which would be more relevant than the comparison with a feedback controller. Furthermore it is desirable to develop a user interface that allows water managers to simply implement new control objectives without requiring detailed knowledge of MPC.

Contents

List of Figures

List of Tables

Preface

"Water is abundant in the south and scarce in the north. We may borrow some from the south to the north if it's feasible."

Mao Zedong (1893 - 1976)

On October 1952 Mao Zedong, founder of the People's Republic of China, uttered this seemingly innocent observation when inspecting the Yellow River. Exactly fifty years later Chinese authorities broke ground to implement Chairman Mao's plans. Triggered by the astonishing magnitude of the South-North Water transfer Project and the possibility to visit China I took the opportunity to do my Master thesis about a section of this gigantic project. Anno May 2010 the result is here, in the form of this report.

For this thesis I stayed in Nanjing (China) for 6 weeks to collect information and data about the project. I was kindly welcomed of by the Jiangsu Water source company and Hohai University. Special thanks to the people who helped me around in complete new world with so much cultural differences. Master student Mei Xu Yu took care of me from the first day I arrived. Thanks for getting me started, showing me around the university campus, places to eat and drink, teach me about your culture and helping me getting in contact with all the persons who could help me with my project. Mr. Feng thank you very much for spending some of your precious time several times to explain me about the project and thanks for all the efforts you made to collect the information and data. Thanks also Mrs. Tingting Mao for all your assistance during my visits to the Jiangsu Water Source company.

I would like to express my gratitude to my committee members for their guidance and advices during my graduation period. Thanks Peter-Jules for sharing your knowledge and experience on real-time control of water systems, for the brainstorm moments we had when I encountered difficulties and above all for your hospitality and providing me a working place in your room with PhD-candidates. Ralph for all the time you took for carefully reading my work; your efforts and willingness to understand every piece of work I produced greatly helped to improve the quality of my research. Hans for all your support, involvement and constructive critics. Eelco for always reminding me not to forget the objective of my study.

I would like to thank the PhD-candidates working in Peter-Jules room for their willingness to help me with my research and the times we spent in room 4.71. Xu Min thank you very much for explaining me the basic principles of MPC and your help in finding errors in my MATLAB codes in the times I got lost. Thanks Steven Weijs for your advises on creating a report in LateX and your input on enabling the connection between my laptop and the super computer; the 'try-catch' function in MATLAB turned out to be crucial for a stable connection.

Thanks also to my family, Klaas, Grietje, Hilbert and Zwanet. Though I wasn't always there for you, you were there for me!

Finally thank you John, Jaap and Rens; you guys reminded me what it means to be friends!

Thank you all!

Meinte Vierstra
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1 Introduction

1.1 Background

The South-to-North Water transfer Project (SNWTP) is one of the largest water transport projects ever undertaken. When ultimately completed in 2050 over 400 million people are expected to benefit from the transfer of 44.8 billion m^3 of water per year from the water abundant Yangtze River. The project responds to China's severe water scarcity and geographically uneven distribution (figure 1). Due to climate and topography, the northern part of China owns as little as 19% of the water resources available within the country where 47% of the population is living and 64% of the cultivated land is located. Water resources exploitation in northern basins has reached up to 90% and groundwater resources are largely exploited. The over-exploitation of water resources has caused withering of some rivers and lakes, increased siltation of river estuaries and increasingly water disputes between regions, cities and townships (Riuxiang [2007]).

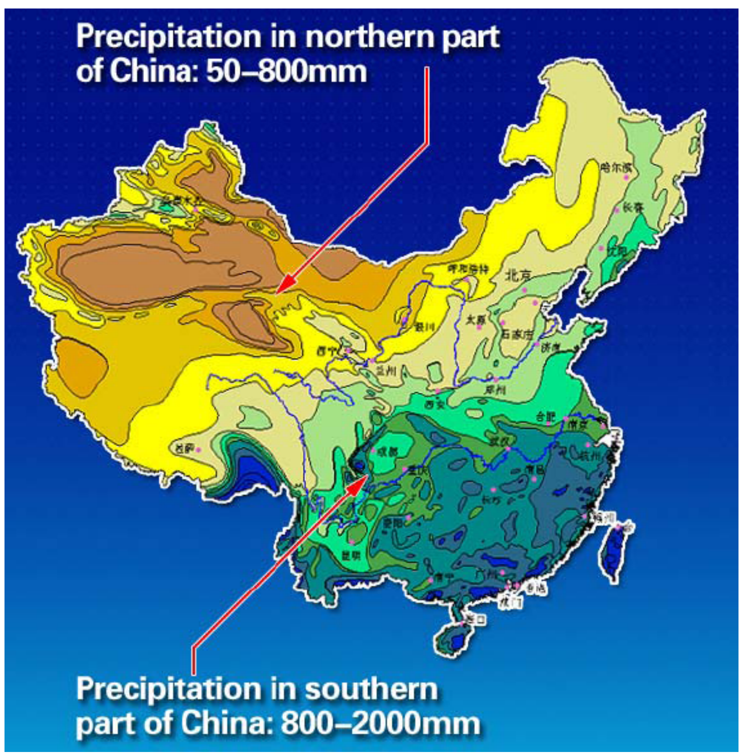

Figure 1: Distribution of rainfall in China.

Planned for completion in 2050, the SNWTP will eventually divert 44.8 billion $\mathbf{m^3}$ of water annually from the Yangtze River in the south to the drier regions in the north. The goal of the water transfer in terms of water utilization is to alleviate the present conflicts caused by competitive agricultural, industrial, domestic and ecological users of water (Riuxiang [2007]). The project consists of three separate routes (East-, Middle-, and West-Route). A considerable part of the East-Route is the scope of this research.

Construction of the East-Route officially began on December 27, 2002, and is planned to be completed in 2013. The East-Route will transport 8.9 billion m^3 from the Yangtze River towards the north (to the provinces Jiangsu, Shandong, Hebei, Beijing, Tianjin and parts of Anhui). The finished transfer will be slightly over 1,155 km long, comprising the construction of 120 km new canals and upgrading of 40% of the existing canals (DeSalle et al. [2008]). For over 600 km the water will be transported uphill, therefore involving the construction of 21 pump stations with a total installed capacity of $235.2MW$. This new to build capacity is in addition to the already existing stations for local supply (Zhou et al. [2007]).

1.1.1 Scope

All though the design for the SNWTP has been drawn on a national level, the execution, operation and maintenance have been outsourced to governmental organizations on a provincial level. This thesis is carried out on behalf of the Jiangsu Water Source Company Ltd (JWS) which is the governmental organization that is responsible for the part of the East-Route located within the province of Jiangsu. Therefore the part of the East-Route located within Jiangsu province comprises the scope of this thesis. The province of Jiangsu is highlighted red in figure 2. The Grand Canal is the main canal of the East-Route and also shown on the map in figure 2. 411 km of the 1,155 km of the East-Route is located within Jiangsu Province. From now on, this part of the East-Route located within Jiangsu Province is referred to as the 'Jiangsu water transfer system'.

Figure 2: The province of Jiangsu highlighted on a map of China.

1.1.2 Framework

The Ministry of Transport, Public Works and Water Management (RWS) of the Netherlands has had contact and meetings with different parties involved in the SNWTP in order to exchange knowledge in the field of real-time control (RTC) of water systems. The Dutch RWS and Chinese Jiangsu Water Source Company Ltd (JWS) can both profit from co-operation by exchanging information and experiences; hence cooperation will be a win-win situation. Several agreements between RWS and JWS have been made on knowledge exchange regarding the Jiangsu water transfer project and committed to paper through several 'minutes-of-meetings'. JWS has large interest in a real-time control system for the complex Jiangsu water transfer system. As technical know-how is available in The Netherlands, RWS wants to offer knowledge and support for the development and tendering of a control system for the Jiangsu water transfer system.

The development of a real-time control system for a water system as large as the Jiangsu water transfer system is complex, not only from a technical point of view, but also because real-time control of a water system is closely connected to all levels of the decision making in the field of ´Operational water management´. From theory, expert knowledge and -experience it is known that a complex, multipurpose water system may require an advanced control mechanism in order to meet the desired system behavior and increase the water system´s performance. RWS proposed to facilitate a pilot-study by a Dutch student from a technical university in The Netherlands to do research to the role an advanced controller can serve in this operational water management problem.

1.2 Problem Statement

The Jiangsu water transfer project is a highly sophisticated civil project with multiple purposes. First there is the goal to supply the usual water quantities throughout Jiangsu Province. Second there is the new goal to divert water through the existing system to the north during dry periods. A third goal is to maintain the water levels throughout the water system to guarantee navigation and other functions. As large quantities of energy will be needed to divert the water along an uphill route, reduction of operational costs is a fourth goal. Real-time control of the complex Jiangsu water transfer system is a difficult issue due to the complexity of the water system and the combination of the (sometimes contrary) goals.

In general, the conventional way of operating a water system is to first translate the goals in target water levels for the individual water bodies and secondly to try to maintain these water levels as good as possible. In this way the water levels are controlled by reactions to changes in the local water level. When the whole system is considered, this local control does not lead to an optimal control of the structures. Also, scheduled demands or forecasts cannot be taken into account if only local control is being utilized. A centralized controller that provides for control of all structures and anticipates on forecasts and off-take schedules can greatly improve the water system´s performance. The Model Predictive Controller is such a controller that is suited to deal with all the phenomenon that play an important role in the behavior of canal systems. It has been suggested by Dutch experts that the Jiangsu water transfer system should preferably be controlled by the advanced Model Predictive Controller in order to be able to meet the system objectives and increase the water system's performance. Research is necessary to test this hypothesis.

1.3 Objective and Research Questions

Real-time control (RTC) of water systems is a specific area of research in the field of water management. Real-time control can result in advantages such as less manpower and higher system performance. A large number of different controllers exists, the majority being based on feedback theory. Feedback controllers range from simple proportional-integral (PI) controllers till the more complex fully centralized Linear Quadratic Regulators (LQR). As controllers become more advanced, they can potentially result in higher performance (Clemmens and Wahlin [2004]). Recently Model Predictive Control (MPC) has been introduced in control of water systems, which is one of the most advanced control mechanisms so far. Research shows that the advanced Model Predictive Controller resulted in a higher performance for a range of different water systems (Zagona [1992], Wahlin [2004], Overloop [2005], Wagemaker [2005], Fambrini [2009], Overloop et al. [2010]). Since JWS has a large interest in the development of a real-time controller for their complex control problem, research should be done to this control problem and the advantages, disadvantages and performance of MPC on this system. From this starting point the research objective of this thesis has been formulated:

> **Assess the performance, advantages and disadvantages of Model Predictive Control for the South-North Water Transfer Project within Jiangsu Province in China.**

Here performance is defined as the score of a controller on so called performance indicators. A performance indicator is a measure of certain system variable that need to be controlled according to a predefined objective (for more information on performance indicators see section 6.1). In order to put the performance of Model Predictive Control into perspective, the performance will, where possible, be compared with the performance of feedback control. Feedback control is a simple, robust and most common used control algorithm for water systems.

To meet the objective, the following research questions have been formulated.

1. What is the control problem and what are the control objectives?
2. How should the Jiangsu water system be schematized and modeled?
3. How should a Model Predictive Controller be designed for the Jiangsu water transfer system?
4. How does a Model Predictive Controller perform on the Jiangsu water transfer system?
5. How does a feedback controller perform on the Jiangsu water transfer system?

The methodology followed in this thesis to achieve the objective can be illustrated in a research model. The research model of this thesis is shown in figure 3 (the colors used here have no specific meaning, but are used for reasons of clarity).

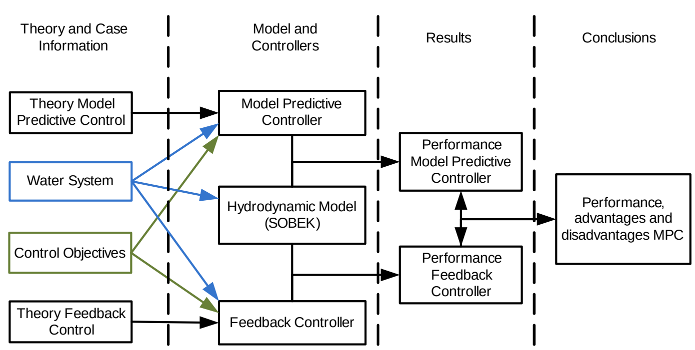

Figure 3: Research Model.

Description of the research model: a study on the theory of Model Predictive Control, on specific case information of the Jiangsu water system and the control objectives should lead to insight on how a Model Predictive Controller should be designed for the Jiangsu water transfer system. The control objectives and information of the water system are used again for the design of an feedback controller using feedback control theory. The performance of a Model Predictive Controller and an feedback controller will be assessed by simulations on a hydrodynamic model of the water system. The outputs of these simulations can then be used to study the performances, advantages and disadvantages of the controllers.

1.4 Outline of this thesis

In the next chapter the water system of Jiangsu is described in more detail. Also the role of JWS in this water system and the control problem are discussed elaborately. In chapter 3 the theory on control of water systems is given with an overview of the controller types followed by more elaborate theory on the two controller types applied in this thesis. In chapter 4 a hydro-dynamic model of the future water system is developed in SOBEK-Rural to be able to simulate the performance of the controllers developed in this thesis. The design of these controllers is discussed in chapter 5. In chapter 6 different scenarios are presented under which the performance of the controllers is tested followed by analysis and results. Conclusions and recommendations can be found in chapter 7.

2 The Jiangsu water system

The world's longest canal, the Grand Canal of China once stretched for almost 1800 km from Běijīng to the city of Hángzhōu (see figure 4). The construction of the Grand Canal spanned many centuries. The first 85 km were completed 495 BC, but the mammoth task of linking the Yellow River and the Yangtze River was undertaken between AD 605-609 by a massive labour force during the Sui Dynasty. The canal enabled the government to capitalize on the growing wealth of the Yellow river basin and to ship supplies from south to north.

Nowadays the Grand Canal is part of an extensive waterway infrastructure. A large part of the Grand Canal is located within Jiangsu province. The water system of Jiangsu province encompasses the third and fourth largest lakes within China. The primary function of this water system is drainage and discharge of excess water out of the system to prevent floods. Secondary functions are navigation, hydro-power production and storage and supply of fresh water. During dry periods, the water system can be used to supply large parts of the province with sufficient water from the lakes as well as the Yangtze River. With the introduction of the South-North water transfer project (SNWTP), a new function is added which is to transfer water through this system to other provinces (Shandong and further). In Appendix C some impression pictures are shown.

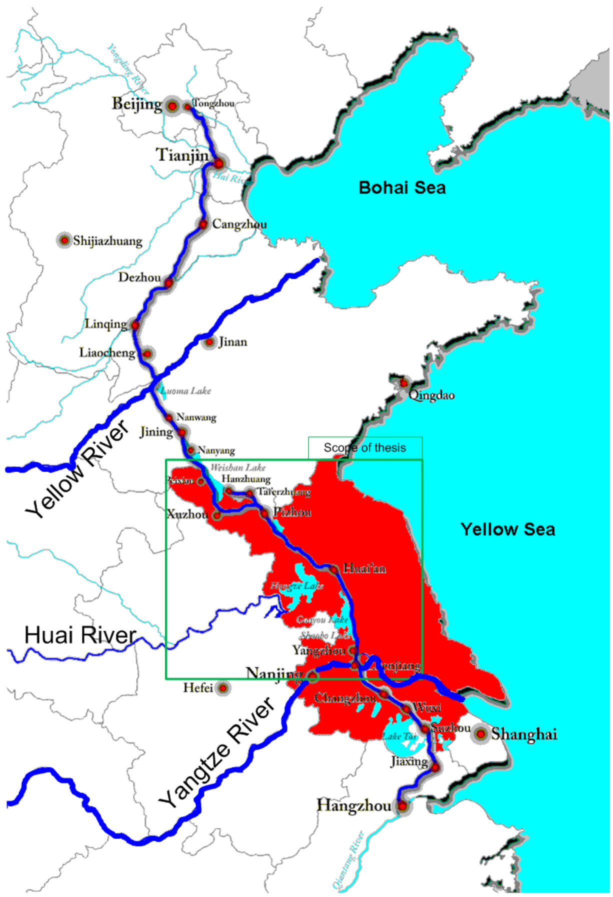

Figure 4: The course of the Grand Canal with the province of Jiangsu highlighted red. The scope of this thesis is framed by the green box.

2.1 System Topography

The existing waterway infrastructure is a complex system covering an area of over 60,000 square kilometers. Along the trajectory of the Jiangsu water transfer system more than a thousand branches exist, hundreds of large structures such as weirs, sluices, hydro-power stations and pump stations have been build in order to be able to operate and manage the water system. In figure 4 the province of Jiangsu has been highlighted red; the scope of this thesis is highlighted by the green framework. The water that is transported through the Jiangsu water transfer system is diverted from the Yangtze River and transported uphill in north-northwest direction through the canal system till the Jiangsu/Shandong border. All the canals and lakes that are part of the Jiangsu water transfer system are highlighted in figure 5, with the blue line being the main route (Grand Canal, 411 kilometers) and green line showing the secondary route. Those two lines are largely existing canals; nearly 90% of the Jiangsu water transfer project comprises existing lakes and canals of which some parts need serious upgrading (e.g. dredging and widening). Moreover, existing pump stations need upgrades and additional stations have to be constructed (Zhou et al. [2007]). For illustration the text-boxes in figure 5 (containing Chinese characters) indicate the locations of the planned construction and dredging works; red text represents construction and/or upgrading of pump stations, whereas the green text boxes indicate canal upgrades. Planned for completion in 2013, the total off take capacity from the Yangtze River will be 500 m^3/s. Along the route, the capacity of the pump stations gradually drops till 200 m^3/s in the north. Table 1 gives an overview of the gradual drop of the system capacity along the route; these planned maximum flows are also shown in figure 7.

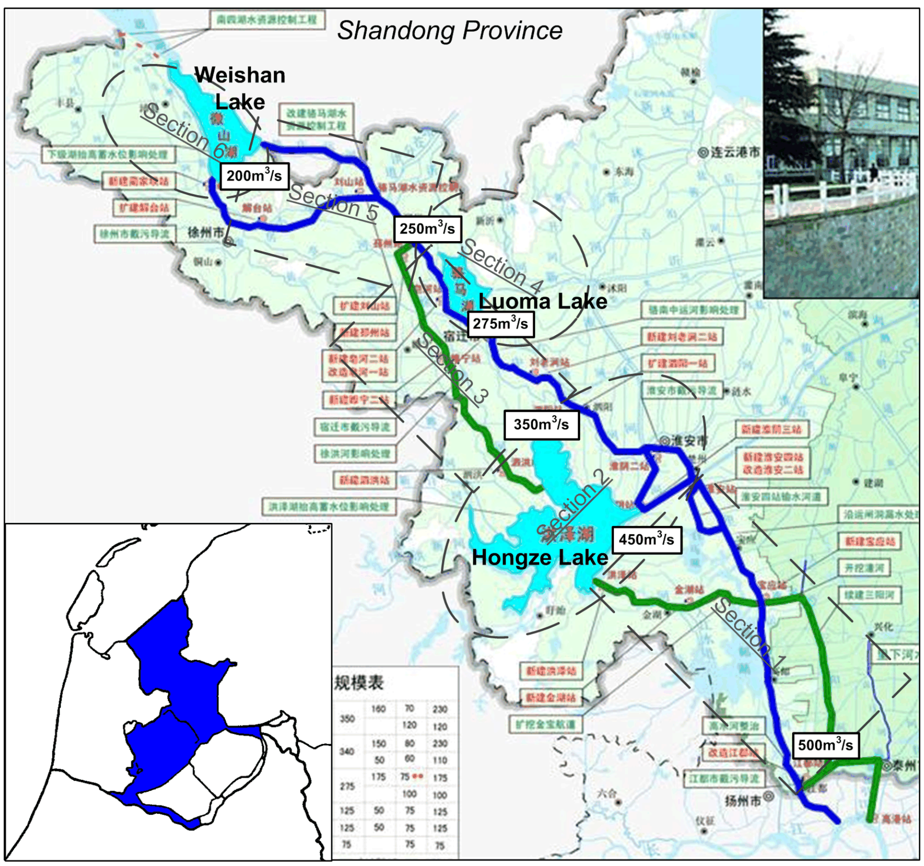

Figure 5: The Jiangsu water transfer system.

Section	Pump capacity $[m^3/s]$	Local water use $[m^3/s]$	Outflow to next section $[m^3/s]$
1. Yangtze River - Hongze Lake	500	50	450
2. Hongze Lake	450	100	350
3. Hongze Lake - Luoma Lake	350	75	275
4. Luoma Lake	275	25	250
5. Luoma Lake - Weishan lake	250	50	200
6. Weishan Lake	200	NA	NA

Table 1: General overview of system capacity divided over 6 sections.

The Jiangsu water transfer system includes three large lakes, the Hongze lake (1960 square kilometers), Luoma Lake (220 square kilometers) and Weishan Lake (660 square kilometers). For comparison, the Hongze lake is larger then the IJssel lake and Marker lake in The Netherlands together (1700 square kilometers; see figure 5). In the flood season the Hongze-, Luoma-, and Weishan Lake serve as a buffer against floods. Before and during the dry season the lakes can be used to store water that can be used during periods of water shortages.

The area of the Jiangsu water transfer system can be described as 'plain'. The average slope of the water level along the route is $6 \cdot 10^{-5}$, which is comparable to the situation in The Netherlands along the large rivers. Also the ground level within the water system boundaries can be described as 'plain', excluding some large hills in the far north of the province. Under normal circumstances water will flow from the north-northwest to the south-southeast towards the Yangtze River or through one of the many (flood) canals in western direction towards the Yellow Sea. The highest point along the trajectory within Jiangsu is the Weishan lake in the far north, 33.3 meters (China's 1985 national elevation benchmark). Water being transported for the water transfer project inevitably has to be pumped through this lake. On the north side of this lake the next province Shandong abstracts the water for further transport. During periods of water shortage, the flow direction can artificially be reversed by operating the pump stations along the route. The total lift of the stations along the East-Route is 40 meters (Ruixiang [2006]). In figure 6 a longitudinal profile of the Jiangsu water transfer system is given which shows the height profile from the Yangtze River till Weishan Lake for the main route. The projected water level comprises the water levels during high flow, uphill transport.

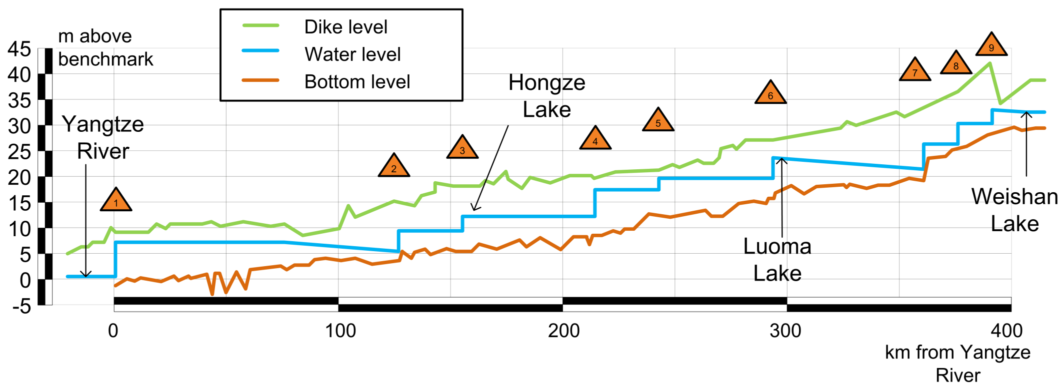

Figure 6: Longitudinal profile of the main route of the Jiangsu water transfer system (411 km).

In this thesis the most relevant structures, canals, lakes and boundaries are included in the schematization of the water system. The most important features are shown on a map in figure 7. The water system schematization in this thesis comprises 20 pump stations, 5 weirs, 3 lakes and 4 boundaries. The majority of the system information has been found Zhou et al. [2007] and Di et al. [1999]. More details of the water system can be found in Appendix A. The schematization and selection of features can be found in chapter 4.

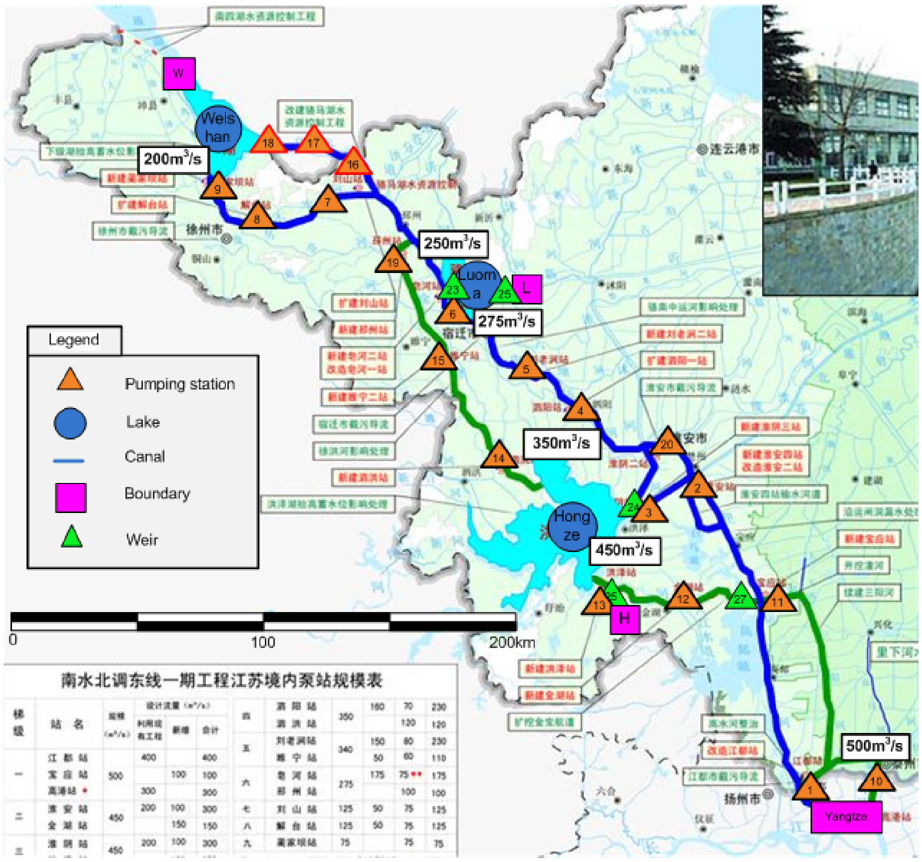

Figure 7: Location of pump stations, weirs, lakes and boundaries.

2.2 Climate

As explained in section 1.1 China's water resources are unevenly distributed over the country. Jiangsu province is located exactly on the transition from the wet southern part and the dry northern part of the country. The province is also located on the edge of the sub-tropical monsoon climate area, making it vulnerable for meteorological disasters such as heavy rainfall, hurricanes, flooding, drought and cold fronts. The average precipitation varies from 1210 mm/y in the south of the province till 724 mm/y in the north-east of the province. The yearly evapotranspiration is between 900 and 1050 mm/year, of which the major part is concentrated in the dry season from June till August. The yearly average temperature in the province is 14.7 °C, but extremes can be large. The summer temperatures rise till 35 °C with a maximum of 41 °C. During the winter months temperatures drop till -10 °C with a minimum of -23.4 °C (JWS, 2009).

2.3 Jiangsu Water Source Company

The Jiangsu Water Source Company (JWS) is a governmental organization established with regard to the SNWTP within Jiangsu Province. JWS is responsible for the construction, maintenance and operation of the new pump stations, those being part of the SNWTP only. Operation of existing stations however has been the responsibility of the Water Conservancy Department WCD (Water Resources Bureau, Jiangsu Provincial Government) ever since the 1960's and will remain their responsibility in the future. Users within the Jiangsu province have been used to water deliveries from the Yangtze River by their provincial government ever since the 1960's and according to the Chinese government the existing water supply should be maintained during and after the completion of the SNWTP. JWS will have to take care of the new additional water transfer towards the next province: Shandong. According to the plans of Beijing, users of the additional transferred water will be charged for the amounts water they receive. Because the SNWTP makes use of the existing water system along which a lot of water can be 'illegally' withdrawn, problems arise for JWS, as they might not able to meet the goals of SNWTP. In any typical dry year, JWS should be able to supply a maximum of 2.9 billion m^3 of water over the border to the next province Shandong (2013). A maximum of 6 billion m^3 of water can be supplied within Jiangsu by WCD, making the maximum yearly withdrawal from the Yangtze River 8.9 billion m^3. Including the local demands in the province, a maximum of 8.9 billion m^3 of water can be diverted from the Yangtze River. Since WCD and JWS are operating and using the same water system, they should undoubtedly work together which makes operation of the water system in dry periods their common task. Any controller for this water system should facilitate the goals of both organizations, since a water system cannot be operated by two different organizations at the same time.

Some actual topics of concern for JWS are:

- An important difference between the WCD and JWS is that WCD is paid by the government, whereas JWS should be paid by the consumers of the water. As investment and maintenance costs also need to be covered, JWS will charge the consumers of the water for both fixed and variable costs.
- Hydro-power stations along the route are sometimes owned by other organizations than JWS or WCD, such as local cities or local governments. Due to the activities of the SNWTP some stations might encounter a structural decline in revenues. Compensating local hydro-power stations for their losses is an actual topic of concern for JWS.
- The amount of water to be delivered to Shandong varies with the yearly weather circumstances. At the beginning of the dry season, JWS and Shandong make agreements on the amount of water to be delivered. In order to be able to supply this water in an (extreme) dry year JWS should anticipate long before the dry season. In a year with sufficient rainfall in Jiangsu it will not be necessary to pump water into the lakes, due to

sufficient available water within the lakes. The difficulty is predicting weather and rain conditions months ahead. JWS has the risk of pumping early in the season (because of an expected dry year) and not needing this water later on in the season. Therefore JWS wants to reduce the amount of 'excess' water which is defined as the amount of water transferred that later on turned out to be unnecessary.

Control objectives In order to be able to control a water system, the desired behavior of the system should be known. The definition of the desired behavior of the system is an essential pre-condition for control. JWS has defined the following control objectives at the end of 2009. One objective is to deliver the required quantities of water along the route. Another objective is to maintain water levels in the canal close to target level. Water levels may not exceed minimum and maximum water levels defined by JWS (see figures **??** and **??** in Appendix A) and should preferably be kept around target level. Given these two objectives, JWS is very interested in reducing the costs of pumping by the pump stations along the route. In order to avoid wear and tear, the frequency of changes in structure settings should be limited; the minimum time for the structures to operate on a certain level is 20 minutes. The policy objectives of JWS for the Jiangsu water transfer system can be summed up as shown below.

1. Deliver required water quantities at the right place at the right time.
2. Maintain water levels within allowed bandwidth, preferably around target level.
3. Given goals 1 and 2: reduce operational costs as much as possible.
4. Limit the change and frequency of change in structure settings.

The first goal includes both, the local supply to users within Jiangsu province and the water transferring of the SNWTP. Note that some goals are implicitly incorporated in other goals. For example, the goal to guarantee navigation depths is implicitly incorporated in the second goal: "maintain water levels within allowed bandwidth".

Though JWS mentioned the limiting the frequency of change from a technical point of view (avoid wear and tear), limiting the change in structure settings is added in this thesis from a control engineering point of view (see section 5.2).

2.4 Control Problem

The control objectives provided JWS in section 2.3 seem to be straightforward at first sight. For an irrigation system consisting of canal pools and small reservoirs this description of control objectives would indeed be sufficient to control a water system with a real-time controller. If a water level in a certain canal pool deviates significant from target level, the right corrective control actions could bring water levels back to target level within a timescale of minutes/hours (depending on the system characteristics). As the surface area of lakes is significant larger then that of canal pools, bringing water levels in a lake back to target level would require significant more time. Due to the extreme size of the lakes in Jiangsu and the relative small size of pump stations the the time required on which the a significant water level deviation can be brought back to target level would be in the order of weeks/months. Therefore the presence of extremely large lakes makes it necessary to consider the control objectives in a broader context, that is considering the interrelation between all levels of operational water management. Before explaining this in more detail it is wise to introduce a framework perspective that covers all levels of the decision making fundamental operational water management. These levels of decision making range from formulation of policy objectives to committing to the demands of hardware and all levels of decision making in between. Brouwer [2008] distinguishes four levels of the decision making process fundamental to operational water management.

1. Strategic level: At a strategic level general policy objectives are formulated by policy makers. The functions of a water system in the society are here described in socio-economic terms.

2. Tactical level: at the tactical level the policy objectives must be translated into a desired behavior of measurable and controllable quantities.

3. Operational level: at the operational level a functional design of the controller is defined in order to be able to implement the desired systems behavior.

4. Technical level: at the technical level the control system is designed and implemented.

This Framework perspective is illustrated in figure 8. Decisions on one level influence the (possible) solutions on the other levels in the form of boundary conditions, basic assumptions or design criteria. A control system should thus preferably be the result of the best decisions on all levels. This complex problem is referred to as the control problem (Brouwer [2008]).

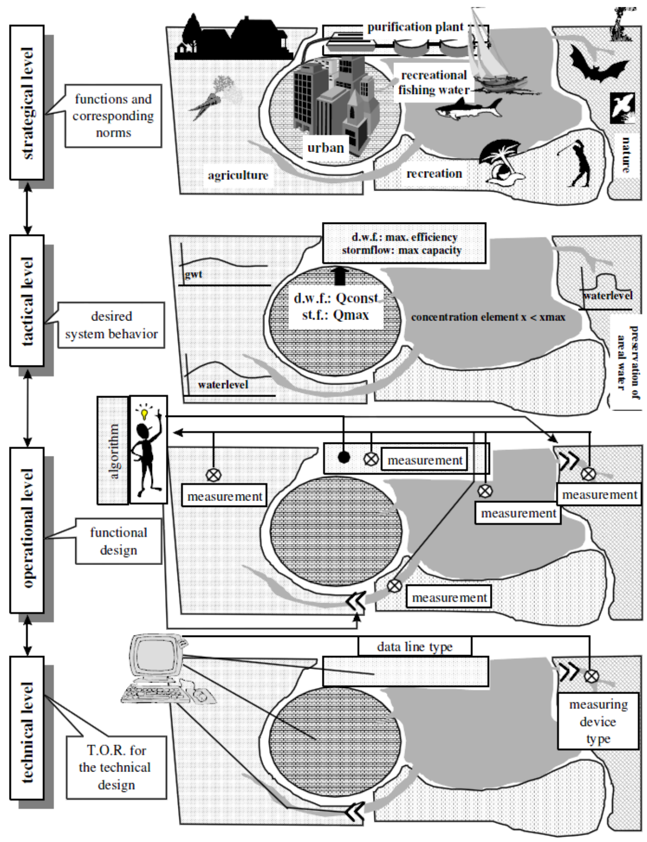

Figure 8: Framework perspective of decision making within operational water management (Brouwer [2008]).

Closer examination of the control problem of the Jiangsu water transfer system reveals that the first control objective ('deliver required water quantities at the right place at the right time') is in fact not a control objective when considering Jiangsu water transfer system, but rather a policy objective. The lakes play a crucial role in ability to provide the required amounts of water at the right time. The storage capacity of the lakes is of such significant size that the system has the capacity to deliver the required quantities under all circumstances provided the lakes have been sufficiently filled well in advance of the possible period of water shortage. If a year will be relatively wet, the lakes do not have to be filled in advance. On the other hand, in an extreme dry year, the lakes should be filled long time before the period of water shortage actually begins. This tactical level decision involves a difficulty that cannot be solved by MPC neither by any other real-time controller, because real-time control systems operate on a timescale of hours/days. Here, a translation of the policy objective into control objectives should be made by the responsible water managers. They could do this by e.g. using long-term predictions models or off-line statistics. This decision making process goes beyond the scope of this thesis. However the decisions made by the water managers would in real-time be input (the control objectives) for the controllers. Without these control objectives the research objective of this thesis cannot be accomplished (see research model in figure 3). In order to provide the controllers with control objectives in this thesis, fictive but realistic assumptions are made regarding the real-time control objectives. The assumptions made regarding each scenario are given in chapter 6.

It turns out that the real-time control objectives depend heavily on the actual situation as well as the agreements made with Shandong province. First the amount of water to be delivered to Shandong varies per year as this amount is determined through negotiations at the beginning of every year and may vary between 0 and a maximum of 2.9 million m^3. Subsequently, the actual situation during the season may be a reason to change the real-time control objectives. For example if in a dry period suddenly a high inflow is received from e.g. the Huai River, which alleviates the pressure on the water resources in the system. Now that the real-time control objectives depend on both the actual situation and the agreements made with Shandong in that specific year, it is obvious that a controller for the Jiangsu water transfer system needs up to date control objectives throughout the season. These control objectives should be provided by responsible authorities/water managers from the tactical level of decision making. With and only with regularly updated control objectives a controller can really adequately control the Jiangsu water transfer system. A meeting e.g. every 10 days to determine new control objectives would be desirable to keep the control objectives up to date. The hierarchy between strategic, tactical and operational level in the Jiangsu water transfer project can be illustrated in the framework perspective as shown in figure 9.

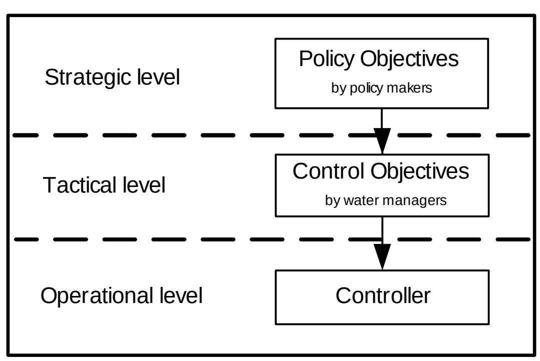

Figure 9: Framework perspective showing the relation between policy objectives, control objectives and the controller.

3 Theoretical Background

Ever since ancient human history, easy accessibility of fresh water resources has been a key factor for development and prosperity. The water was used for drinking, washing, sewerage and irrigation. As long as settlements were small, the locally available water was enough to fulfill people's needs. Due to growing populations, industrialization, urbanization and improved agricultural practices, water has become more and more a scarce resource all over the world and proper management of the available water is essential. Large water systems have been developed that are able to deliver water in the most remote areas.

In order make better use of those systems, long-term water management strategies have to be developed which concern the distribution of available water from various sources over the various users. The daily operation of water systems infrastructure concerns how the operator will get the water at the right moment at the right place by operating water structures such as pumping stations, sluices, weirs and other operational structures. In order to increase efficiency of the system, daily operation has become more and more complex and resulted in higher demands on operational management. Nowadays, traditional control objectives, such as "flood prevention" are being replaced by more complex interdependent and often conflicting water objectives. To meet these objectives sophisticated planning and control is necessary which is made possible thanks to the rapid progress in the development of sensors, communication systems, control algorithms, and methods and tools to calculate and predict the water system behavior accurately (Brouwer [2008]).

Real-time control (RTC) is the continuous operation of water structures in order to constantly meet the requirements. A controller is a set of logical and mathematical rules that determines how water structures are operated. There exist different types of controllers, such as feedback, feed-forward, MPC, heuristic, neural, fuzzy logic, etc. (Brouwer [2008]). The structures have to be operated in such a way that intended and desired behavior of the water system is effectuated. Scientific research has contributed many methods and algorithms to the field of operational water management in order to be able to control water systems more efficiently and more accurately (Malaterre et al. [1998]). The large majority of these methods apply to single in-line irrigation and drainage systems. Few papers have been drawn on branching canals (e.g. Clemmens et al. [2006]) or more complex water systems (Overloop [2005], Fambrini [2009]). To the authors knowledge no papers have been drawn on real-time control of water systems as complex and large-scale as the Jiangsu water transfer system. This is probably because research and literature on real-time control of water systems mainly focuses on irrigation and drainage systems, where system efficiency is a key-factor. These irrigation and drainage systems are typically single in-line or simple branching canal networks. In this thesis the existing literature on irrigation and drainage technology has been used and sometimes adapted to the Jiangsu situation in order to design controllers for the Jiangsu water transfer system main water system. In the next sections, first an introduction is given on control theory in general, followed by theory on feedback control and Model

Predictive Control.

3.1 Control Theory

Control theory is an interdisciplinary sub-field of science, which originated in engineering and mathematics. There exist many definitions of a control system. According to Jacobs [1996] a control system is a system in which a controller interacts, by way of one or more controlling variables, so as to influence the state of a controlled object. More specific in the field of 'Operational water management' Malaterre et al. [1998] describe a control system as elementary system (algorithm + hardware) in charge of operating structures, based on information from the canal system. This information may include measured variables, operating conditions (e.g. disturbances) and objectives (e.g. water level target levels). Boundaries of the control system are outputs of the sensors placed on the canal system, and inputs to the actuators controlling the structures. There exist many different types of control algorithms and these can be classified in many different ways (Malaterre et al. [1998], Overloop [2005]). In this thesis a classification based on general control theory is given. This general classification clearly distinguishes the two types of controllers applied in this thesis.

Feedback control Feedback control is at present the most robust way to control dynamic water systems. Control actions are directly based on the actual deviation between the measured state variable and its target level. The control action is a function of the deviation from target level (error). Within canal control, often the well-known Proportional Integral (PI) controller is used in which the change in structure setting is computed from a proportional gain factor and an integral gain factor multiplied by the change in error and the error itself, respectively. The advantage of feedback control is that it is a very robust way to control a dynamic system. The algorithm is simple and therefore very fast. The disadvantage of feedback control is that it is per definition always lagging behind: a deviation from target level is necessary in order to change a structure setting.

Feedforward control Feedforward control uses measurements or predictions of a disturbance and is aimed to precisely cancel out the effect this disturbance. Feedforward uses an inverse model of the effect this disturbance has on the water level. The control action is thus independent of the output variable. An advantage of feedforward is that it can anticipate on disturbances. The main shortcoming of feedforward is that it does not take into account what is actually going on in the system itself.

Optimal control Optimal control is a control technique in which the control signal minimizes an objective function by using a numerical optimization algorithm. In the objective function the square of the water level deviation from target level is weighted against the square of the effort to restore deviations from target level. Model Predictive Control (MPC) and controllers based on the Linear Quadratic Regulator theory (LQR) are two examples of optimal controllers. It should be noted that the term 'optimal' could be misleading. It refers to the least cost solution of the defined problem, which of course contains assumptions and simplifications of the real system.

Heuristic control Unlike the previous three deterministic control methods, heuristic control decisions are not based on physical laws, but are based on knowledge and experience of operator(s). Examples of these methods are control based on rules-of-thumb, neural networks, fuzzy logic and genetic algorithm. A drawback of all these methods is that the dynamic behavior of the water system is seen as a black box. Another drawback is that the experience gained at one water system is not transferable to another system.

Each algorithm has its advantages and disadvantages with respect to flexibility in formulation of objectives and constraints, computing time, computer storage, robustness of the control performance, etc. The choice of a control algorithm depends on a lot of factors such as the size of the system, the complexity, objectives, number and type of structures, etc. The selection of the best controller often means that the simplest controller is selected that is able to reach the objective in a satisfactory way (Overloop [2005]).

3.2 Feedback Control

Feedback control is at present the most robust way to control dynamic water systems. Control actions are directly based on the actual deviation between the measured state variable and its target level. After adjusting the actuator the state variable is measured again, and a new control action is determined. This implies that as long as there is a deviation, the controller will adjust the actuator in an effort to return to target level. Feedback control is also referred to as closed loop control, since the system output variable is input for the controller and the controller output is in turn input for the system (Brouwer [2008]). The most straightforward controller is a proportional controller, whereby the control action is proportional to the deviation. A proportional controller always has the problem that it does not return the water level to target level, that is it has an offset. Integral feedback control is often added to proportional controllers to force the water level to return to the target level (PI-control, Clemmens and Schuurmans [2004]). The main disadvantage of any type of feedback control is that the control action is per definition always lagging behind the deviation. In case the disturbance exceeds the capacity of the actuator, the deviations may exceed the allowed bandwidth around target level.

When a feedback-controlled structure is located near the water level being controlled, a properly tuned PI controller should provide good water level control. However, for a series of canal pools, PI controllers of adjacent pools can interfere with each other. While the single controller might be stable, in combination the system can become unstable. Thus control is complicated by the hydraulic interactions between neighboring pools. Control is further complicated by the fact that PI controllers do not always deal properly with pools that have a significant delay time. The time required for upstream flow changes to be felt downstream require either long times between control actions (i.e. wait-and-see approach), or a sophisticated controller design to avoid control instability (overshooting and oscillations). For control of (branching) irrigation and drainage systems many different feedback techniques exist, varying from a series of individual PI controllers (each gate is adjusted based on one water level) to fully centralized controllers (each gate adjusted based on all water levels) that include the effects of lag time. A large range of feedback controllers between these two extremes can be defined (Clemmens and Schuurmans [2004]).

Ruiz-Carmona et al. [1998] show that many proposed control algorithms can be expressed in more or less a common format: the state-feedback form, where control actions are determined from:

$$u(k) = -Kx(k) \tag{1}$$

Where $u(k)$ = the vector of control actions at time step k; K the controller gain matrix; and $x(k)$ the vector of states at time step k. Tuning is a process whereby the coefficients in K are determined by minimizing a quadratic penalty function J (objective function):

$$J = \sum_{k=0}^{\infty} e(k)^T \cdot Q \cdot e(k) + u(k)^T \cdot R \cdot u(k) \tag{2}$$

Where T = transpose operator; $e(k)$ the vector of water-level errors at time step k; Q the penalty function for water-level errors; R penalty function for control actions. The solution of K is subject to the dynamic characteristics of the physical system, as described by the discrete-time state-space model:

$$x(k+1) = A \cdot x(k) + B_u \cdot u(k) + B_d \cdot d(k) \tag{3}$$

$$y(k) = C \cdot x(k) \tag{4}$$

Where A is the system matrix; x is the vector with the states of the water system; B_u the control input matrix; B_d the disturbance matrix; u the inputs calculated by the controller; d the disturbances. This is called a Linear Quadratic problem (LQ problem) and optimization of a LQ problem can be done with a Linear Quadratic Regulator (LQR). The solution is a control gain matrix K in Eq. (1) that minimizes J in Eq. (2) subject to Eq. (3) and Eq. (4). Procedures for solving these equations can be found in standard control engineering textbooks e.g. Åström and Wittenmark [1997].

3.3 Model Predictive Control

This chapter discusses the control methodology 'Model Based Predictive Control'. Recently, in literature, the name Model Predictive Control (MPC) is mainly used. Model Predictive Control is a control technique originated in the seventies in the industry sector, where it is applied in a wide range of, mainly chemical, industries ever since. MPC has proved to achieve highly efficient control of processes during a long period of time with hardly any intervention in a broad range of applications. During the last two decades the academic research community has contributed important results (Camacho [2009]). Because of the increasing complexity of modern water systems and increasing demands on the flexibility of water systems, more and more use is made of advanced control methods such as MPC. The term MPC does not refer to a specific control strategy. Instead, it refers to a broad range of control methods that explicitly use a simplified process model of the real system to obtain control actions by minimizing an objective function (Camacho and Bordons [1999]). This optimization process is subject to the system constraints e.g. capacity of pumps. An example trajectory of a water level in a canal with limited pump capacity controlled by MPC, feedback (and feedback+feedforward) is shown in figure 10. The target level is -0.4 mMSL and the red dotted lines indicate the system constraints: the minimum and maximum allowed water levels and the pump capacity ($60m^3/s$). The graph shows that the feedback controller is able to maintain the water level close to target level (-0.4 mMSL) until the disturbances in the canal exceeds the pump capacity. This happens around 21:00 hour and from that moment the water level rises above the maximum water level. The strength of MPC is that it 'sees' the disturbances coming (e.g. heavy rainfall) and takes corrective control actions well in advance. Thereby the violation of the maximum water level at the end (around 6:00 hour) is smaller than under feedback control. This example illustrates how MPC minimizes the violation of minimum and maximum water levels by taking corrective control actions far earlier then feedback or feedforward controllers. The strength of a controller with a model of the system is thus that it can anticipate on events instead of only correcting them.

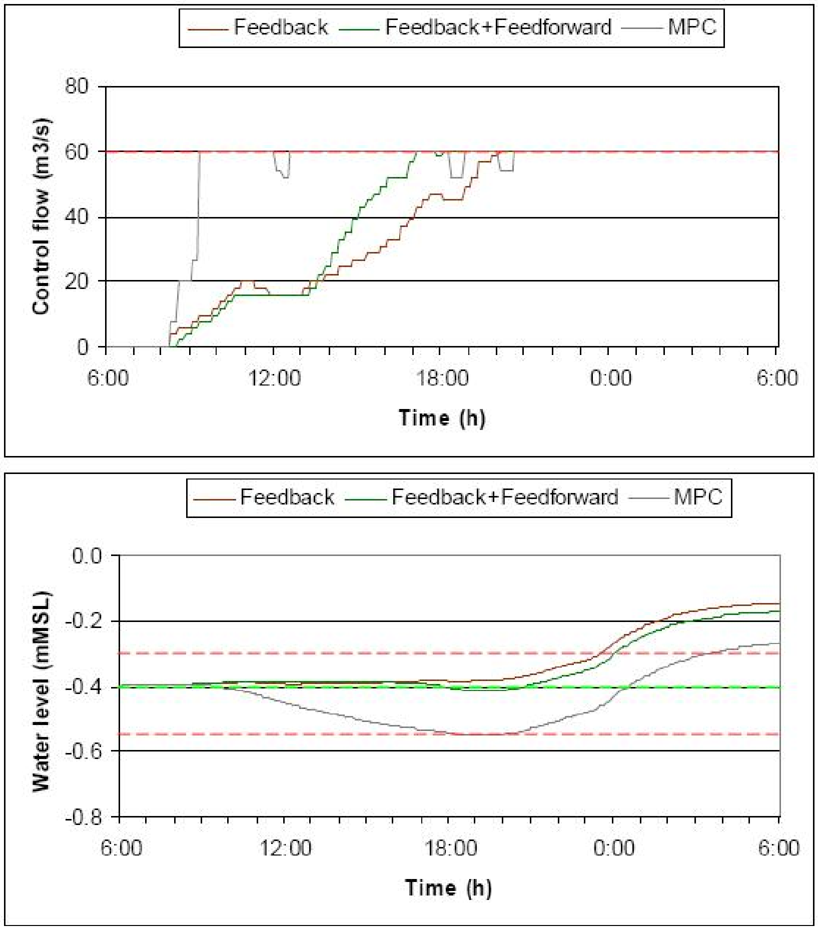

Figure 10: Example of a canal pool controlled by MPC, feedback and feedback+feedforward.

Every type of MPC has three characteristics in common (Camacho and Bordons [1999]):

- **Internal Model**: a simplified model of the water system is used to predict the future output of the system, $y(k+i \mid k)$. The present state is indicated by time index k. The counter i represents the number of time steps into the future, ranging from 1 to n, the prediction horizon. The output predictions have both a free response and a forced response. The free response is the expected behavior of the system assuming no future control actions. The forced response is the additional component of the process output that corresponds to unknown future control action, $\Delta u(k+i \mid k)$. The forced response is predicted into a control horizon nc. This control horizon can be less than, but is usually equal to the prediction horizon n. The total response is the sum of both the free response and the forced response.

- An **objective function** which is typically the sum of some combination of the water level errors and control actions over the prediction horizon, is minimized by adjusting the future unknown control actions. This optimization problem is subject to the constraints that are imposed on the system.
- After the sequence of future control actions is calculated, only the first control signal $u\,(k \mid k)$ is sent to the actuators. The next sampling step the optimization is done all over again with the updated information on the system. This strategy is known as the **receding horizon strategy**.

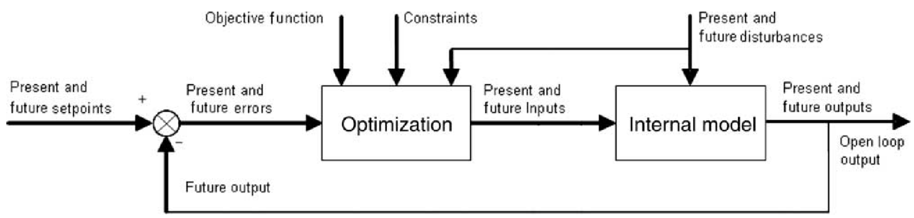

Figure 11: Block diagram of MPC (Xu et al. [2010]).

In figure 11 a block diagram of Model Predictive Control is given. In the next sections all components of MPC are discussed.

3.3.1 Internal Model

MPC is a model based controller. The internal model is used to predict the future states of the controlled water system, also called a process model. Like any real system, the actual water system is non-linear. In order to use linear algebra and generally available computational tools to solve the control problem, the non-linear water system is converted into linear sub-systems and written in the state-space notation. The state-space representation is a discrete-time linear model of a physical system describing the state transition from one state to the other and is currently used in most applications of MPC on water systems. The state-space notation has been given before in Eq. (3) and Eq. (4).

When the initial state x(k) and inputs are known, future states of the system can be computed directly. Overloop [2005] showed that, when the state-space representation is extended over the prediction horizon n, large equations arise that can be written in more compact form as large matrices. This matrix notation can be written as following:

$$X = A \cdot x(k) + B_u \cdot U + B_d \cdot D \tag{5}$$

$$Y = C \cdot X \tag{6}$$

With:

$$X = \begin{bmatrix} x(k) \\ x(k+1 \mid k) \\ \vdots \\ x(k+n \mid k) \end{bmatrix} \; U = \begin{bmatrix} u(k) \\ u(k+1 \mid k) \\ \vdots \\ u(k+n-1 \mid k) \end{bmatrix} \; D = \begin{bmatrix} d(k) \\ d(k+1 \mid k) \\ \vdots \\ d(k+n-1 \mid k) \end{bmatrix}$$

$$A = \begin{bmatrix} I \\ A \\ A^2 \\ \vdots \\ A^{n-1} \end{bmatrix}$$

$$B_u = \begin{bmatrix} 0 & 0 & \cdots & 0 \\ B_u & 0 & & 0 \\ A \cdot B_u & B_u & & 0 \\ \vdots & & \ddots & \vdots \\ A^{n-2} \cdot B_u & & & B_u \end{bmatrix}$$

$$B_d = \begin{bmatrix} 0 & 0 & \cdots & 0 \\ B_d & 0 & & 0 \\ A \cdot B_d & B_d & & 0 \\ \vdots & & \ddots & \vdots \\ A^{n-2} \cdot B_d & & & B_d \end{bmatrix}$$

$$C = \begin{bmatrix} C & \cdots & & 0 \\ \vdots & C & & \\ & & \ddots & \\ 0 & & & C \end{bmatrix}$$

Matrix D represents the prediction of the disturbances over the prediction horizon n. The process model of the system needs to be set-up in such a way that it contains the dynamics that are most relevant for real time control. However, detailed discretization results in long computation times, which makes it difficult to use accurate process models in real-time applications (e.g. De Saint Venant equations). Schuurmans et al. [1995] developed the integrator-delay model (ID model) to represent canal pool response. This is a lumped-parameter linear approximation model of the De Saint Venant equations that can be written in state-space notation. The ID model divides a canal reach into two parts: the uniform flow part and the backwater part (figure 12). This model uses two parameters to describe the basic dynamics of a canal pool: the delay time k_d and storage area A_s. This simplified process model is accurate enough to capture the basic dynamics relevant for water systems control. The strength of this model is that it is very compact and therefore fast and thus very suitable for the internal model of MPC. Disadvantage is that the parameters delay time k_d and storage area A_s are only valid at one working point. The values of these parameters change when the flow changes, which is not incorporated in the ID model due to the linearization. Another disadvantage is that it does not describe resonance waves which may occur in short reaches with a small slope (Overloop [2005]).

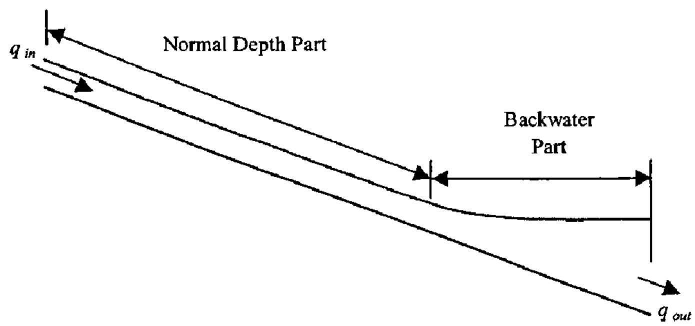

Figure 12: Integrator Delay model on a canal reach.

The water level deviation from target level *e(k)* is an obvious state variable to control, because it is easy measurable with $e(k) = targetlevel - waterlevel(k)$. The ID model on a canal pool is given by the following equation (Schuurmans [1997]):

$$e_i\left(k+1\right) = e_i(k) + \frac{\Delta T}{A_s} \cdot \left[u_i\left(k-k_d\right) - u_{i+1}(k) + d_i(k)\right] \quad (7)$$

Where $\mathrm{e_i(k)}$ = water level deviation from target level in pool i at time step k in meters; $\Delta\mathrm{T}$ = the time step in seconds; A_s = backwater surface area of the pool in square meters; $u_\mathrm{i}(k)$ = control action by structure i at time step k in cubic meters per second; $d_\mathrm{i}(k)$ = disturbance flow in pool i at time step k in cubic meters per second. Overloop [2005] concluded that, though the internal model is always a considerable simplification of the real system dynamics, the controlled water systems in his dissertation function in a satisfactory manner. Overloop subscribes this to the receding horizon principle.

3.3.2 Constraints

The water levels and control actions are subjected to constraints, such as minimum and maximum water level, minimum and maximum capacity of a structure and minimum and maximum change of a structure per time step. The optimization algorithm used by MPC is able to narrow its solution by taking these constraints into account. Constraints can cause problems, e.g. when the water level is outside the bandwidth due to extreme circumstances. States outside the allowed bandwidth, can cause the optimization to become infeasible. To prevent the optimization to become infeasible, distinction is made between hard constraints and soft constraints. Hard constraints may never be violated, because it is simply not possible e.g. pump capacity. Other constraints are less rigid and may be violated to some extent. The difference in implementation is that hard constraints are put into the optimization as a hard limitation to a state or input, while soft constraints are implemented as extra penalties when the state or input violates its limitation. Soft constraints are preferred over hard constraints, because they guarantee a solution of the optimization (Malda [2005]).

Soft constraints A soft constraint is implemented by using a virtual input and a virtual state. The virtual state (e^*) is computed by subtracting the virtual input (u^*) from the state that needs to be constrained. By putting a high penalty on the virtual state e^* the virtual input u^* will set e^* to zero. Subsequently a hard constraint is applied to the virtual input, so that whenever a violation of the water level occurs, the virtual state e^* will not be zero anymore and create a very high penalty to the objective function immediately (Overloop[2005]). The controller will thus try to avoid a violation as much as possible, but when it occurs it does not lead to an infeasible solution. The equation for the virtual state is:

$$e^*(k+1) = e(k+1) - \frac{\Delta T}{A_s} \cdot u^* \tag{8}$$

With: e^* = the virtual state; u^* = the virtual input

Hard constraints A hard constraint simply cannot be violated, because that would be impossible e.g. the capacity of a pump station. The optimization problem is be subjected to constraints in the general form $A \cdot x \leq b$. Hard constraints can be applied on states and control actions and hard constraints determine if an optimization problem is feasible.

3.3.3 Objective Function

The objective function formalizes the goals of the controller. "The objective function contains sub-objectives that are added up. These sub-objectives can be conflicting. When a relative penalty is given to each of these sub-objectives to indicate the relative importance of the sub-objective, a quantified and dispassionate solution can be computed by minimizing the objective function" (Overloop [2005]). The objective function is set up using Quadratic Programming (QP). The reason is, that using the square of the states and inputs, penalizes both positive and negative deviations and higher deviations are penalized more than proportional due to the power of 2. It is therefore a common used method. Another advantage of this type of programming is that it makes programming not too complex. The finite horizon objective function over the prediction horizon n can be written as:

$$J = X^T \cdot Q \cdot X + U^T \cdot R \cdot U \tag{9}$$

where J is the objective function; X the system state vector; U the vector with control actions; Q the penalty matrix on the state vector; R the penalty matrix on the control input vector. There are many convenient methods by which to solve an optimization problem if it is expressed as a quadratic programming problem (Wahlin [2004]).

Not only are the system state variables part of the objective function, but also the control actions, because control is preferably done with as little structure adjustments and/or energy consumption as possible. This optimization is performed on every discrete time step over the control horizon n. The control actions u over the prediction horizon n can be varied, thus by changing these values the minimum value for the objective function J should be found. The objective function over the prediction horizon subject to the constraints on states and inputs, needs to be minimized using an optimization algorithm. An optimization algorithm calculates the control actions over the prediction horizon that need to be implemented to get the lowest possible value of J as given in Eq. 9. The minimum value of J can be calculated by procedures outlined in standard control engineering textbooks (e.g., Åström and Wittenmark [1997]), by using built-in numerical methods found in programs such as MATLAB (MathWorks [2000]) or with fast commercial solvers such as TOMLAB (Edvall and Göran [2009]).

The weighting of the water level errors and control actions is done through the penalty matrices. The penalty matrices should be tuned such that the desired system behavior is effectuated (see section 5.2.2 on the tuning of these values). Exact tuning rules do not exist, though a sensible approach is to use Maximum Allowed Value Estimate (MAVE), which is a realistic estimate of how much a state or input may vary. For water level deviations the MAVE may be the maximum water level deviation and for pump stations the pump capacity is a sensible value (see Overloop [2005] for more details on the use of MAVE).

3.3.4 Disturbances

Any uncontrolled input on the water system is called a disturbance e.g. rainfall run-off, off takes by users, etc. Disturbances are defined as separate inputs on the water management process and act in the same way as the actuators on this process. From a control point of view, disturbances can be seen as changing boundary conditions e.g. run-off that changes due to a storm event or changes in off takes. Disturbances induce changes to the water system and need to be corrected or preferably anticipated by a controller when the disturbance can be predicted. Predictions of disturbances (e.g. weather forecasts) are denoted in the disturbance matrix D (see Eq. 5). See section 6.2 for more information on the data series used in this thesis.

4 Hydrodynamic Flow Model (SOBEK)

In order to assess the performance, controllers should preferably be tested on a hydrodynamic model of the real water system. In this chapter the hydrodynamic model of the Jiangsu water transfer system will be presented. It should be noted that the Jiangsu water transfer system will not be completed before 2013 and therefore the real system does not exist (completely) yet.

The water system schematization is presented in section 4.1. In section 4.2 the schematization is implemented in SOBEK. In section 4.3 the functioning of the hydrodynamic model is compared to the functioning of the system as intended by Chinese engineers. This is called "model acceptation" and can be considered as an alternative to model calibration and validation. The model should represent the future system as accurate as possible in order to have representative results for the future Jiangsu water transfer system. Finally in section 4.4 the most important hydraulic parameters that are required for development and tuning of the controllers are determined with steady state simulations.

4.1 Schematization

The function of the hydrodynamic model in this thesis is to simulate the system behavior of the water system as a result of control actions taken by the controllers. The better the hydrodynamic model is able to simulate the behavior of the real system, the more relevant the results are. For modeling convenience, the water system as described in chapter 2 is schematized and all features are given Id's. The schematization is shown in figure 13 and includes 27 structures, 4 boundaries and 18 pools[1]. All structures are labeled with numbers (1 till 27). For practical reasons all pools are labeled with an 'e' followed by the number of the pool (e1 till e18). The system has numerous canals to discharge excess water out of the system. Most of these canals connect the major lakes Hongze and Luoma with the Yellow Sea or the Yangtze River. The discharge canals have been defined as boundaries and can be used to discharge excess water out of the system. More details of the system such as target levels, bottom heights, bottom widths, minimum and maximum water levels, etc. are given in Appendix A.

The water system of Jiangsu is large, complex and has hundreds of structures and pools. In the schematization only a part of these features/characteristics can be modeled. Below the selection criteria have been given that have been used to produce schematization for the hydrodynamic model.

[1]Terminology: a pool can be a lake or a canal pool (a part of a canal in between two structures)

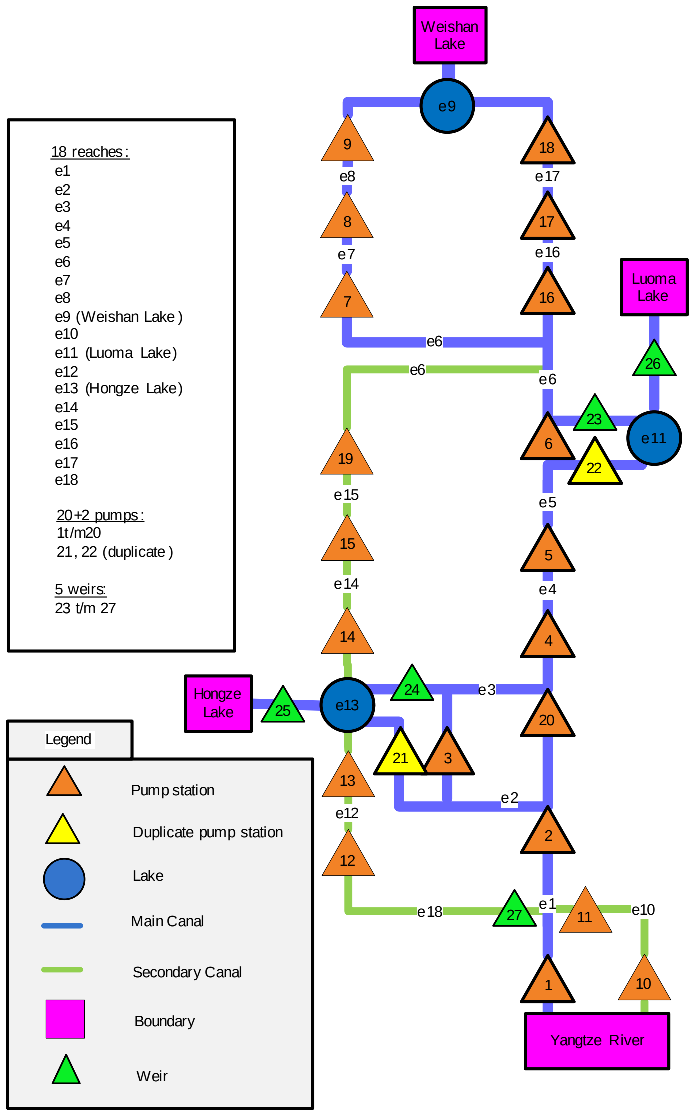

Figure 13: Schematization of the Jiangsu water transfer system.

Selection criteria All features that are included in the schematization are selected in a consequent manner according to the following principles. All dark blue and green canals and dark blue lakes in figure 5 are included, because together these pools facilitate the water transfer within Jiangsu. All structures that both abstract from- and discharge to any of the above defined pools are included. In other words, the structures that transport water from one pool to the other within the Jiangsu water transfer system. Thus structures that abstract water from the route for e.g. local supply are not included. The influences of these structures are modeled as disturbances. Also all canals and rivers that are connected to the pools of the Jiangsu water transfer system are modeled as disturbances. Logically the boundaries of the system are the intake points along the Yangtze River and the boundary with the next province Shandong whereto the water is transported. The Hongze Lake and Luoma Lake have several large flood ways to be able to discharge excess water out of the system. These are schematized as boundaries with a controllable structure (weir) so that the flow through the a can be controlled. It should be noted that these structures/boundaries are not used in this thesis if the controllers are tuned correct, since within the framework of this research only periods of the dry season are simulated.

Duplicate stations In the schematization in figure 13 two duplicate stations have been introduced that are not present on the map shown in figure 7. These duplicate stations do not exist and neither have been planned, though have been introduced to overcome a limitation of the ID model. The ID model as presented in section 3.3.1 does not allow stations to discharge into more then one pool. Pump station 6 in reality is a group of pump stations with a total capacity of 275 m^3/s. These pumps discharge water from reach e5 into reach e6, however a part of these pumps have an option to discharge water into Luoma Lake (e11). The capacity of these pumps is 100 m^3/s. For this 100 m^3/s a duplicate station has been created. The capacity of the original station and the duplicate station together now is 375 m^3/s where the real station's capacity is still limited to 275 m^3/s. The sum of both stations should be constrained to 275 m^3/s. Therefore an extra state is added to the internal model which is the sum of the pump and its duplicate and which is subsequently constraint at $275m^3/s$. A similar situation has been found for pump station 3, which is able to discharge water into reach e4 as well as towards the Hongze Lake (e13). Details on the exact implementation of the extra state in the b model can be found in section 5.2.1.

4.2 SOBEK Model

According to Clemmens et al. [2005] there exist three unsteady-flow simulation packages that allow end users to write their own control schemes (e.g. write a control algorithm in MATLAB). These are CanalCAD from the Univ. of Iowa, Hydraulics Lab, Mike11 from the Danish Hydraulic Institute and SOBEK from WL/Delft Hydraulics. They found all three programs useful for studying various aspects of canal automation. In this thesis the hydrodynamic package SOBEK (WL/Delft hydraulics 2000) has been chosen. SOBEK is a powerful software package for the integral simulation of processes in canal- and river systems.

This section shows how the schematization of the water system presented in the previous section has been modeled in SOBEK; a visualization is shown in figure 14. With all available information from China an as good possible model of the future water system has been constructed.

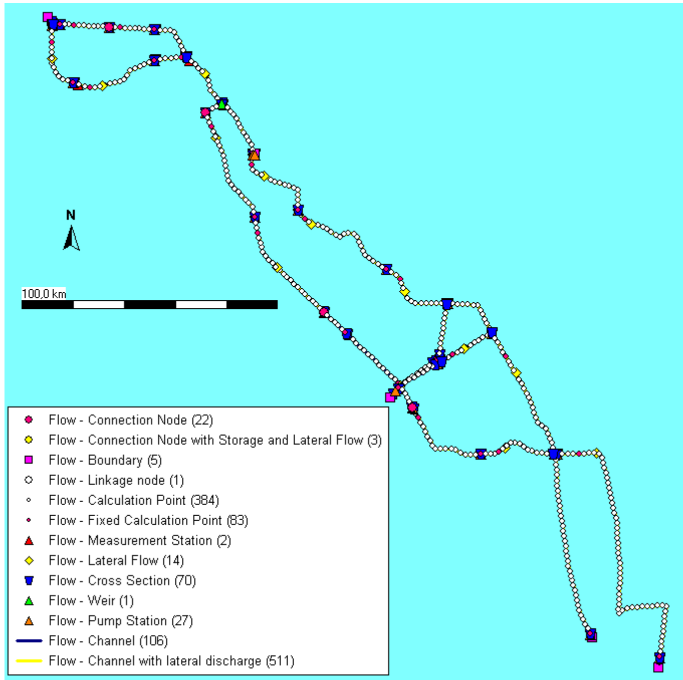

Figure 14: Schematization of Jiangsu water transfer system in SOBEK.

Branches According to JWS more than a thousand small branches exist along the East-Route trajectory. Due to their large number, these branches cannot be modeled individually in the schematization, if even detailed information were available. However, their aggregated influence on the system can be large and should therefore somehow be modeled. This aggregated influence can be extracted from the data series that have been provided by JWS. The aggregated outflow of all these small branches can be found in the data series given in section 6.2. From Eq. 7, it can be derived that the ID model requires one disturbance per canal pool. Therefore the data series have been distributed over all canal pool's with respect to their length, that is the height of the disturbance is proportional to the length of a canal pool (see section 6.2 for details).

Discretization in space and time The SOBEK hydrodynamic model is a time- and space discrete model. The choice of the size of computation time step and space step is an assessment between computation time and model accuracy. In the tests a simulation time step of 5 minutes has been used for all control tests, whereas the discretization in space has been chosen 2000 meters so to make sure that the most important dynamics were included.

Cross-sections The following characteristics of the canals are known: the average bottom width of canal reaches and the projected water depth h. Detailed cross-sections are not available and therefore it is assumed that the cross-sections of all canals have a trapezium form, with a slope of 1:1. The height of the cross-section is extended significantly above the water surface level, such that the 1:1 slope continues above the surface level (see figure 15).

Bottom shear stress and spatial variations of cross-section along the canal pools are not available. JWS explained that the bottoms of all canals consist mainly of normal (medium size) sand. Base values for Manning roughness coefficient of a canal with sand bottom, range between 0.012 and 0.026 (Arcement [1984]). It is assumed that the roughness is uniform over the whole water system with Manning roughness coefficient $n = 0.02[-]$.

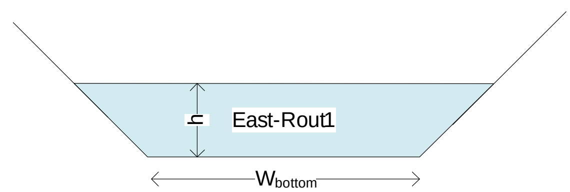

Figure 15: Random cross-section.

4.3 Model Acceptation

Since the real water system does not exist yet and detailed data series are unavailable, calibration and validation of the hydraulic model is not possible. However, at least some form of validation is necessary in order to prove that the hydraulic model does resemble the real system in such a way, that it is a sufficient accurate to assess the performance of controllers. In this section two important characteristics of the Jiangsu water transfer system provided by JWS are compared with steady state simulations results of the hydrodynamic model. These given characteristics are the projected water levels and flow velocity through the system under high flow conditions.

Water level trajectory The by SOBEK calculated steady state water levels under high flow conditions are shown in figures 16 and 17. The trajectory of the water level throughout the whole system under design capacity (high flow) is defined by Chinese engineers in Zhou et al. [2007]. This projected water level trajectory is visualized by the red lines in figures 16 and 17. Although certain characteristics such as cross section profiles and bottom roughness are unavailable, the projected water levels by Chinese engineers include indirect a lot of information about these unknown characteristics. The results of the steady state calculation show a good resemblance between the projected and calculated water levels in the main route. In the secondary route there are some canal pools where the projected water level is significant steeper than the calculated water level. This occurs especially in relative short and narrow canals.

Figure 16: Steady state situation during a design capacity run for the main route (Grand Canal): the blue line in figure 5.

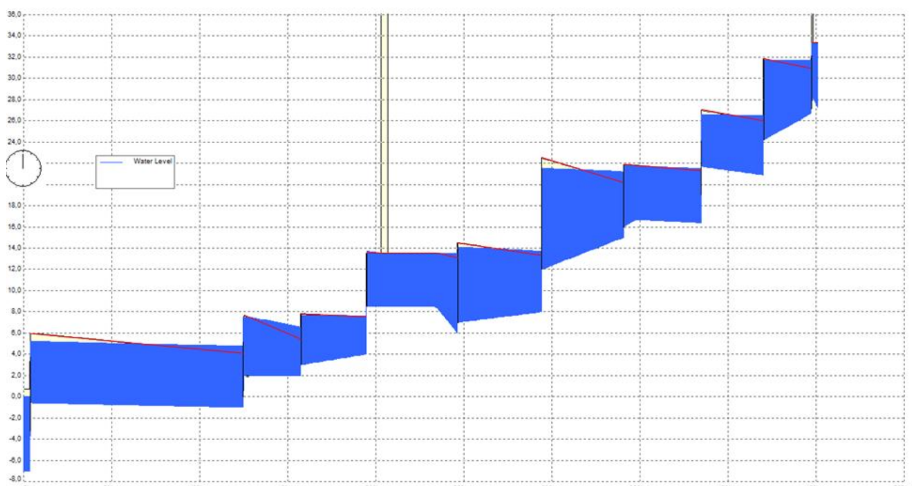

Figure 17: Steady state situation during a design capacity run for the secondary route: the green line in figure 5.

Flow velocity A second model verification is to analyze the flow velocity of the flow through the system under these maximum flow conditions. According to JWS the projected time for water to travel from the intake point at Jiangdu (pump station 1) till Weishan Lake should approximate 7 days under high flow conditions. The flow velocity of the water through the hydrodynamic flow model has been estimated at 9 days.

The discrepancies in flow velocity and projected water levels could be caused by the fact that some canals may have been narrower in Chinese calculations, which is suggested by the steeper projected water levels. Because for some canal pools a bottom width range (instead of an exact value) has been given, narrowing the canals within this range has been tested, but resulted in uncontrollable canals as the canals became to narrow to transport high flow conditions. Too narrow canals are difficult to control by controllers as detailed dynamics of the flows cannot be captured by the ID model (see section 3.3.1). Another source of discrepancy can be the assumption regarding the bottom roughness. The lower flow velocities in SOBEK can (partially) be explained by a too high bottom roughness coefficients. The discrepancies are probably a combination of both.

The calculated water levels show sufficient resemblance with the projected water levels. It is assumed that the hydrodynamic model is a sufficient accurate representation of the future water system to assess the performance of controllers.

4.4 Hydraulic Parameters

In section 3.3.1 it has been shown that some hydraulic parameters of the water system are required for the design and/or tuning of controllers. Since the ID model is used as process model, the hydraulic parameters required by the controllers are the delay times and surface areas. These hydraulic parameters are derived from the steady state calculations in SOBEK, which is explained in this section.

4.4.1 Backwater Surface Areas

In this section the backwater surface areas A_s required by both controllers are determined. There are different ways to determine the backwater surface area A_s of a canal pool. Brouwer [2008] proposed to simulate a steady state situation for the minimum and maximum operational flow and integrate the water surface width over the backwater part of the canal. The average of the results can be taken as the surface area A_s for a pool. However, the steady flow simulations in section 4.3 show that it is reasonable to assume the whole length of all pools are always under backwater, because when the water level in a pool increases, it is divided over the complete pool. Since the target levels at the beginning and end of every pool are known, the values for A_s are estimated by multiplying the average surface width by the canal length. The surface area of the lakes has been chosen such that it corresponds with the target level of the lake in the summer. Table 2 gives an overview of all backwater surface areas.

Pool Id	Surface area $A_s[m^2]$ (high and low flow)	Pool Id	Surface area $A_s[m^2]$ (high and low flow)
e1	13,194,240	e10	5,246,560
e2	6,160,460	e11	220,000,000
e3	6,930,700	e12	11,407,100
e4	3,905,700	e13	1,960,000,000
e5	2,688,840	e14	1,686,250
e6	6,335,000	e15	1,389,200
e7	2,464,000	e16	2,017,620
e8	1,939,680	e17	3,397,200
e9	660,000,000	e18	1,889,600

Table 2: Backwater surface areas of canal pools.

4.4.2 Delay Times

There exist different ways to determine the delay times of the canal pools. This can be done using system identification tools e.g. the Pseudo Binary Random Sequence test (PRBS) (Malda [2005]). This is a laborious test preferably executed on the real canal. In this thesis the hydrodynamic model is used to determine the delay times. First a steady flow through the model is simulated ($Q_{in} = Q_{out}$). At a certain moment the steady flow (Q_{in}) is suddenly increased with an additional flow ΔQ. The time it takes for this additional flow to affect the downstream end of the reach is the delay time of that reach (see figure 18).

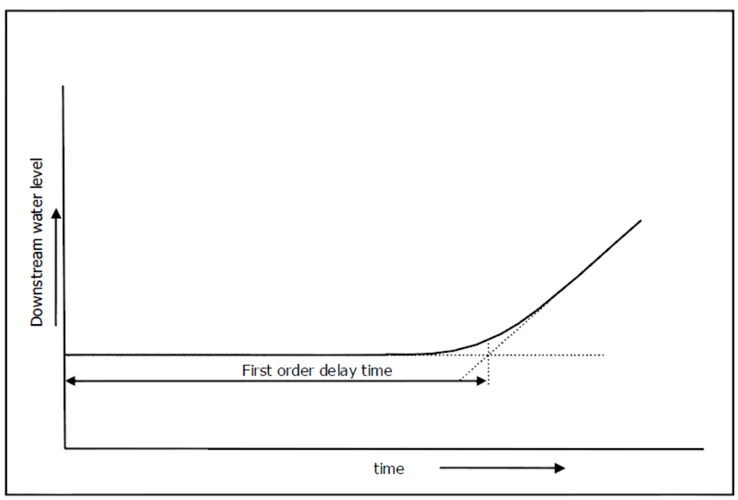

Figure 18: Determination of the delay time of a reach.

The delay times vary with the flow conditions. Under high flow the delay times are normally shorter then under low flow. Table 3 shows the delay times of all structures under both high and low flow. As explained in section 3.3.1 the ID model is a linear approximation model valid at only one working point. Within this thesis the operation of the controllers is tested under mainly high flow conditions and thus the high flow delay times are used in the internal model of MPC. For the tuning of the feedback controller, both high and low flow delay times are required (see section 5.1.1 and Overloop et al. [2005] for details).

Structure	Low flow [h:min]	High flow [h:min]	Structure	Low flow [h:min]	High flow [h:min]
Pump 1	4:15	3:30	Pump 12	1:05	1:00
Pump 2	0:45	0:35	Pump 14	1:25	1:20
Pump 3	1:35	1:20	Pump 15	1:27	1:20
Pump 4	1:23	1:05	Pump 16	0:30	0:25
Pump 5	0:52	0:45	Pump 17	0:37	0:30
Pump 6	2:05	1:45	Pump 19	1:50	1:30
Pump 7	1:02	0:50	Pump 20	0:51	0:40
Pump 8	0:50	0:40	Weir 23	2:05	1:45
Pump 10	3:50	3:20	Weir 24	1:35	1:20
Pump 11	1:53	1:40	Weir 27	0:55	0:50

Table 3: Delay times of structures for high and low flow. Not listed structures have a zero delay time.

5 Controller Design

In the previous chapter the hydrodynamic model of the water system has been presented. In chapter 3 first the control theory has been expounded followed by the different types of controllers used in this thesis. The current chapter shows how the theory of chapter 3 is used to design controllers for the Jiangsu water transfer system as presented in chapter 4. Before presenting the controllers, the measuring locations are defined as well as the filter that has been used on the water level measurements. The measuring locations need to be known before a controller can be designed.

Measuring locations and filtering

One of the control objectives is to keep the water levels around target level. Control of water levels can be anywhere in a canal pool, though often it is chosen to maintain constant water levels at the downstream end of each pool, with the assumption that downstream water demands are then satisfied (Clemmens and Schuurmans [2004]). Therefore all water levels are measured at the downstream end of a canal pool. Moreover navigational depth is always guaranteed since the bottom slope is downhill in upstream direction (e.g. see figure 6).

In this thesis all measurements are filtered to damp the effect of possible oscillations that are not caused by resonance waves, but by overshooting due to narrow canals. The filtered water level error e_f is given by Overloop et al. [2005]:

$$e_f(k) = F_c \cdot e_f(k-1) + (1 - F_c) \cdot e(k) \tag{10}$$

Where F_c= filter constant; e = water level error $[m]$. In this thesis the minimum value of $F_c = 0.667$ turned out to be sufficient to cancel out all oscillations.

5.1 Feedback controller

The general theory on feedback control of water systems has been presented in chapter 3. It should be noted that the presented theory covers control of mainly irrigation and drainage systems, which are relative simple water systems compared to the Jiangsu water transfer system. Most feedback controllers are tested on single in-line canals (e.g. Clemmens & Schuurmans [2004], Overloop et al. [2005]) or simple branching canal networks (e.g. Wahlin and Clemmens [2006]). These networks can be represented as in figures 19 and 20. In this representation the Jiangsu water transfer system is shown in figure 21. The network is not only more complex, but also serves more functions than irrigation and drainage networks. Hence, it is not sure whether application of feedback controllers to a system as large and complex as the Jiangsu water transfer project would lead to the same performance found as on simple irrigation and drainage canals.

Figure 19: Irrigation and drainage networks used in literature: single in-line canal (e.g. Clemmens & Schuurmans [2004], Overloop et al. [2005]).

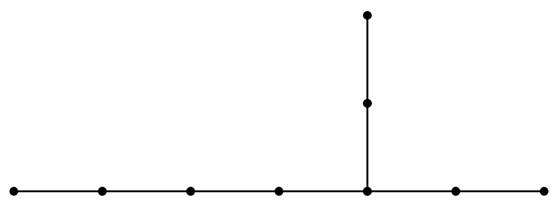

Figure 20: Irrigation and drainage networks used in literature: branching network (e.g. Wahlin and Clemmens [2006]).

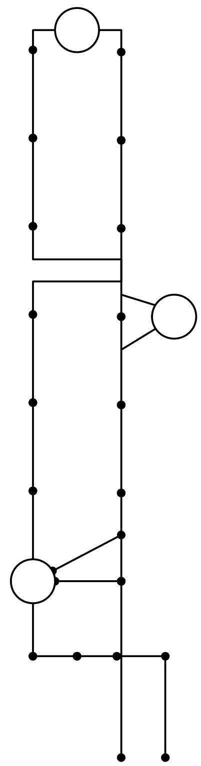

Figure 21: Representation of Jiangsu water system.

As explained in chapter 3.2 the control action of a feedback controller is a function of a deviation from target level of one or more variables to be controlled. A broad range a water-level feedback controllers for canal reaches exist ranging from a series of individual PI-controllers to fully centralized controllers (Clemmens and Schuurmans [2004]). Individual PI-controllers adjust check flows based only on the water level immediately upstream and/or downstream of the check. Schuurmans [1992] showed that sending control actions within a given pool to an upstream check structure made significant performance improvement to PI-controllers; he referred to this as Decoupler I. Clemmens & Wahlin [2004] showed further improvement when control actions within a given pool are sent to multiple upstream pools. Sending information also downstream resulted in further performance improvement. Sending all control actions to all other pools might result in even better performance, but also further increase controller complexity. Clemmens and Wahlin [2004] showed a good compromise between controller complexity and performance is provided by controllers that pass feedback from a given water level to all upstream and one downstream check structures. Finally, with centralized control, observations and actions are done from a remote site. The control system can adjust the check structures in the whole system based on simultaneous observation of water levels in many pools. As more information can be used, centralized control can potentially result in a higher performance than decentralized control (Schuurmans et al. [1999], Wahlin and Clemmens [2006], Overloop et al. [2005]).

Given the large number of different feedback controllers, the question arises to which feedback controller MPC should be compared. A good choice would be the feedback controller that most closely resembles the current type of control done by the control engineers on the Jiangsu water system. However, this is difficult to assess due to many reasons e.g. interpretation of available information, the language barrier, etc.

It has been suggested to assess the performance of individual PI-controllers and a centralized form of feedback control. The reasoning behind this choice is that the first controller is one of the most simple (and robust) forms of real-time control. The second controller is more advanced controller, and can potentially result in higher performance. When comparing these feedback controllers with the MPC, MPC is the most advanced controller of these three. By comparing MPC with different levels of feedback, the interested parties can select which controller most closely resembles the current form of control and what potentially might be the improvement of one controller over the other.

Clemmens & Schuurmans [2004] state that optimal controllers such as the fully centralized feedback controller have limitations when faced with real-world physical constraints. They give an example of a gate that is already closed, but where the optimal solution is to reduce the flow through the gate. This limitation has become clear when tested on the Jiangsu water transfer system. Therefore a centralized feedback controller turned out not to be able to control the Jiangsu water transfer system (results not shown). The centralized feedback controller calculates the optimal feedback control actions for the whole system. It will try to distribute the available water in such a way over the system that the the sum of the square of all water levels deviations is minimized. This distribution may result in large negative flows in certain parts of the system. Negative flows are not allowed within the scope of this research and therefore the inability of feedback control to handle constraints has to be corrected manual by setting the negative flows to zero. Since all flows are tuned to each other, this results in large water level deviations throughout the whole system, making this controller unsuitable for the Jiangsu water transfer system. Therefore only one controller, a series of local PI-controllers has been tested in this thesis. Note that local PI-controllers have the same inability regarding system constraints, though due to the local character the failure is local. In this thesis the measured water levels are filtered before being used in the calculation. When a filter is added to a PI controller this is also referred to as PIF, where the 'F' is added to indicate that a first order filter is applied on the input of a PI controller (Overloop et al. [2005]).

5.1.1 Tuning

Individual PI-controllers adjust check flows based on only one water level, normally downstream of the check structure. Tight control might result in strong corrective actions; there is a chance of destabilizing the system though. With loose control it might take very long to bring the water levels back to target level. The process of determining the tightness of control is called tuning. The control action is the change in structure setting and is defined as:

$$\Delta Q_{(k)} = K_p \cdot [e_f(k) - e_f(k-1)] + K_i \cdot e_f(k) \tag{11}$$

Where $\Delta Q_{(k)}$ = required flow change through control structure in cubic meters per second; K_p = proportional gain; K_i = integral gain; $e_f(k)$ filtered error at present control time step in meters; $e_f(k-1)$ = filtered error at previous control time step in meters. Tuning of individual PI controllers in a system with multiple pools can be a difficult and time-consuming task for mainly two reasons. First control actions of one structure affect the water level in other pools. Overloop et al. [2005] show a disturbance amplification caused by the hydraulic interaction among the controllers for adjacent pools. Second, the dynamics of open-channel flow are highly non-linear. In order to avoid the tedious task of manually tuning the PI controllers and in order to avoid instability due to interference between controllers, tuning should preferably be done for an entire water system at once by using optimization techniques. Since none of the existing tuning algorithms apply to such complex networks, it has been chosen to divide the system into several single in-line canal reaches and apply central tuning on these canals reaches (this division is shown in figure **??** in Appendix B). The simple PI controllers in these canal reaches are centrally tuned using optimization techniques described by Overloop et al. [2005]. The required inputs for tuning decentralized PI controllers are the storage areas of the pools A_s and the delay times k_d during both high and low flow. For some pumps that are not part of one of the canal reaches, the tuning parameters have been determined with rules of thumb given by Schuurmans [1997]:

$$K_p = \frac{A_s}{(3 \cdot \tau)} \tag{12}$$

$$K_i = \frac{(A_s . T_c)}{(18 \cdot \tau^2)} \tag{13}$$

Table **??** in Appendix B shows all K_p and K_i values for feedback controller used in this thesis.

5.1.2 Time aspects

The MPC uses a time step of of 60 minutes, but a smaller control time step is not possible due to the required computation time. Feedback control does not have this limitation and a high performance is normally achieved with a smaller control time step. In the tests a control time step of 20 minutes was used. This is the minimum time for pump stations to function at a fixed rate (JWS, 2008). It should be noted that this requires two times more structure changes than MPC which (though allowed) might be worse for structures due to wear and tear.

5.2 MPC

In this section the design of the Model Predictive Controller developed for the Jiangsu water transfer system is presented. The design includes extensions that are not covered by existing theory due to the quite extraordinary dimensions of the water system of Jiangsu Province. The main reason for these extensions arise from the presence of extreme large lakes as explained in section 2.4.

In the first section the internal model of the MPC in this thesis is given; the extensions that were necessary for the control of the Jiangsu water transfer system are explained. Subsequently the tuning of the controller is discussed, which turned out to be dominated by the presence of the lakes and the penalties on pumping costs.

5.2.1 Internal Model

The internal model is a set of ordinary linear differential equations describing the state transition of the water system from one time step to the next. Together all the states describe the most important system dynamics for control of a water system.

Due to the dimensions of the Jiangsu water system, the number of states in the internal model is large. The larger the number of states, the longer the calculation time needed. For a 1 hour control time step, the number of states is 86 [the number of states varies with the size of the control time step (see section 3.3.1)].

Table 5 gives an overview of the types of states used in the internal model. Here 5 different types of states can be distinguished. The water level error and virtual states have been discussed in the theory in chapter 3. The states numbered with 2, 3 and 4 are discussed in the next paragraphs.

#	State	Notation	Dimension	Number of states ($\triangle T$=1h)
1	Water level deviation from target level	$e_i(k+1)$	$[m]$	18
2	Current structure setting	$Q_{\mathrm{i}}(k)$	$[m^3/s]$	27
	History structure settings (if $k_{\mathrm{d,i}} \geq 0$)	$Q_{\mathrm{i}}(k-*)$	$[m^3/s]$	15
3	Sum of structure settings for pump stations 3 and 20	$Q_{sum21}(k)$	$[m^3/s]$	1
	Sum of structure settings for pump stations 6 and 21	$Q_{sum22}(k)$	$[m^3/s]$	1
4	Positive water level errors in lakes (if $e_{\mathrm{i}}(k+1) \geq 0$)	$e^*_{\mathrm{i},plus}(k+1)$	$[m]$	3
	Negative water level errors in lakes (if $e_{\mathrm{i}}(k+1) \leq 0$)	$e^*_{\mathrm{i},minus}(k+1)$	$[m]$	3
5	Virtual states	e^*_{i}	$[m]$	18
			Total:	86

Table 5: Overview of the types of states used in the internal model.

Control actions (2) In an early version of the MPC developed in this thesis the control actions $Q_{\mathrm{i}}(k)$ were denoted matrix B_{u}. Tests with this early version of MPC showed bad performance of the controller due to strong oscillations of water levels (results not shown). These oscillations were caused by (too) strong changes in control actions. Flows through structures could rise from 0 m^3/s till capacity flow in just one control step and back to 0 m^3/s in the next step. Overloop et al. [2005] show that the ID model can be a good approximation of the Saint-Venant equations as long as the flow rates and water levels do not change too much (i.e. a few percentages). Thus in order to avoid strong changes in the flow rates, the internal model has been rewritten to a notation that allows penalties on the change of structure settings; this is given in Eq. 14. Enabling penalties on the change in structure settings should prevent instabilities caused by strong fluctuations in control actions.

$$Q_i(k) = Q_i(k-1) + \Delta Q_i(k) \tag{14}$$

State with sum of structures (3) In section 4.1 the function of duplicate stations has been explained and why the sum of two stations should be constraint. This type of state is the sum of two other states: $Q_{sum21}(k)$ is the sum of pump station 3 and 21; $Q_{sum22}(k)$ is the sum of station 6 and 22. Subsequently the capacity of the original station is put as a hard constraint on each state. To the authors knowledge this has not been done before in other applications of Model Predictive Control of water systems and therefore it was not known whether the optimization algorithm would deal with this state correctly. These additional states have been tested and functioned as intended under all flow conditions.

States for linear penalties (4) As shown in section 3.3.3 the objective function for MPC on water systems is preferably set up by using Quadratic Programming, because the square of the states and inputs guarantees a positive penalty always and higher deviations are penalized more than proportional (Overloop [2005]). For the Jiangsu water transfer system the MPC controller has initially been set up with quadratic penalties on all states and inputs. In this set up MPC did not seem to be able to keep water levels in the canals around target level, especially when water level deviations in the lakes are large. A quadratic penalty turned out not to be prudent for all states and inputs, due to the characteristics of this water system i.e. lakes are extremely large compared to canal reaches. The average surface area of the lakes is about 500 times larger than the surface area of a canal pools. As a consequence, the water levels in the lakes have a complete different time response then the canal pools. A canal pool can be lowered one meter in just a few hours, while the same meter in the largest lake (Hongze) might take up to months depending on the conditions. Depending on the time of the year a lake might be at target level or as far as 3.2 meters away from target level. It may not seem appropriate to penalize e.g. a 1 centimeter additional deviation completely different under both circumstances. Due to the quadratic penalty an extra one centimeter deviation around 3.2 meters deviation is penalized $3.2^2/0.01^2 \approx 100,000$ times more than the same extra deviation in case the lake is at target level. In order to reduce this undesirable effect, a linear penalty is introduced. A linear penalty on the water level deviation in lakes would be more appropriate, because large errors in lakes will not be penalized extremely heavy. With the introduction of linear penalties an important advantage of quadratic penalizing is lost, namely that the penalties are always positive. A negative deviation from target level still needs to be penalized positive. The solution found here, is to introduce two extra states per lake which are defined as following in state-space notation.

$$e^*_{i,plus}(k+1) = e_{i,plus}(k+1) - u^*_{i,plus}(k) \tag{15}$$

$$e^*_{i,minus}(k+1) = -e_{i,minus}(k+1) - u^*_{i,minus}(k) \tag{16}$$

Subject to:

$$e^*_{i,plus}(k+1) \geq 0 \tag{17}$$

$$e^*_{i,minus}(k+1) \geq 0 \tag{18}$$

$$u^*_{i,plus}(k) \leq 0 \tag{19}$$

$$u_{i,minus}^{*}(k) \leq 0 \tag{20}$$

Where $e_{i,plus}^{*}$= positive water level deviation from target level in lake i; $e_{i,minus}^{*}$= negative water level deviation from target level in lake i;u_{i}^{*} = virtual control action.

The first state $e_{i,plus}^{*}$is always equal to the deviation from target level $e_i\,(k+1)$ as long as the deviation is above target level; else this state is zero. The second state $e_{i,minus}^{*}$ is the inverse of the deviation from target level $e_i\,(k+1)$ as long as the deviation is below target level; else this state is zero. This notation allows for a linear penalty on the lakes. The virtual control action is necessary to force the water level back to target level. Now, due to the quadratic penalty on water level deviations in the canal pools and a linear penalty on the deviation in the lakes, the water levels in the canal pools have a larger priority than the levels in the lakes. This is in line with the response time of lakes and canal pools. It may take a few hours to get a large water level deviation in a canal pool back to target level, where else bringing a lake back to target level might take a time span in order of weeks/months. As long as the water levels in the canal pools are around target level, the MPC will try to force back the lakes to target level.

Linear penalties are also preferred on the pumping efforts. The penalty increase on a pump increase from 0 to 1 m^3/s should be the same as for a pump increase from 300 to 301 m^3/s, because every cubic meter of water that is pumped will cost the same amount of money. For illustration: if pumping 1 cubic meter costs 1 Euro, pumping 300 cubic meter costs 300 Euro and not 300^2= 90,000 Euro. Thus also on the pumping efforts a linear penalty is preferred over a quadratic penalty. An advantage of the pumping efforts is that these are always positive and thus a linear penalty can be applied to this state directly without having to define new states such as for the linear penalties on the lakes. When the linear penalties are added to the objective function J as presented in Eq. 9 the objective function now becomes:

$$J = X^T \cdot Q \cdot X + U^T \cdot R \cdot U + X \cdot Q_{lin} \tag{21}$$

Where Q_{lin} is a 1-by-na matrix, with na is the number of states. All linear penalties are denoted in matrix Q_{lin} and the corresponding entries in matrix Q are left zero, so that the corresponding quadratic penalties are removed.

All these states together form the internal model that MPC uses to compute the behavior of the water system into the future. The internal model of the Jiangsu water system is given below in Eq. (22):

$$
\overbrace{\left[\begin{array}{c}
e_1(k+1)\\ \vdots \\ e_{18}(k+1)\\ \hline
Q_1(k)\\ Q_1(k-1)\\ Q_1(k-2)\\ Q_2(k)\\ Q_3(k)\\ \vdots \\ Q_{27}(k-1)\\ \hline
Q_{sum21}(k)\\ Q_{sum22}(k)\\ \hline
e_{9,plus}(k)\\ \vdots \\ e_{13,minus}(k)\\ \hline
e_1^*\\ \vdots \\ e_{18}^*
\end{array}\right]}^{x(k+1)}
=
\overbrace{\left[\begin{array}{ccc|cccccccc|ccc}
1 & & & & & +\frac{\triangle T}{A_s} & -\frac{\triangle T}{A_s} & & & \cdots & & 0 & \cdots & 0\\
 & \ddots & & & & & & & & \vdots & & \vdots & & \vdots\\
 & & 1 & & & & & & & \cdots & & 0 & \cdots & 0\\ \hline
0 & \cdots & 0 & 1 & 0 & \cdots & & & & & 0 & 0 & \cdots & 0\\
\vdots & & \vdots & 1 & 0 & \cdots & & & & & 0 & \vdots & & \vdots\\
 & & & 0 & 1 & & & & & & \vdots & & & \\
 & & & \vdots & 0 & & 1 & & & & & & & \\
 & & & & \vdots & & & 1 & & & & & & \\
 & & & & & & & & & \ddots & & & & \\
0 & \cdots & 0 & 0 & 0 & \cdots & & & & & 1 & 0 & \cdots & 0\\ \hline
0 & \cdots & 0 & & & & & & & \cdots & & 0 & \cdots & 0\\
0 & \cdots & 0 & & & & & & & \cdots & & 0 & \cdots & 0\\ \hline
 & \cdots & & & & \cdots & & & & & & 0 & \cdots & 0\\
 & \vdots & & & & \vdots & & & & & & \vdots & & \vdots\\
 & \cdots & & & & \cdots & & & & & & 0 & \cdots & 0\\ \hline
1 & & & & & +\frac{\triangle T}{A_s} & -\frac{\triangle T}{A_s} & & & & & 0 & \cdots & 0\\
 & \ddots & & & & & & & & & & \vdots & & \vdots\\
 & & 1 & & & & & & & & & 0 & \cdots & 0
\end{array}\right]}^{A(k)}
\cdot
\overbrace{\left[\begin{array}{c}
e_1(k)\\ \vdots \\ e_3(k)\\ \hline
Q_1(k-1)\\ Q_1(k-2)\\ Q_1(k-3)\\ Q_2(k-1)\\ Q_3(k-1)\\ \vdots \\ Q_{27}(k-(k_d-1))\\ \hline
0\\ 0\\ \hline
e_{9plus}(k+1)\\ \vdots \\ e_{13minus}(k+1)\\ \hline
0\\ 0\\ 0
\end{array}\right]}^{x(k)}
$$

$$
+\overbrace{\left[\begin{array}{ccccc|ccc|ccc}
 & -\frac{\triangle T}{A_s} & & \cdots & & 0 & \cdots & 0 & 0 & \cdots & 0 \\
 & & & \cdots & & \vdots & & \vdots & \vdots & & \vdots \\
 & & & \cdots & & 0 & \cdots & 0 & 0 & \cdots & 0 \\
\hline
1 & 0 & 0 & \cdots & 0 & 0 & \cdots & 0 & 0 & \cdots & 0 \\
0 & 0 & \vdots & & \vdots & \vdots & & \vdots & \vdots & & \vdots \\
\vdots & 0 & & & & & & & & & \\
 & 1 & & & & & & & & & \\
 & & 1 & & & & & & & & \\
 & & & \ddots & & & & & & & \\
0 & 0 & 0 & \cdots & 1 & 0 & \cdots & 0 & 0 & \cdots & 0 \\
\hline
 & & & \cdots & & 0 & \cdots & 0 & 0 & \cdots & 0 \\
 & & & \cdots & & 0 & \cdots & 0 & 0 & \cdots & 0 \\
\hline
 & & & \cdots & & -1 & & & 0 & \cdots & 0 \\
 & & & \vdots & & & \ddots & & \vdots & & \vdots \\
 & & & \cdots & & & & -1 & 0 & \cdots & 0 \\
\hline
 & -\frac{\triangle T}{A_s} & & \cdots & & 0 & \cdots & 0 & -1 & & \\
 & & & \cdots & & \vdots & & \vdots & & \ddots & \\
 & & & \cdots & & 0 & \cdots & 0 & & & -1
\end{array}\right]}^{B_u(k)}
\cdot
\overbrace{\left[\begin{array}{c}
\triangle Q_1(k) \\
\triangle Q_2(k) \\
\triangle Q_3(k) \\
\vdots \\
\triangle Q_{27}(k) \\
\hline
u^*_{9,plus} \\
\vdots \\
u^*_{13,minus} \\
\hline
u^*_1 \\
\vdots \\
u^*_{18}
\end{array}\right]}^{u(k)}
$$

$$
+\overbrace{\left[\begin{array}{ccc} +\frac{\triangle T}{A_s} & & \\ & \ddots & \\ & & +\frac{\triangle T}{A_s} \\ \hline 0 & \cdots & 0 \\ \vdots & & \vdots \\ & & \\ 0 & \cdots & 0 \end{array}\right]}^{B_d(k)} \cdot \overbrace{\left[\begin{array}{c} Q_{d,1}(k) \\ \vdots \\ Q_{d,18}(k) \end{array}\right]}^{d(x)} \tag{22}
$$

5.2.2 Tuning

In this thesis the weight matrices Q, R and Q_{lin} are used to give relative penalties to states and control actions described in the internal model. These variables include water level deviations, pump efforts, change in structure settings, virtual states and virtual inputs (see section 3.3.1 for details). By tuning these values, the behavior of the controlled water system is shaped.

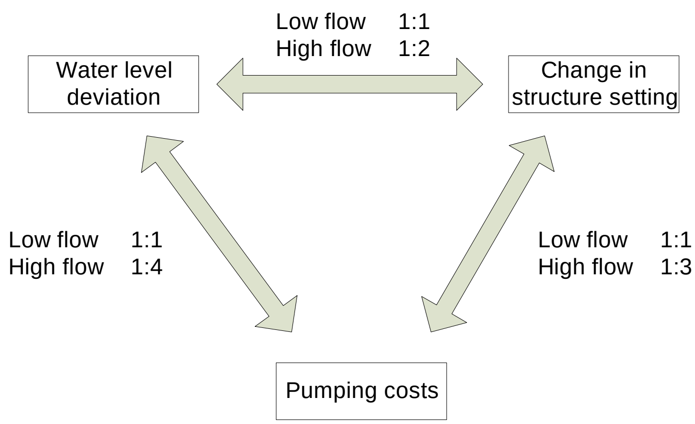

Figure 22: Example of changing trade-off relations under low flow and high flow conditions.

In many controllers that minimize an objective function to find the optimal control actions, the penalties on water level errors provide a trade-off with check flow changes, respectively in matrices Q and R. In this thesis the penalties within matrices Q, R and Q_{lin} not only provide a trade-off between water-level errors and check flow changes, but also a second trade-off between pumping costs and water level errors and a third trade-off between pumping costs and check flow changes. This triangle relation is visualized in figure 22 (numbers are fictive). Relative high penalties on water level deviations results in tight control. Too tight control might destabilize the actual controlled system due to un-modeled dynamics of the actual water system or model mismatches (Overloop [2005]). Relative high penalties on costs of pumping, will result in lower operation costs, but might lead to larger water level deviations and/or fluctuations. And finally, relative high penalties on check flow changes results in a more static system, less capable in handling large disturbances changes.

There do not exist basic tuning rules for determining the height of penalties. Many times, tuning is done through trial-and-error techniques. In several papers (e.g. Clemmens & Schuurmans [2004], Wahlin [2004], Wahlin & Clemmens [2006]) tuning is done by setting matrix Q to unity (I), which implies that the penalty on water level deviations is the same for every canal pool. Subsequently the first value of matrix R is chosen related to the scale of the problem (i.e. capacity of the canal) relative to the degree of water-level control. It also has to do with the time step of the control actions relative to the delay times in the canal. All other values of matrix R are scaled according to the relative capacity of each structure.

Information for the tuning should be derived from the control objectives and their relative importance (described in section 2.4), but these control objectives lack a certain level of detail. To maintain a certain water level seems to be straightforward, but what is the optimal level and how to interpret dynamic variations of the actual levels? Another difficulty is how to deal with conflicting objectives. Against which price may water levels deviate from target level and which dynamics are allowed against which price? How are water level deviations in lakes weighted against water level deviations in canal pools? A third difficulty is that the importance of the objectives might change through time (Brouwer [2008]). Finally the relative weighting of the penalties vary with the flow conditions(!). This has been illustrated in figure 22. If a controller has been tuned under low flow conditions and one describes all relative trade-offs as 1:1, the relative trade-off during high flow can be very different. The MPC has been tuned such that the desired system behavior is effectuated under high flow conditions. This resulted also in a satisfactory performance under flow conditions.

In section 3.3.3 it has been explained that using MAVE (Maximum allowed value estimate) is a sensible approach for estimating the height of the values in the penalty matrices. Here MAVE is used to estimate the order of size of the penalties, not the exact penalties, which may be time- and structure dependent. In table 6 an overview is given of all states and inputs that are penalized. The table shows the matrix in which the penalty is denoted, the MAVE and subsequently the penalty or the formula for determining the penalty (in case a penalty is time- or structure dependent). Where in this table $p(k)$ is the relative price of energy (day tariff = 1). Below the determination of the penalties (tuning) is elucidated per state.

#	State / input	Matrix	Extreme value	MAVE	Penalty [-]
1	Pump efforts	Q_{lin}	500 m^3/s	500	$h_{\text{i}}/2500 \cdot p(k)$
2	Water level deviation in lake (use water)	Q_{lin}	3 m	3	$1/3^2$
	Water level deviation in lake (save water)	Q_{lin}	0.01 m	0.01	$1/0.01^2$
3	Water level deviation in canal	Q	0.05 m	0.05	$1/0.05^2$
4	Check flow change	R	5%	$\frac{Q_{\text{i,max}}}{20}$	$1/\left(\frac{Q_{\text{i,max}}}{20}\right)^2$
5	Virtual input	R			$1 \cdot 10^{-6}$
6	Virtual state	Q			$1 \cdot 10^{6}$

Table 6: Overview of penalties used in weight matrices Q, R and Q_{lin}.

Pump efforts (1) In the internal model the flows through the check structures are being penalized. However, what actually needs to be penalized/minimized is the cost of pumping in monetary units. Therefore the height of the penalties on the pumping efforts in matrix Q_{lin} should vary per structure as well as in time. The values of Q_{lin} vary in time, due to day-night variation in energy prices. During hours with night tariff, all penalties on pump efforts are lowered with a factor linear proportional to the energy price (note that in the results there is an MPC variant aimed at cost reduction in which the day penalty is multiplied by a factor 100) . Furthermore the values of Q_{lin} vary per structure because every structure has a different head and characteristics. The energy consumption is assumed to be proportional to the head of a pump station. The exact energy consumption depends on the characteristics of pumps, which have been neglected here. A difficulty with penalizing costs is that a $MAVE$ cannot be determined. That is because it is not possible to define a maximum cost for pumping efforts; the costs should only be minimized as much as possible. Though, to find a order of magnitude for the penalties on pumping costs, the $MAVE$ that would have been used for penalizing the check structure flow is used. The largest pump station has a capacity of 500 m^3/s, resulting in a $MAVE$ of 1/500 (linear penalty). The average head h of all the pump stations is 5 meter. For the penalties to be in order of size 1/500, the height of the penalties is defined as $h_i/500 \cdot 5 = h_i/2500$.

Lakes (2) A major issue here is how to deal with penalties on the lakes. Depending on the actual situation the controller should deal different with the lakes (e.g. fill or use water of the lakes? how much? etc.). In section 2.4 it has been explained that these long-term decisions should be taken by the responsible authorities/water managers. The decision on each lake determines the penalty on the water level error in that lake. If it is decided that water may unlimited be abstracted from the lake (e.g., because water is abundant at that moment), the penalty on the lake will have the lowest value. The MAVE in this case is about 3 meter, the order of size of the maximum water level deviation in the lakes. This results in a penalty of $1/3^2$.

If the long-term control objective states that water should be saved as much as possible (e.g. because it is expected that it will be very dry and water shortages are expected to be high), the penalty on the lake will have to be the largest value. What is the largest value is hard to determine with MAVE, because what is the MAVE in that case (1mm, 1cm, 10cm?). Tests with different penalties (results not shown) revealed that the MAVE should be in the order of size $1 \cdot 10^4$ which suggest a maximum deviation of 1 cm ($1/0.01^2 = 1 \cdot 10^4$).

Canals (3) Canals are kept well around target level as long as penalties on the lakes are small. However, when penalties on the lakes are increased, the deviations in the canals increase also, which is very unpleasant side-effect of the penalties on the lakes. This can be explained by the higher volumes being pumped through the system that are needed to maintain the water levels in the lakes. These higher volumes will result in higher pump efforts and thus the trade-off between pumping effort and water level deviation changes when changing from low flow to high flow (see example in figure 22). However, this trade-off should not change, because larger water level deviations in the canals are not desirable. The solution found here is to use the soft constraints. The system constraints range from 0.4 m till 2.4 m from target level (see Appendix A, table **??**). Though these large margins give a lot of freedom to the controller, it is not desirable to actually deviate such far from target level. Therefore the minimum and maximum water levels are all set to till 0.1 meter. As a result the controller may fluctuate within this bandwidth, but will not go far above or below this bandwidth due to the extreme high penalty on the virtual states.

Check flow change (4) Section 5.2.1 explains why the internal model is set-up in such a way that it allows for penalties on the change of structure settings. Overloop et al. [2005] show that the ID model can be used as long as the flow rates and water levels do not change too much (i.e. a few percentages). Therefore it is assumed that the maximum flow change is 5% of the structure capacity. This results in a structure dependent MAVE: $\frac{Q_{\mathrm{i,max}}}{20}$.

Virtual state and input (5 and 6) As explained in section 3.3.2, virtual states are used to implement system constraints as soft constraints. Using virtual states instead of hard constraints prevents the solution to become infeasible. Through JWS the minimum and maximum water levels have been collected, which show a large variation from pool to pool (see Appendix A) and thus a large variation in the allowed bandwidth around target level. The introduction of penalties on pumping costs in this thesis, made it necessary to use virtual states for another goal then system constraints. Tuning of the Model Predictive Controller turned out to be a complex trade-off between water level deviation, change in structure setting and costs of pumping. Finding a satisfying trade-off for one flow condition results in unsatisfying results in for other flow conditions. By reducing the bandwidth around target water level to a low and fixed value for all canals (0.2 meters), the controller will find solutions within this bandwidth, irrespectively the relative size of the trade-off. The condition here is that the penalties on the virtual states are significant higher then all other penalties.

5.2.3 Time aspects

The Model Predictive controller is an optimal controller which means the solution should be found by means of optimization. The optimization is only run once every control time step. Due to the size of the Jiangsu water transfer system, strong computation power is necessary to solve the optimization problem within the control time step. Computation times on a personal computer with 2Ghz processor turned out to be insufficient for real-time implementation of MPC, because control actions need to be available before the next control time step. Using a 1 hour time step and a prediction horizon of 24 hours, the computational time of one optimization on a personal computer is in the order of days. The solution found here is the use of a commercial solver (TOMLAB) on a 64-bit computer. With the commercial solver the total time (building up matrices and solver time) is reduced to less then 10 seconds (see Appendix A, table **??** for time statistics of calculation and simulation).

5.2.4 Issues related to the ID model

A big advantage of the ID model is that it is compact and therefore very fast. Though due to the compactness, the ID model has its limitations. The Jiangsu water transfer system is a large, complex and and extraordinary water system whereby some implications arise when using the simple ID model. This section explains how is dealt with some of these limitations.

Existing literature about controlling canal reaches using the ID model to describe the dynamic behavior of canal, deal with irrigation or drainage canals with down sloping, relatively short canal reaches (Malaterre et al. [1998], Clemmens & Schuurmans [2004], Montazar et al. [2004], Overloop [2005], Wahlin & Clemmens [2006]). All canal pools of the Jiangsu water transfer system are long and have a negative slope (see figures 16 and 17), which is quite extraordinary. To the authors knowledge, the ID model has not been used before to describe the basic dynamics of a very long canal (>100km) pool with a negative slope. It is therefore not known from literature how well the ID model is able to capture the basic dynamics of such canal pools. The results in chapter 6however show that the ID model is able to capture the basic dynamics of such canals pools sufficiently.

As explained in chapter 3, the ID model captures two (most important) hydraulic parameters of a canal pool for canal control, namely the delay time k_{d} and surface area A_{s}. One limitation of using this model is that it is not possible to model canal reaches that split or structures that can discharge into different pools. However, within the Jiangsu water transfer system these characteristics are present. If these characteristics are not modeled in the internal model, the internal model does not capture the basic dynamics of the real system. Canal pool e2 is an exceptional canal, because it splits right after pump station 2 (Huai an) into two branches. Both branches have a different end point and pump station, however, within the ID model, only 1 delay time can be defined for per canal pool. The ID model does not allow branches within one canal pool. This implication has been overcome by assuming the surface area A_s of this canal pool is the sum of both branches and the delay time k_d is the longest delay time of the two branches.

For structures that can discharge into two different pools, a duplicate pump is created, which is a copy of the existing structure and has the same characteristics as the original station, but does discharge into a different pool (see section 4.1 and Annex A for details).

6 Control Tests

The hydrodynamic model of the Jiangsu water transfer system is presented in chapter 4. In order to assess the performance of the controllers they are tested on the hydrodynamic model under different scenarios. In this chapter presents the control test, results and analysis. As explained in section 2.4 realistic assumptions have been made regarding the control objectives for every simulation. The largest impact will be the assumptions made regarding the lakes and depending on the goals of the lakes, a controller should be tuned different. In this thesis the choice has been made to use the same Model Predictive Controller and the same feedback controller for all simulations and to tune the controllers differently per (sub)scenario by changing the height of the penalties only (thus no changes are made to the controller design).

This chapter first describes the performance indicators that are used to judge the performance of the controllers where possible. Subsequently the data series that have been provided by JWS are given with an explanation on how these are converted to appropriate input for the control tests. A description of the initial conditions and how these are determined is given in section 6.3. Section 6.4 presents the scenarios, the results and analysis.

6.1 Performance Indicators

Performance indicators can be used to judge the performance of controllers. A performance indicator is an output variable or an equation of output variables that needs to be controlled according to a predefined target level. Standard performance indicators have been presented by Clemmens et al. [1998] for the ASCE canal on which canal controllers should be tested before publishing. Because these performance indicators are specially developed for the ASCE canal and because the goals of the controllers in this thesis are partially different from controllers on irrigation canals, it does not seem reasonable to use these performance indicators for other water systems.

Performance of irrigation systems can also be expressed in the portion of the water demand that is actually delivered on the right time (Wagemaker [2005]). Also this is not a valid option for the Jiangsu water system, because the water to be delivered to the next province is discharged and stored in Weishan Lake (660 km^2). The buffer of this lake is such large that water delivery failures to Shandong will only occur whenever the lake has reached its dead level. As this concerns the long-term decisions made by the water managers, it will not provide any information of the performance of a controller. Therefore the following performance indicators have been chosen for for judging the performance of the controllers in this thesis: maximum absolute error (MAE), energy consumption (E) and operational costs (c). A calculation module is designed in MATLAB to calculate the values of all performance indicators for the different controllers for all simulations.

The maximum absolute error (MAE) is a measure of the maximum deviation in water level from target level and defined as following:

$$MAE = max\left(\mid e_i(k) \mid \right) \tag{23}$$

The first 24 hours of all simulations are not accounted for in order to avoid that the initial conditions affect this performance indicator.

The energy consumption of a structure is defined as the sum of the structure flows over the simulation period n multiplied by the average head of that structure. The sum of these values over all pump stations (no weirs!) is the total energy consumption:

$$E = \sum_{k=1}^{m} \sum_{i=1}^{22} Q_i(k) \cdot 9.81 \cdot \triangle T \cdot h_i / 3600 \tag{24}$$

Where E = the total energy consumption of the pumping efforts of all pump stations over the simulation horizon m; $Q_{\text{i}}(k)$ = the check flow through pump station i; h_{i}= the head of pump station i. The calculation of costs is defined as the energy consumption multiplied by the time-variant price of energy:

$$c = \sum_{k=1}^{m} \sum_{i=1}^{22} Q_i(k) \cdot 9.81 \cdot \triangle T \cdot h_i \cdot P(k) / 3600 \tag{25}$$

Where c = the total cost of the pumping efforts of all pump stations over the control horizon m; $P(k)$ = the price of 1 kWh electricity on time step k. The operational cost c is expressed in the same monetary unit as $P(k)$.

6.2 Data Series

Data series have been provided by JWS. Detailed data series for the complete water system are not available within this organization, neither within other organizations, though aggregated data series with a time step of 10 days and a space step of around 100 km are available.

Inflow and outflow data have been provided separately by JWS. The outflow has been given for a wet, average, dry and extreme dry year. The inflows are given for a wet, average and dry year. Since wet years are outside the scope of this thesis and of an extreme dry year inflows are not available, the data series that can be used in this thesis are a average year and a dry year, which are shortly discussed below.

Average year (1969-1970) Normally, the highest water demands occur in the period June-August. In this period temperatures can reach up to 40 °C, evaporation is extremely large, the agricultural demands are high due flowering season of the most important agricultural crops (e.g. rice) and rainfall/river inflow is normally limited. For scenario 1 ('base case') data series have been used of the period 1969-1970. This is defined as a 'average' year in Chinese documents which implies that the chance that a typical year is dryer then this year is 50%. The sum of inflows and outflows in 1969-1970 is shown in figure 23.

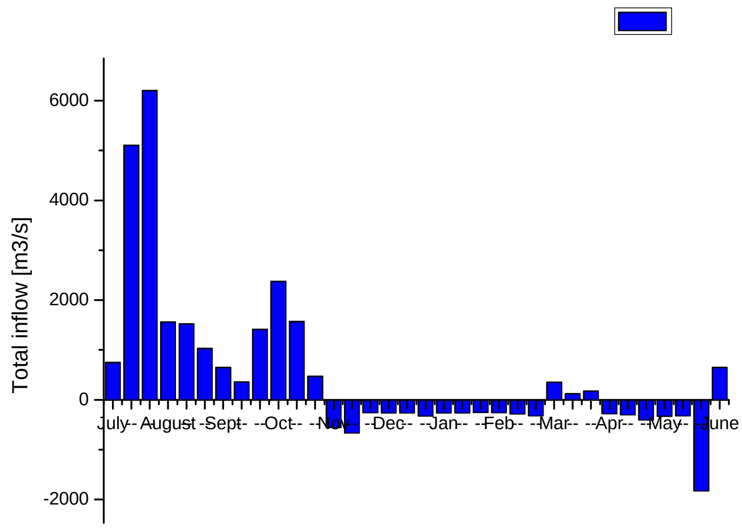

Figure 23: Average flow into the Jiangsu water system in 1969-1970 (50% dry year).

Dry year (1980-1981) The year 1981-1982 has been described as a 'dry' year, which implies that the chance a certain year is dryer than this year is 25%. The sum of inflows and outflows in 1969-1970 is shown in figure 24.

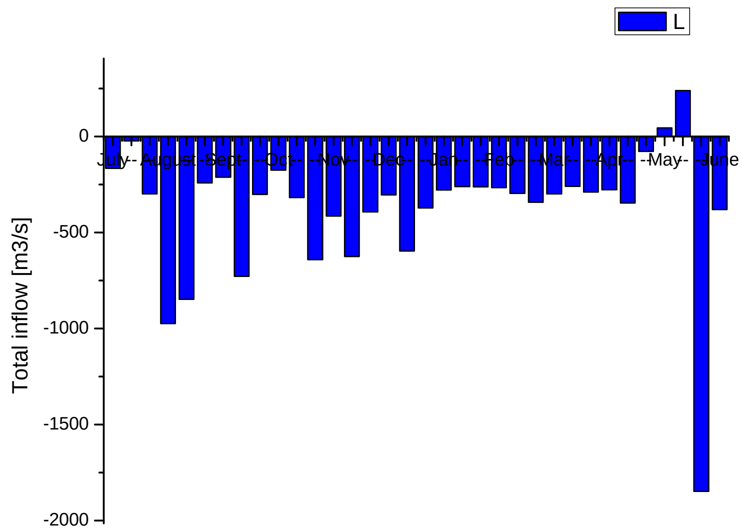

Figure 24: Average flow into the Jiangsu water system in 1981-1982 (75% dry year).

The data series are aggregated series with a time step of about 10 days (3 data points per month) and in space the data series are divided per section (see figure 5). These aggregated series give a good impression of the magnitude of system disturbances throughout the year, though disturbances that are constant over a period of 10 days are not suitable for simulating real time situations, because in real time a system is constantly subject to changes. A static system might occur during a 10 day period. In order to prevent this, the data series have been subjected to interpolation. The interpolation technique that has been used is linear interpolation. The general equation for linear interpolation on the interval (x0, x1) is given by:

$$y = y_0 + (x - x_0)(y_1 - y_0)/(x_1 - x_0) \tag{26}$$

Setting Δx equal to the size of the time step of the controller results in new data series with a time interval equal to the size of the time step. A graph showing a 6-day example of these interpolated data series is shown in figure 28. Since the data series are given for the lakes and the trajectories in-between the lakes, it is not known what the data series per canal pool are. However, MPC requires data series per canal pool and in order to acquire data series per canal pool the data has been divided over the pools, proportional to their length. Within SOBEK these disturbances have been implemented as lateral disturbance, because this is more realistic then a single discharge point. The lateral disturbance in SOBEK is defined as:

$$q_i(k) = \frac{Q_i(k)}{L_{section}} \tag{27}$$

Where q_i is the lateral discharge in pool i; Q_i the total disturbance within section; $L_{section}$ the total length of the section. The disturbance d (see Eq. 3) used as input for the MPC is given by the following equation.

$$d(k) = \frac{q_i(k) \cdot L_i}{L_{section}} \tag{28}$$

WhereL_i the length of canal pool i.

Accuracy of predictions used by the internal model For the calculation of the lateral discharge (see Eq. 27) rounded values for the length of the canal pools L_i are used, which thus slightly differ from the exact canal pool length in SOBEK (0 till 2%). No efforts have been made to determine the exact lengths in SOBEK, because this would imply striving to 100% exact prediction of disturbances which would not make any sense. It is though important to remark that almost exact (98-100%) predictions have been used by the MPC. Under real world circumstances the accuracy of predictions would be lower definitely.

6.3 Initial Conditions

Initial conditions (hydraulic model) The initial conditions of the hydrodynamic model are generated by simulating a short period before the actual scenario so that the flows and structure settings are in the order of size typical for that scenario. It is made sure that the water levels in the canals are close to target level. By doing this, the initial conditions have the lowest impact on the control tests. The water level in the lakes can be assumed any value, since it is unknown what has happened to the system before the start of the simulation. The only demand is that the initial values are realistic. For practical reasons the initial values in the lakes are always around or a few decimeters below target level. Since the initial conditions differ per scenario, the values of the initial conditions are given individually for each scenario and elucidated where necessary.

Initial structure settings (controllers) All controllers require the previous structure settings to calculate the control actions, since the new structure setting is a function of the current structure setting and, depending on the controller, also previous control actions (e.g. MPC). The initial structure settings are read from SOBEK before the first simulation step. The previous structure settings cannot be provided by SOBEK. Since a more or less steady state is used for generating the initial conditions of the hydrodynamic model, it is assumed that previous structure settings are equal to the current structure settings.

6.4 Results & Analysis

All simulations are done under circumstances of water water shortage at the beginning or during the dry season. This implies that under all simulations water will be transported uphill only. Control objectives that require reverse flow through certain parts of the system might be realistic during certain circumstances e.g. at the end of the dry season where still large volumes of water are available within the lakes. However, these circumstances are outside the scope of this research.

The control tests comprise 5 different scenarios, some of them with sub-scenarios. Every section contains a scenario and has been divided into three parts: (a) the first part contains a description of the scenario, the data series used, the assumptions regarding control objectives and other relevant information. b) in the second part the results of the simulations are shown in graphs and tables; the results display the water level deviations through time and the corresponding control actions. Shown are the water levels in all pools and the structure flows of all structures together c) the third part contains an analysis of the results.

For every scenario the results of three runs are shown: 1) control by a feedback controller 2) control by MPC with normal day-night variation and 3) control by a MPC tuned for cost reduction (day-night penalty exaggerated by a factor 100). The second MPC is added after the first MPC turned out not to be able to significantly reduce operational costs. The second MPC with 100 times exaggerated day-night variation is a rather extreme end of cost reduction and has been chosen to show the boundaries of possible cost reduction.

For all simulations a control time step of 20 minutes was used for the feedback controller and a control time step of 60 minutes for the MPC. The prediction horizon of the MPC is 24 hours. This is sufficient to anticipate on disturbances and day-night variation, because measures on disturbances or day-night variation can be taken less then 24 hours before the disturbance or energy tariff change actually occurs. Anticipating control actions do not have to be taken more then 24 hours in advance, because the capacity of the hydraulic structures largely exceeds the height of possible disturbances (because the structures are build for large volumes of water transport and can easily handle the relative small local disturbances, even if these are very large for local circumstances). In other words, the structure are over dimensioned with respect to local supply and demand. A longer prediction horizon could be used to stop pumping long before a heavy shower actually occurs, but in section 2.4 it has been explained that these decisions will be made on a tactical level and not by the controller.

In the control tests SOBEK (WL/Delft Hydraulics 2000) and MATLAB (The MathWorks) have an explicit coupling every control time step. This explicit coupling works with a limited number of MATLAB-versions and under operating system Windows XP only. Therefore all controllers have been programmed in MATLAB R2007a. The coupling occurs every control time step and thus varies with the implemented controller (20 min for the feedback controller and 60 min for the MPC, see chapter 5).

6.4.1 Scenario 1: base case

Scenario Details For this scenario the period from the 7th till of the 13th May 1970 has been chosen. The average total water usage within the water system in this period is around 320 m^3/s, which is about 2/3 of the system capacity. The lakes are assumed to be more or less filled (-0.05, -0.26 and -0.22 m are the initial values in SOBEK). This is a realistic assumption, since it is still the beginning of the dry season and sufficient inflow has been measured earlier in the year (see figure 23). With sufficient stored volumes of water in the lakes, it is assumed that the water managers have decided that the water stored in the lakes may be used unlimited. Thus the water levels in the lakes do not have to be brought towards target level. Therefore the penalties on all lakes have been set to the lowest value. This implies that the controllers will try to maintain the water levels in the canals only and that to that goal water may freely be taken from the lakes. Table 7 gives an overview of this scenario.

Simulation Characteristic	Value/date	Information
Data series	1969-1970	Average year (50%)
Start of simulation	07-05-1970	
End of simulation	13-05-1970	
Average net system outflow	320 m^3/s	
Initial water level deviation Hongze Lake	-0.05 m	Control objective: use water
Initial water level deviation Luoma Lake	-0.26 m	Control objective: use water
Initial water level deviation Weishan Lake	-0.22 m	Control objective: use water
Initial water level deviation in canals	$<$0.05 m	

Table 7: Summary of Scenario 1.

Results Below the results of scenario 1 are shown.

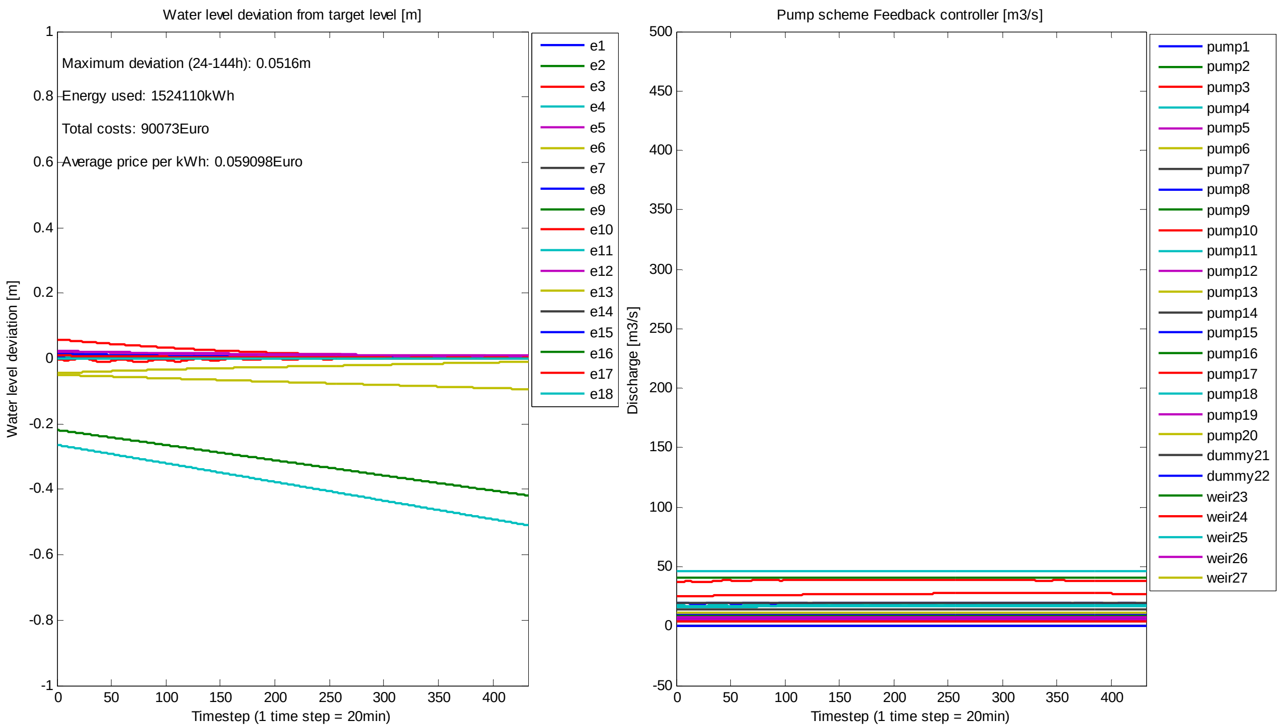

Figure 25: Scenario 1 - feedback control.

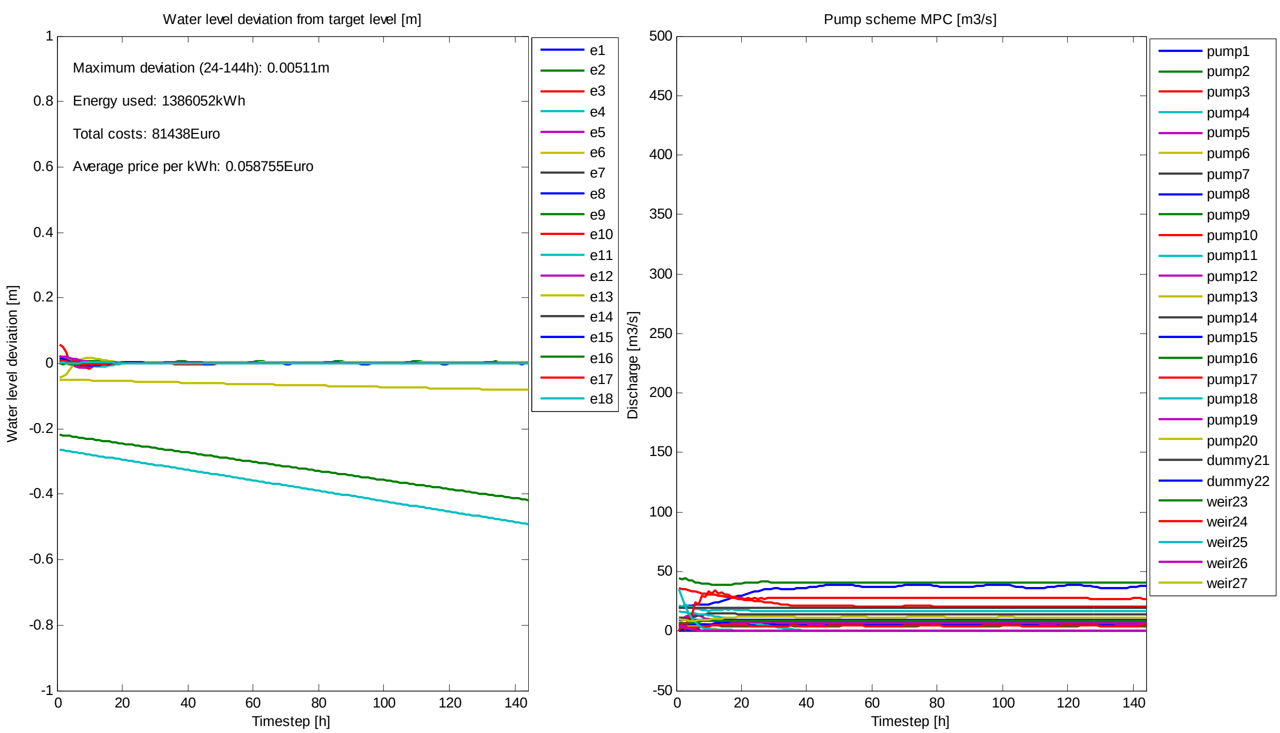

Figure 26: Scenario 1 - MPC.

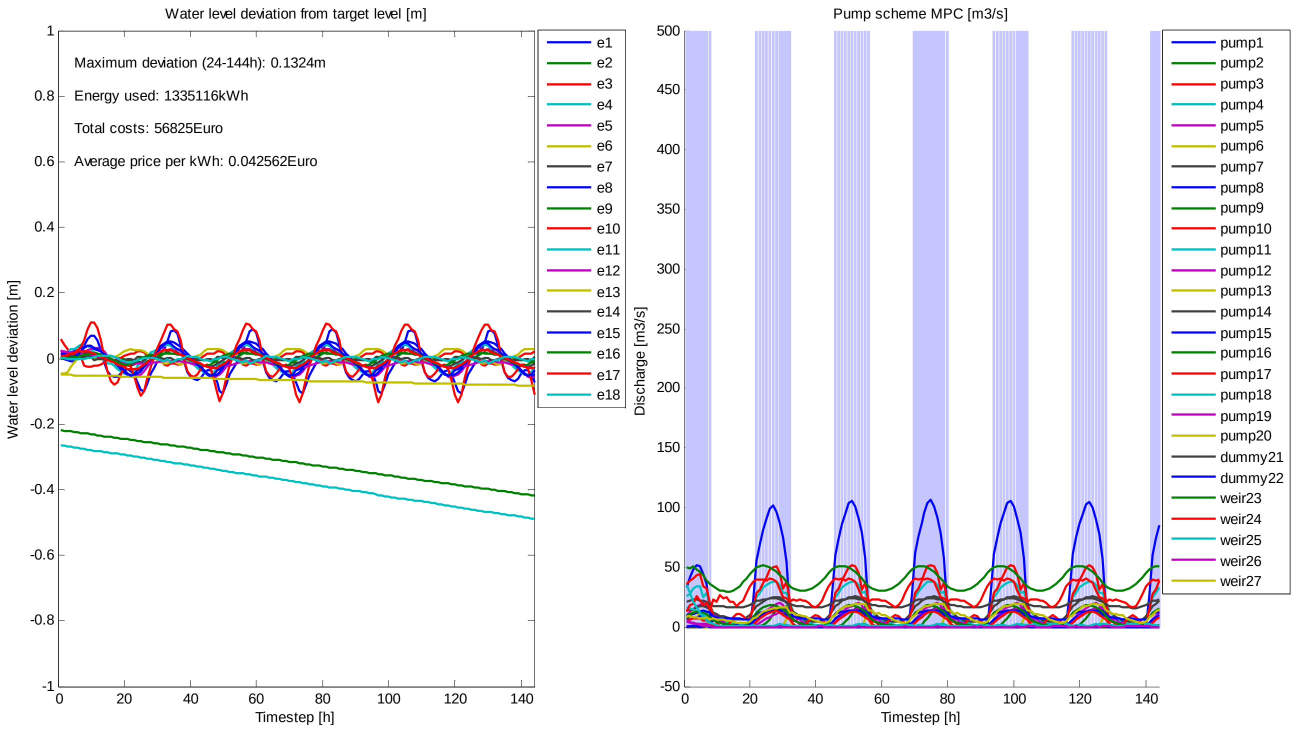

Figure 27: Scenario 1 - MPC cost reduction.

	MAE [m] (24-144h)	E [GWh]	c [10^3€]	€ per kWh	Percentage cost reduction based on average price per kWh (feedback = 0)	Estimated daily costs (based on 0.25 GWh/day) [10^3€]
Feedback controller	0.05	1.52	90	0.0591	0	15
MPC	0.01	1.38	81	0.0587	-1%	15
MPC cost reduction	0.13	1.34	57	0.0426	-28%	11

Table 8: Results Scenario 1.

Analysis & Discussion Under these relatively wet circumstances with limited water demands and no need to save water, the whole system is under low flow conditions; the flows through the structures system range from 0 till 70 m^3/s. The water levels are kept around target level by both controllers. The maximum water level deviation (MAE) by the local PI controller is 0.05 meters, where the MAE by the Model Predictive Controller is 0.01 meters. A significant difference can be observed in the rate that the controllers correct water level deviations from target level. The small water level deviations in the initial conditions, are corrected within a matter of 2 hours by the MPC, while the feedback controller requires significant more time to achieve the same correction. The control of the feedback controller can be described as 'loose' control. This can be explained by the fact that tuning has been done as described in Overloop et al [2005] which takes into account a lot of factors that may generate oscillations (see section 5.1.1), such as interactions between neighboring pools and significant delay times. This might have resulted in a controller that does not show any oscillation, but thereto is rather 'loose' and thus requires significant time to correct water level errors. Another factor can be that the water level error is small ($<$0.05m) as well as the difference in water level error between the current and previous error, resulting in a 'loose' control action (see Eq. 11). It is clear that, though both controllers effectuate the desired system behavior under these circumstances, the MPC scores better than feedback control on all performance indicators.

Figure 27 shows the results of the MPC that is tuned for cost reduction. The blue background indicates the period of night tariff. The control actions of the 'MPC cost redcution' show a sinusoidal pattern in the most canal pools with a return period of 24 hours. The controller reduces the pump efforts during the day tariff and increases the effort during the night tariff in order to reduce operational costs. With this shift towards costs saving, the MAE rises to 0.13 meters, while considerable cost reduction is accomplished. Operational costs have been reduced by 28% based on day-night variation.

Note that the water levels in the three lakes are gradually dropping; the MPC takes as much water as necessary out of the lakes, because this is cheaper then pumping the water all the way from the Yangtze River.

6.4.2 Scenario 2: extreme period in a dry year (fill Weishan Lake)

Description This scenario includes the most extreme off-take schedule within a 75% dry year (see figure 24). For this simulation the period 22-05-1970 till 28-05-1970 has been chosen. Exactly in the middle of this 6-day period a 'nod' can be recognized in the data series, which is a data point of the 10 days data series (see figure 28). The average system outflow during this period is around 1500 m^3/s. This is trice the system capacity of 500 m^3/s, thus the water levels in the lakes should inevitable drop during the whole simulation period. It is assumed that the control objectives state that only the most northern lake, Weishan Lake, water should be saved, while water may be freely taken from the other lakes (Hongze Lake and Luoma Lake). This can be the case when enough water is available within Jiangsu, but that the northern provinces have water shortages and thus water should be transported according to the SNWTP. By putting a high penalty on Weishan lake, water is pumped into Weishan lake and the SNWTP demand is satisfied.

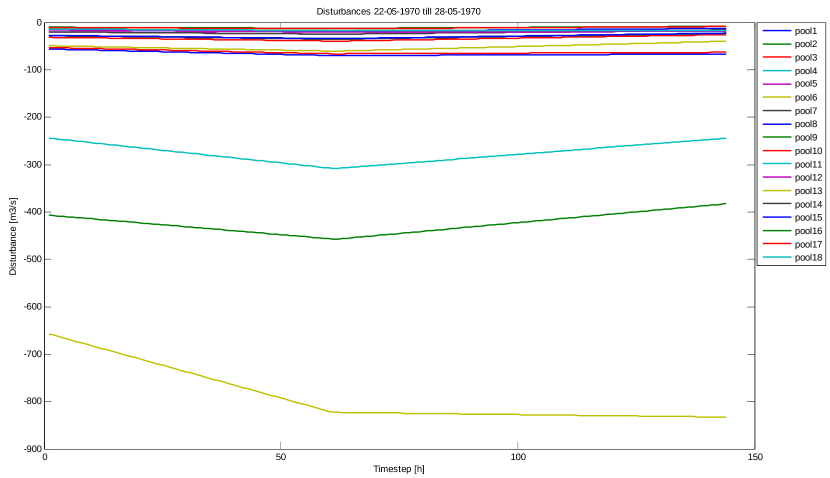

Figure 28: Disturbances during simulation period 22-05-1970 / 28-05-1970.

Simulation Characteristic	Value/date	Information
Data series	1980-1981	Dry year (75%)
Start of simulation	12-06-1981	
End of simulation	18-06-1981	
Average net system outflow	1500 m^3/s	
Initial water level deviation Hongze Lake	-0.07	Control objective: use water
Initial water level deviation Luoma Lake	-0.34	Control objective: use water
Initial water level deviation Weishan Lake	-0.07	Control objective: save water
Initial water level deviation in canals	~0	

Table 9: Summary of Scenario 2.

Results Below the results of scenario 2 are shown.

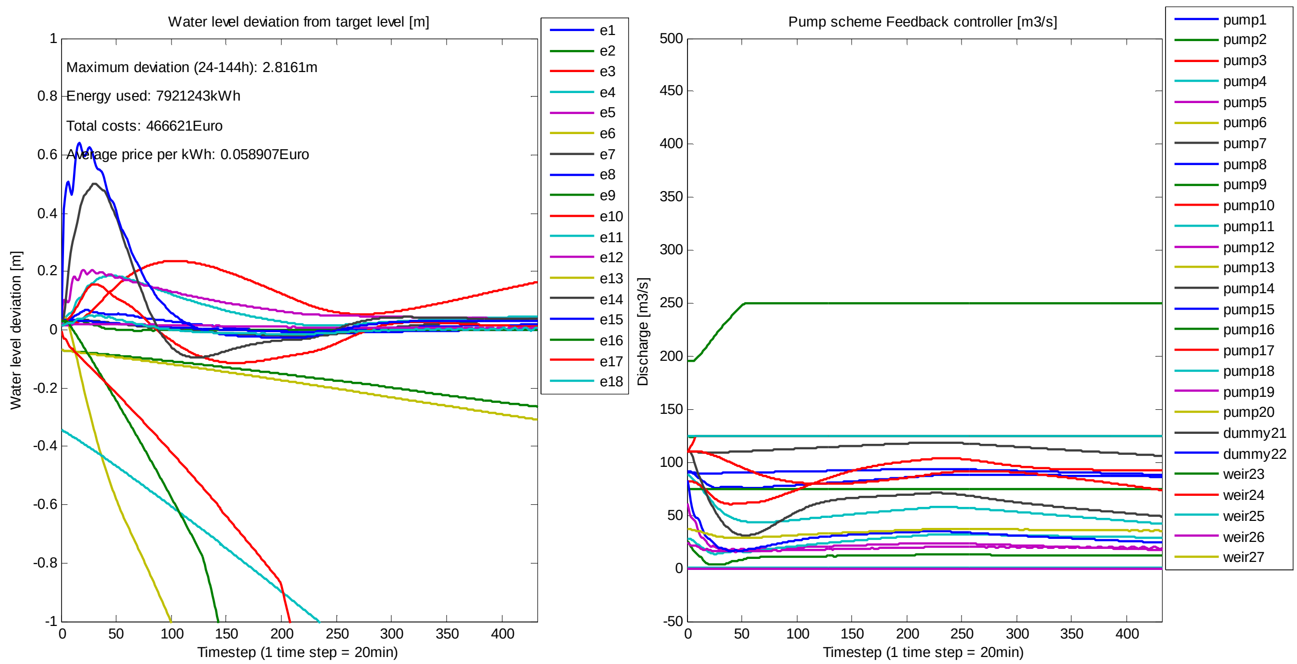

Figure 29: Scenario 2 - feedback control.

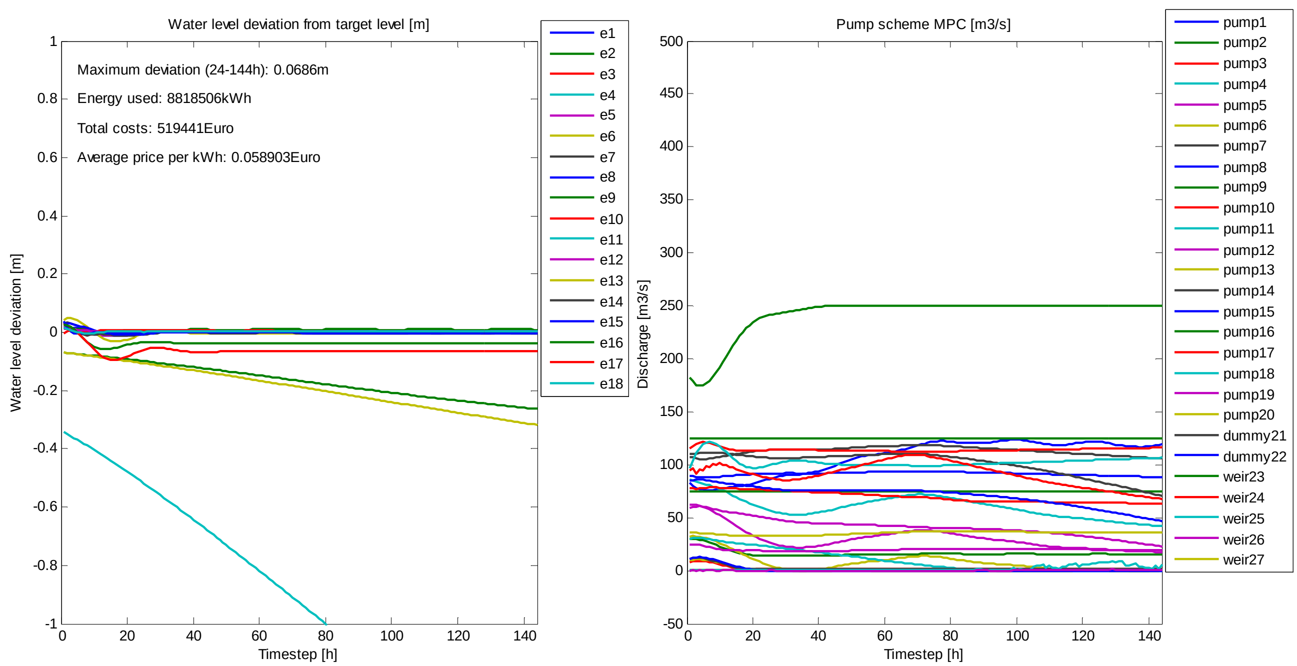

Figure 30: Scenario 2 - MPC.

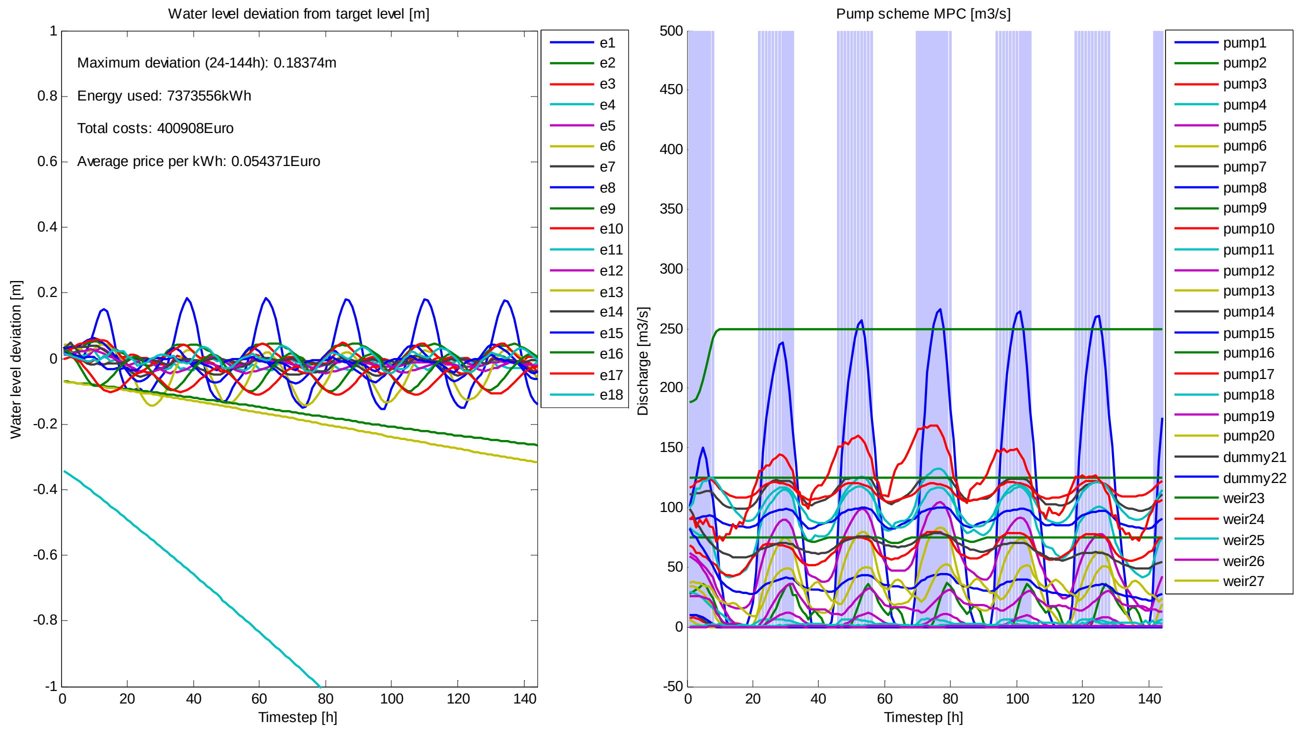

Figure 31: Scenario 2 - MPC cost reduction.

	MAE [m] (24-144h)	E [GWh]	c [10^3€]	€ per kWh	Percentage cost reduction based on average price per kWh (feedback = 0)	Estimated daily costs (based on 1.32 GWh/day) [10^3€]
Feedback controller	NA	7.92	467	0.0589	0	77.8
MPC	0.07	8.82	519	0.0589	-0%	77.8
MPC cost reduction	0.18	7.37	400	0.0543	-9%	70.8

Table 10: Results scenario 2.

Analysis & Discussion Due to the control objective that states to pump water into Weishan Lake, the flow through the most northern canals increases till capacity flow. The feedback controller is unable to maintain the water level in 3 canal pools. This can be explained by the inability of the feedback controller to handle system constraints. If two sequential stations have the same capacity and are set to maximum capacity by the controller in order to maintain water levels, an off-take in-between those stations cannot be corrected and consequently the water level in this canal pool will continuously drop till bottom level. While the feedback controller fails to maintain the water levels it fails on another control objective as well, which is to supply water demands in the region (Jiangsu local demands).

The Model Predictive Controller is able to maintain all water levels within a bandwidth of 0.07 meters around target level while the operational cost reduction is 0%.

The percentage cost reduction by the MPC is trice as low as in scenario 1 (-9% versus -27 % in scenario 1). However the daily potential costs savings are 3 thousand Euros higher than in scenario 1 (7 thousand versus 4 thousand Euros in scenario 1). It should be noted that the cost reduction requires sacrifices on the water level errors. This cost reduction can only be achieved by allowing a daily water level deviation up to 0.18 meters form target level in canal reach e1; this is the largest canal reach with the largest flows (up to $500m^3/s$).

The lower percentage cost reduction can be explained by the larger volume flows through the system: the higher the flow, the more 'difficult' it will be to reduce the flows through the system, because high flows are required to maintain the water levels. Moreover the penalty on the change of structure setting will be higher when the difference between the peak flow (during night tariff) and low flow (during the day tariff) will be larger.

Also cost reduction might have been realized by choosing the cheapest route (main or secondary route). How large this cost reduction is, is difficult to determine. One would have a difficult time to assess how volume differences in lakes and canals should be valuated in terms of monetary units. Hence an assessment of the cost reduction by choosing the 'cheapest' route is not possible.

In all three graphs with the control actions, a rising and dropping of the average flow height can be recognized. This the effect of the nod in the data series (see figure 28).

6.4.3 Scenario 3: extreme period in a dry year (fill all lakes)

Scenario description This scenario is the same scenario as scenario 2, however, it is now assumed that an extreme dry period is expected and that therefore the control objectives are different than under scenario 2. In this scenario the control objectives state that in all lakes water has to be saved as much as possible to prevent water shortages at the end of the season. Hereto the penalties on all lakes are set to their maximum value.

Simulation Characteristic	Value/date	Information
Data series	1980-1981	Average year (50%)
Start of simulation	12-06-1981	
End of simulation	18-06-1981	
Average net system outflow	1500 m^3/s	
Initial water level deviation Hongze Lake	-0.07	Control objective: save water
Initial water level deviation Luoma Lake	-0.34	Control objective: save water
Initial water level deviation Weishan Lake	-0.07	Control objective: save water
Initial water level deviation in canals	~0	

Table 11: Summary of Scenario 3.

Results Below the results of scenario 3 are shown.

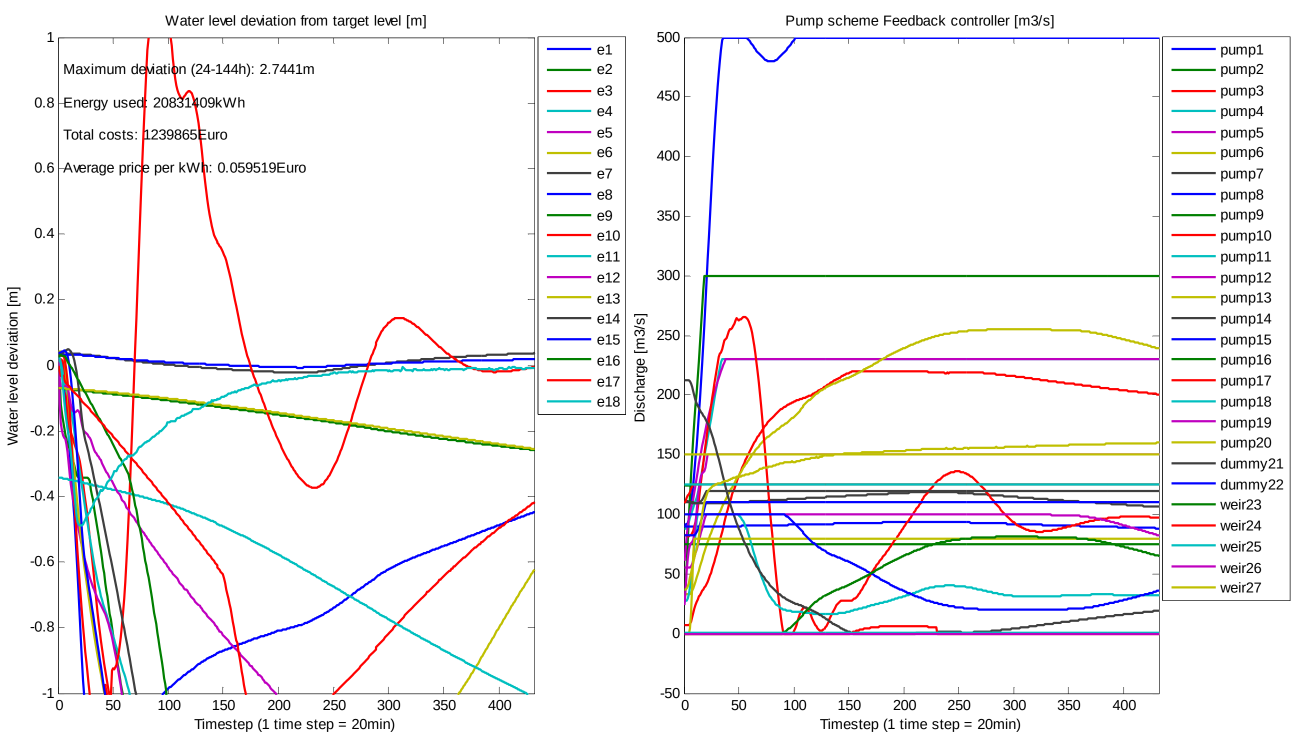

Figure 32: Scenario 3 - Local PI.

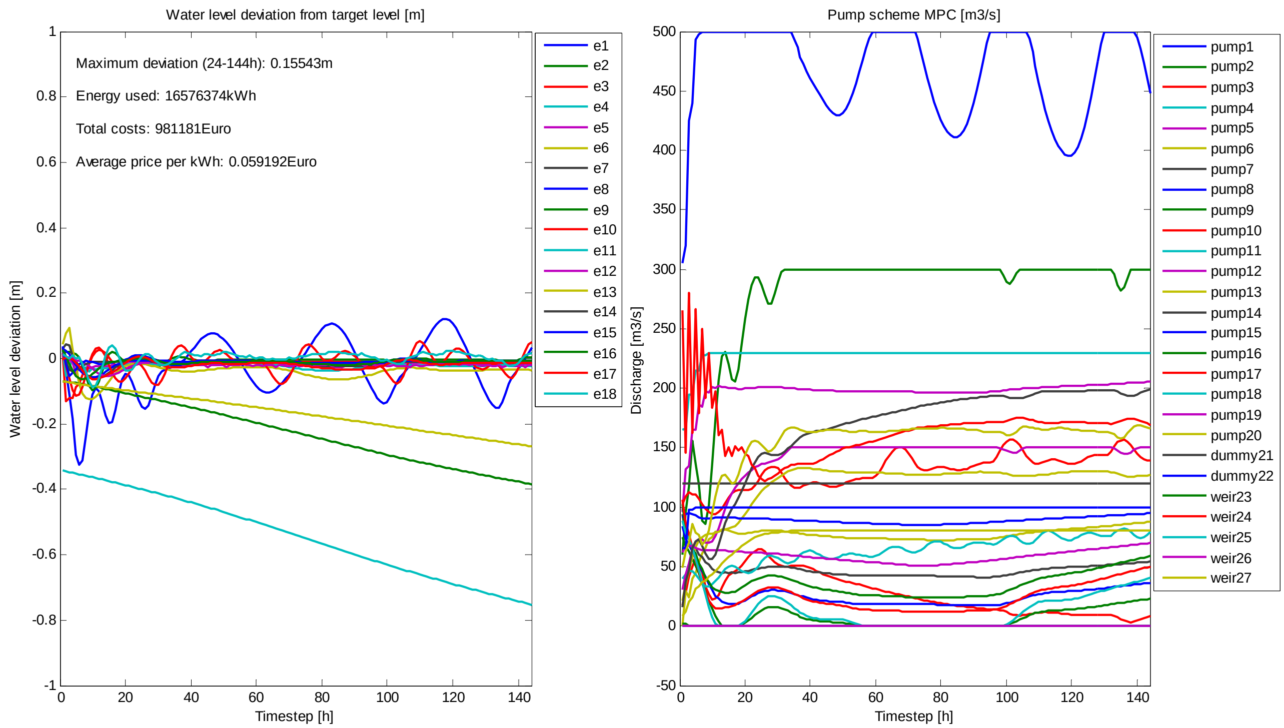

Figure 33: Scenario 3 - MPC.

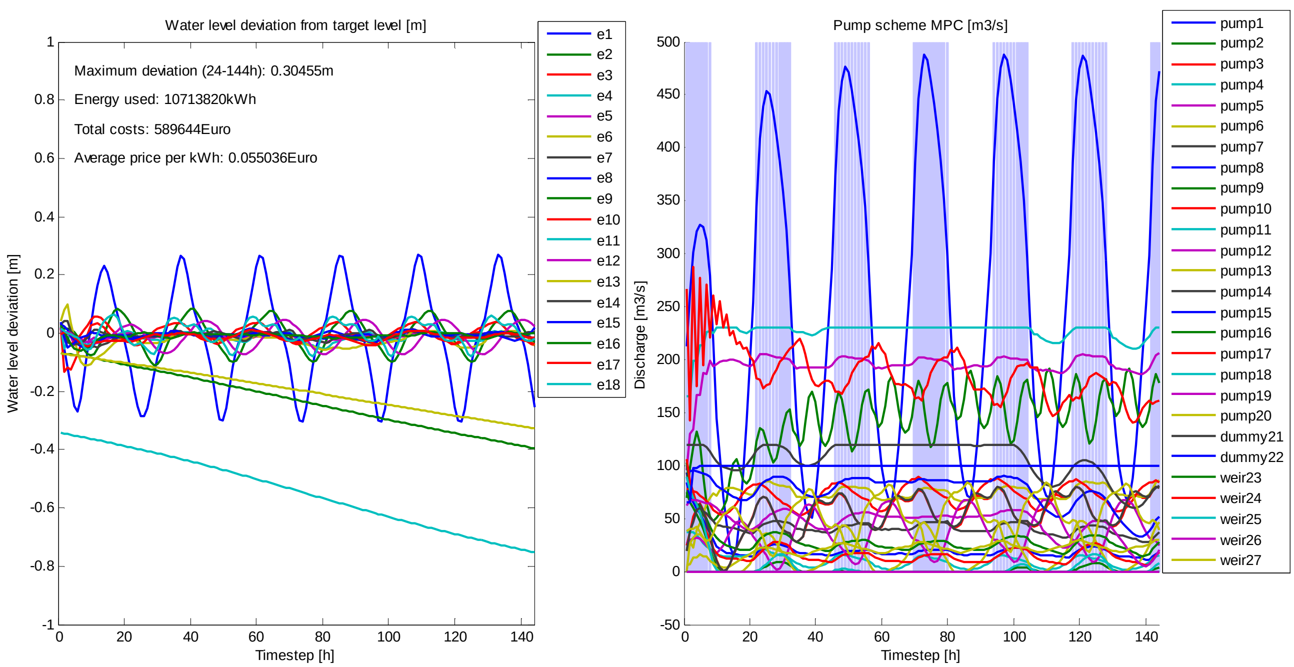

Figure 34: Scenario 3 - MPC cost reduction.

	MAE [m] (24-144h)	E [GWh]	c [10^3€]	Euro per kWh	Estimated cost reduction based on price per kWh (feedback = 0)	Estimated daily costs (based on 3.47GWh/day) c [10^3€]
Feedback controller	NA	20.8	1,239	0.0595	0	206
MPC	0.16	16.5	981	0.0592	-0%	205
MPC cost reduction	0.30	10.7	590	0.0550	-7%	191

Table 12: Results Scenario 3.

Analysis Due to the extreme water demands throughout the whole system, all pump stations are operating at (almost) full capacity. The feedback controller in unable to maintain water levels in a large number of canals. Also here the main reason is the inability to handle system constraints.

The normal MPC shows a maximum deviation from target level of 0.16 meters. Reach 1 [fed by pump station 1 (500 m^3/s)] shows an oscillating pattern with a frequency larger than the day-night frequency and thus cannot be caused by the day-night variation. This is related to dynamics that have not been captured by the underlying process model. The use of the ID model in underlying process model here is less suitable for high flow conditions. It might be desirable to develop a more accurate process model by further improvements of the process model e.g. with Proper Orthogonal Decomposition (POD) .

The MPC aimed at cost reduction, achieves a percentage cost reduction of 7%. The trend from scenarios 1 till 3 shows that the higher flows through the system, the lower the percentual cost reduction. Though the absolute costs reduction is still rising with the height of flow (14 thousand Euros can be saved on a daily bases in scenario 3 compared to 7 thousand Euros in scenario 2).

The maximum amount of water that can be withdrawn from the Yangtze River will be 8,900,000,000 m^3 of water per year of which 2,900,000,000 $m^3/year$ can be supplied over the border to Shandong. If in a dry year this complete volume has to be withdrawn from the Yangtze River, the total amount of energy necessary is estimated at 600 million kWh[2]. With the average price realized by feedback control, the operational costs will be about 38 million Euro (380 million Yuan) resulting in maximum costs savings around 3 million Euro in a dry year. However, again it should be mentioned that in order to achieve this cost reduction, large sacrifices have to be made to the water levels and the structures. This cost reduction can only be achieved by allowing a daily water level deviation up to 0.30 meters form target level in canal reach e1.

[2] 2.9 billion m^3 with an average head of 40m and 6 billion m^3 with an average head of 20m

6.4.4 Scenario 4: disturbance handling (predicted and unpredicted)

Scenario description Disturbances can cause water level to deviate from target level; controllers will try to correct them. In this scenario the abilities of the controllers to correct disturbances is tested. Since MPC can incorporate predictions, MPC is tested under two sub-scenarios. In sub-scenario A the disturbance is not predicted; in sub-scenario B the disturbance is predicted. It should be noted that the feedback controller would react in the same way under both sub-scenarios, because it cannot deal with predictions; therefore the feedback results are only shown once. This scenario is a copy of scenario 1; see table 7 for the summary of this scenario. An extra disturbance of 20 m^3/s is added to reach e4 on 10-05-1970 from 0.00h till 12.00h; this is halfway the simulation period (see figure 35).

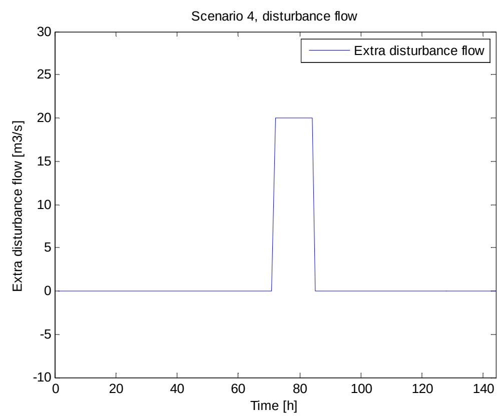

Figure 35: Extra disturbance flow scenario 4.

Results Below the results of scenario 4 are shown.

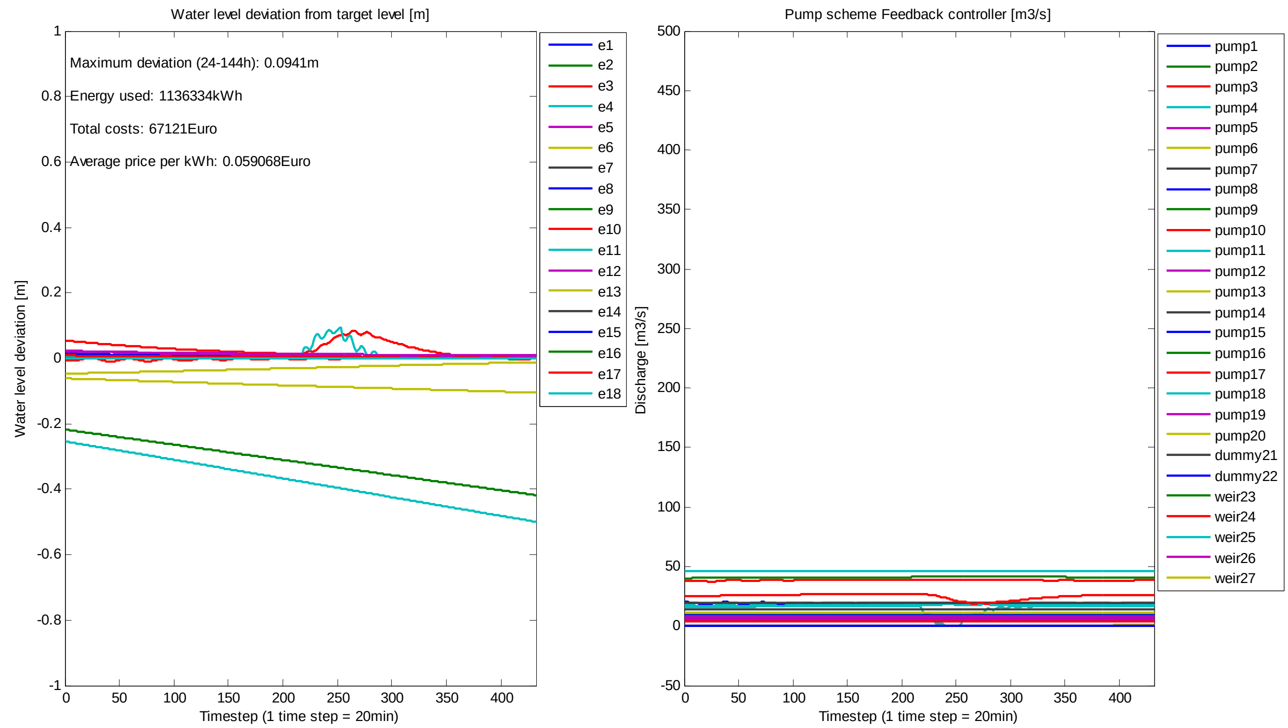

Figure 36: Scenario 4A and 4B - feedback control.

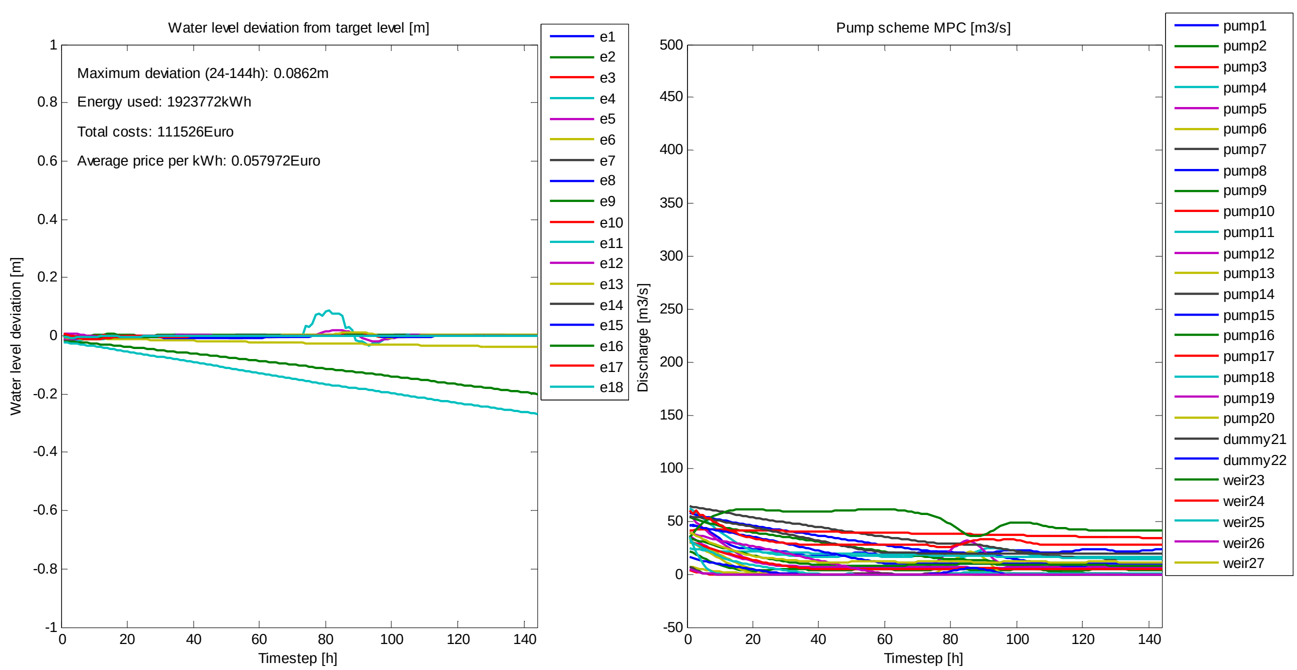

Figure 37: Scenario 4A - MPC (unpredicted disturbance).

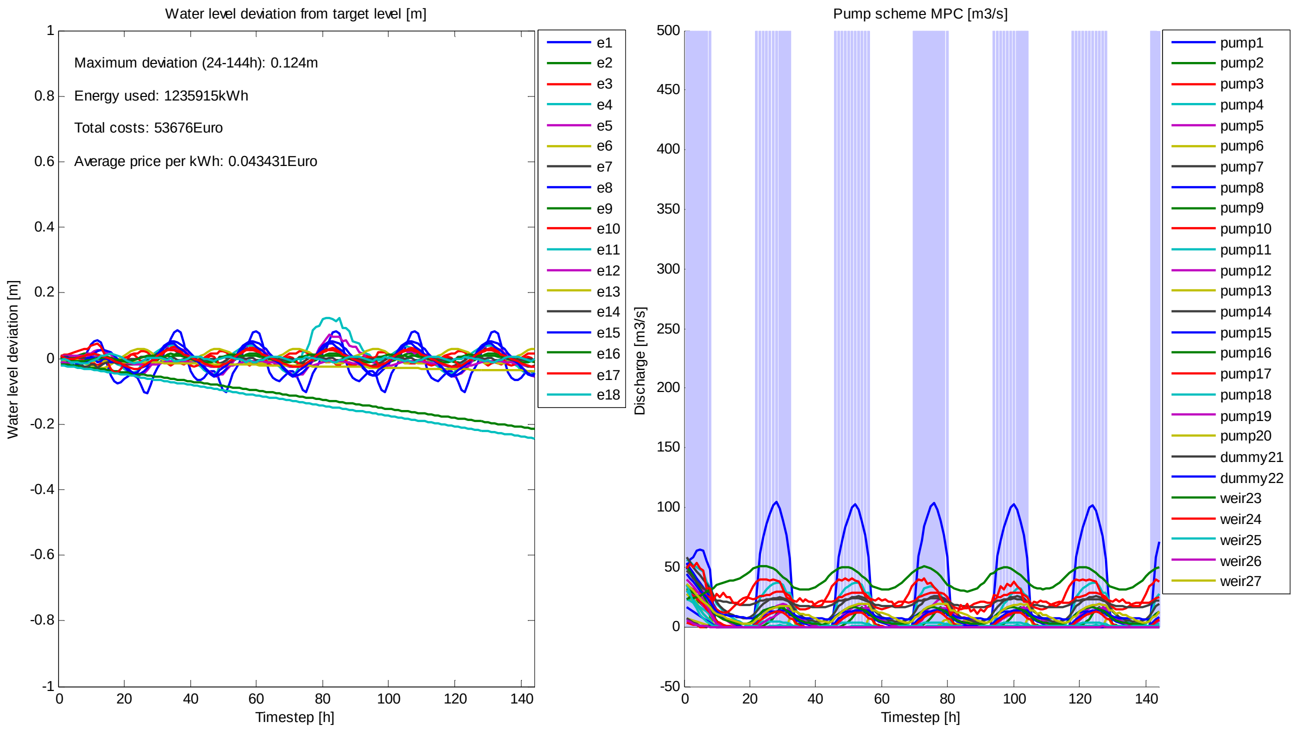

Figure 38: Scenario 4A - MPC cost reduction (unpredicted disturbance).

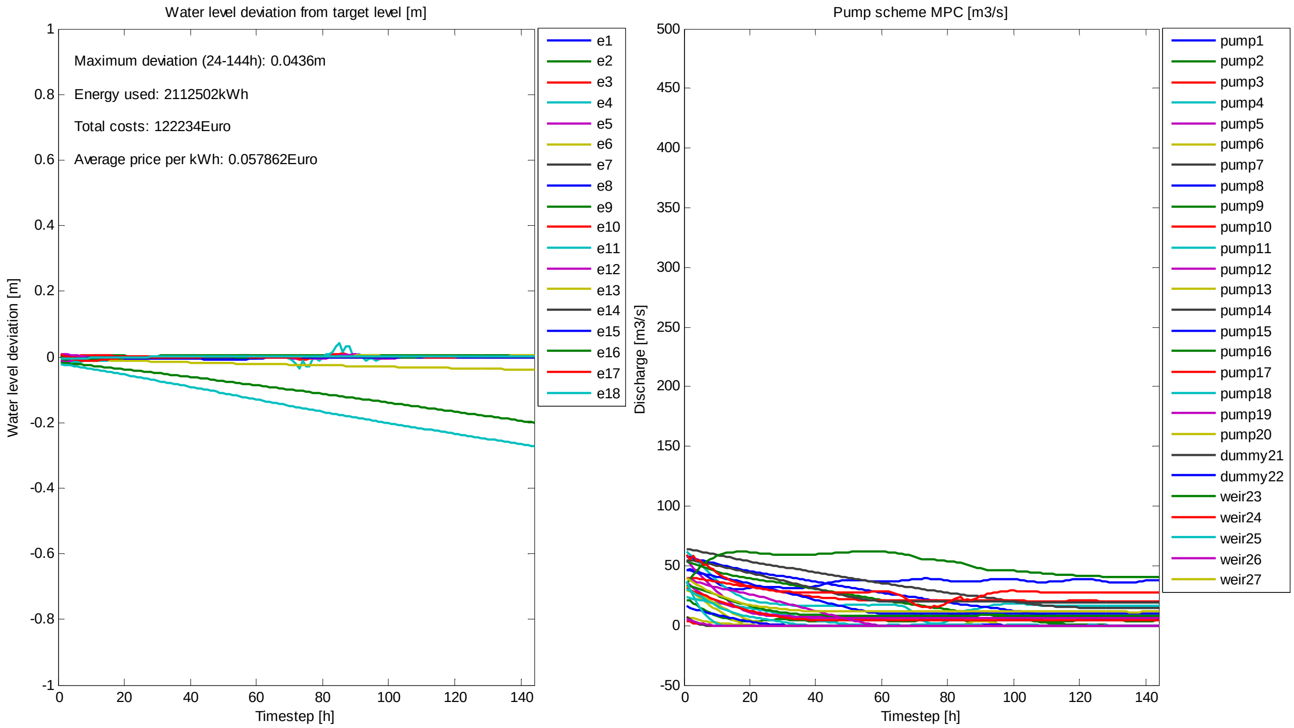

Figure 39: Scenario 4B - MPC (predicted disturbance).

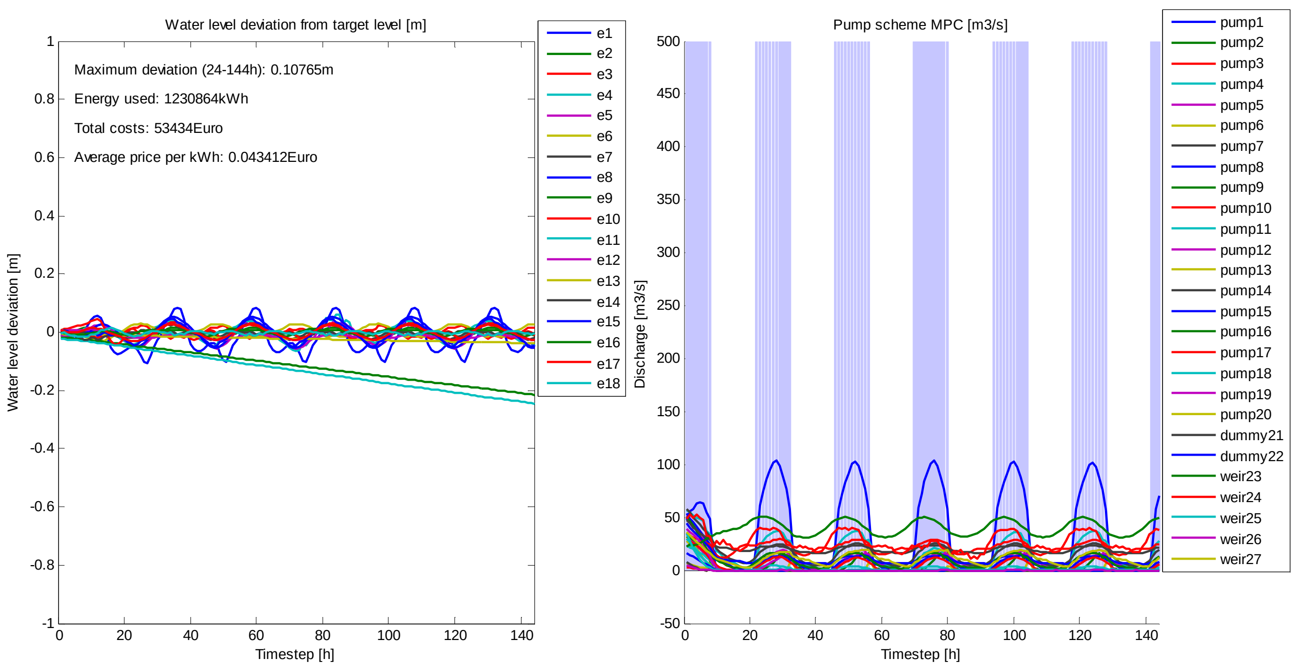

Figure 40: Scenario 4B - MPC cost reduction(predicted disturbance).

	MAE [m] (24-144h)	Recovery time [h]
Feedback controller	0.09	38
MPC (unpredicted disturbance)	0.09	14
MPC cost reduction (unpredicted disturbance)	0.12	18
MPC (predicted disturbance)	0.04	8
MPC cost reduction (predicted disturbance)	0.11	8

Table 13: Results Scenario 4

Analysis & Discussion An enlargement of the disturbance handling by feedback control and MPC (predicted and unpredicted disturbance) are shown in figures 41, 42 and 43. The disturbance does have a significant raising effect on the water level in canal pool e4. The water level raise in canal pool e4 is about 0.09 meters for both controllers. Adjacent canal pools may be affected due to hydraulic interaction between pools. The effect on adjacent pools is the largest under feedback control where the water level deviation in e3 is increased around 0.08 meters. The effect on adjacent pools under MPC is negligible ($<$0.02 meters, see figure 43). The time a controller needs to return the water level back to target level is called 'recovery time' here. The recovery time for the feedback controller is significant longer than under MPC. Figure 39 (and 43) shows the performance of MPC when the disturbance is predicted. The controller starts in-/decreasing the flows well in advance of the moment the actual disturbance affects the water system. Hereby the water level deviations are kept close around target level ($<$0.05 meters). This shows the feedforward component of the MPC.

Under 'MPC cost reduction' the effect of a disturbance may 'disappear' in the water level fluctuations that are all ready going on in the system. This can be seen in figure 40 where the disturbance can hardly be recognized. However, if a disturbance is unpredicted, the effect might be enlarged if the disturbance acts on the system during the the rather extreme day tariff. In figure 38 the water level deviation in canal pool e4 is higher than under the normal MPC. If the unpredicted disturbance occurs during night tariff, it will be barely noticed.

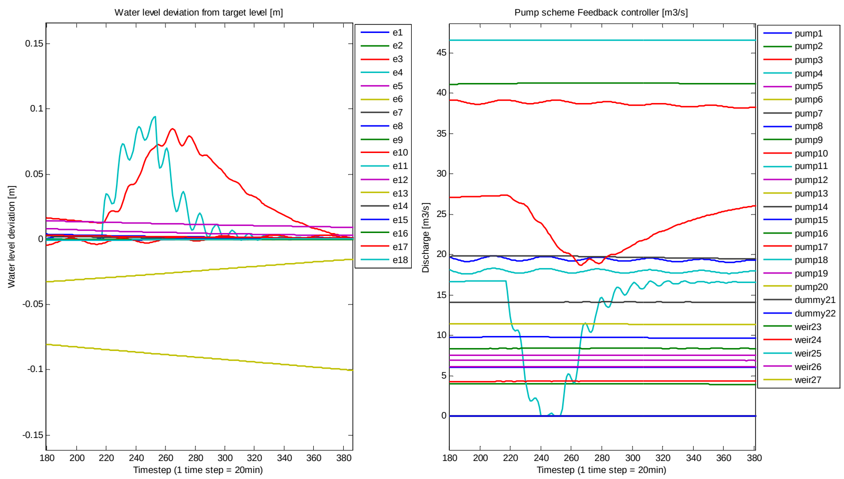

Figure 41: Enlargement of the disturbance handling by the feedback controller in scenario 4.

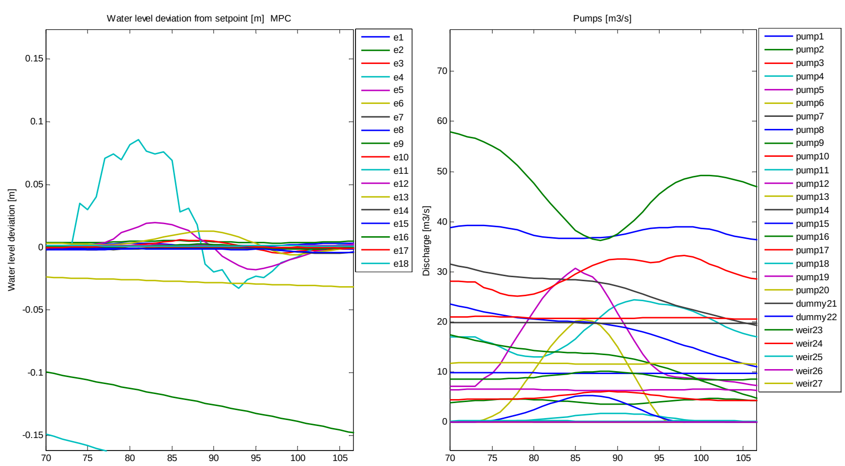

Figure 42: Enlargement of the disturbance handling by the MPC (unpredicted disturbance).

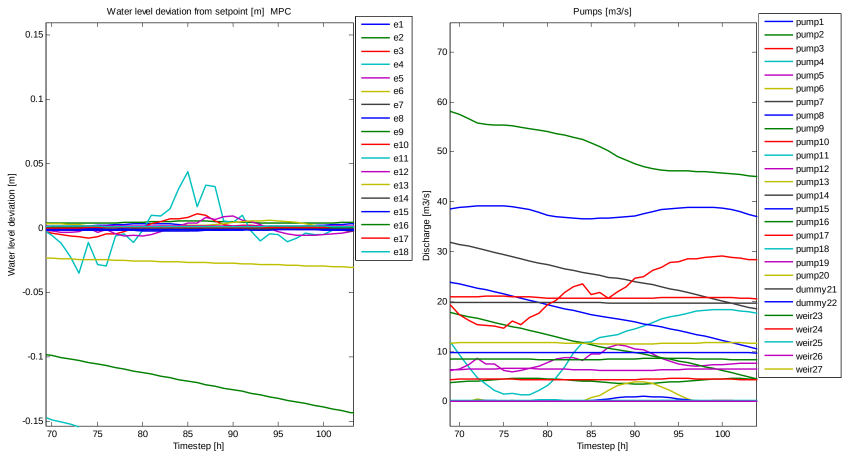

Figure 43: Enlargement of the disturbance handling by the MPC (predicted disturbance).

6.4.5 Scenario 5: structure failure

Scenario description Irrespectively of the reliability of system structures or the strength of implemented policy, unexpected circumstances can always occur. This scenario simulates the effect of a pump station that (partially) cannot operate due to any reason. This could be e.g. a mechanical failure, lightning strike or sabotage, but also due to a dangerous pollution in a canal pool that is imposed to be isolated from the rest of the water system by authorities. Since a large part of the Jiangsu water transfer system has parallel branches, there are always opportunities to supply (at least a part of the) water towards the users. In this scenario, the performance of the controllers under two unexpected conditions is tested. This scenario is the same as scenario 3, thus high flows occur throughout the whole system.

In sub-scenario A, pump station 19 which is located in the secondary canal (the green line in figure 5) is completely out of order on 15-06-1981 from 0.00h till 12.00h. In sub-scenario B half of the capacity of pump station 4, located in the main canal (the blue line in figure 5) which has a capacity of $230m^3/s$, is out of order on 15-06-1981 from 0.00h till 12.00h.

Results Below the results of scenario 5A and 5B are shown. Since the feedback controller failed in scenario 3, the feedback results are not shown. No comparison can be made between MPC and feedback on any performance indicator relevant for this scenario.

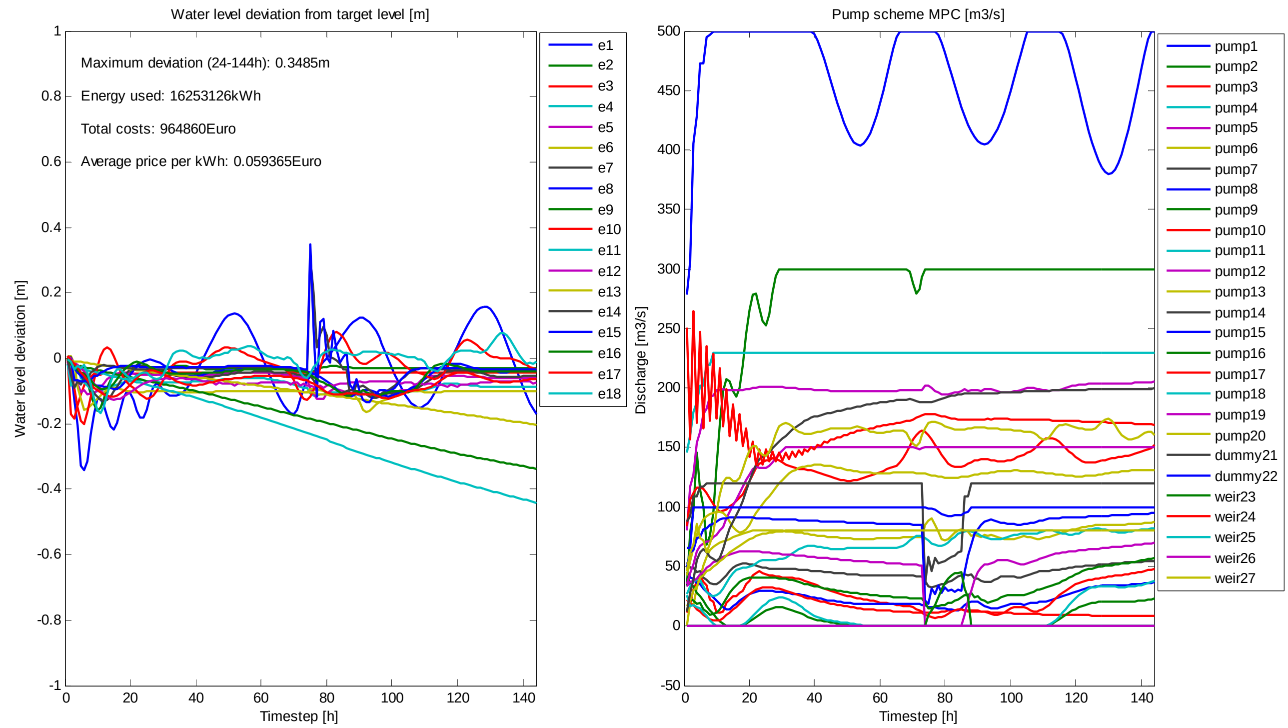

Figure 44: Scenario 5A - MPC

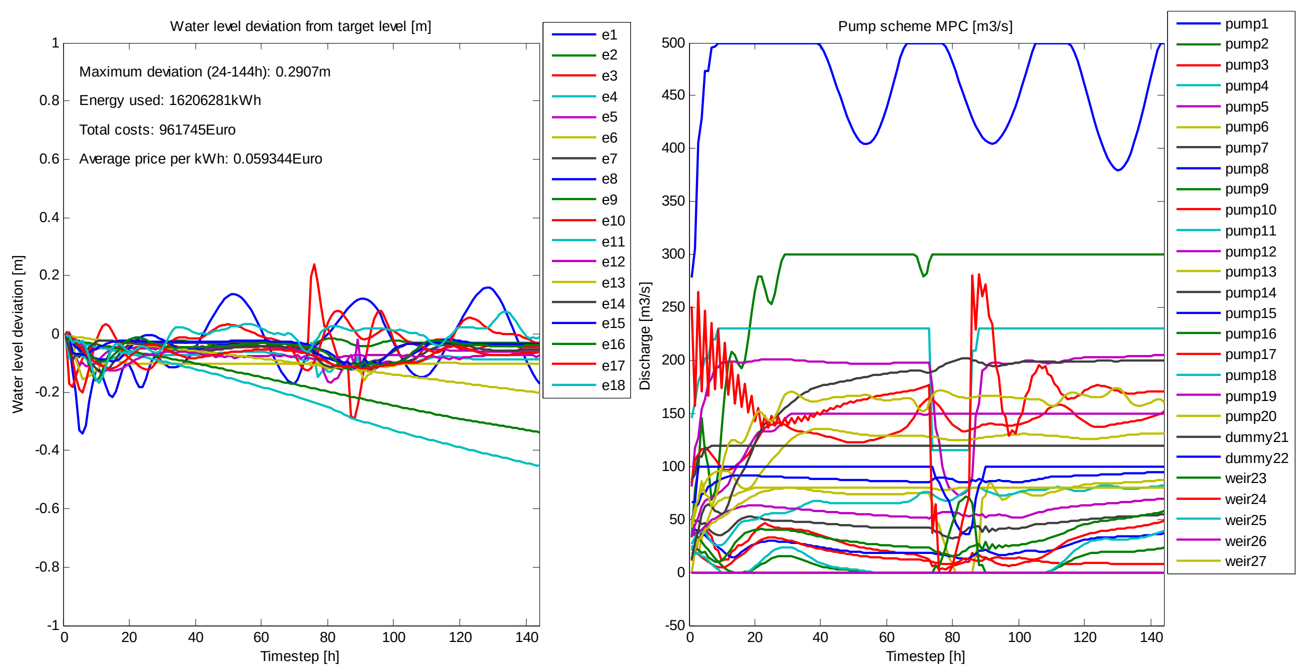

Figure 45: Scenario 5B - MPC

Analysis & Discussion Since any kind of failure is always unexpected, the feedback component of MPC will try to correct the unexpected large water level deviations. The MPC shows a water level deviation of 0.36 and 0.32 meters the first hour after the failure in canals reaches e14 and e15 that are both located just upstream of failing pump station 19. In the second hour after the failure, the water level deviations have been corrected till 0.12 meters. The MPC immediately shuts down pump stations 14 and 15; however the flows that have all ready been pumped in the previous time step cannot be corrected, since these are all ready traveling towards the failing station. The delay times of canal reaches 14 and 15 are 80 minutes which explains the inevitable large water level deviation in the first 2 hours after the structure failure. After the first hour, the corrective control actions have their effect on the water level. Corrective actions are immediately executed throughout the system by 7 structures at the same time, which illustrates the hydraulic interaction between all canal pools that is anticipated for by the MPC.

The partial failure of pump station 4 on the main route (scenario 5B) results in a sudden deviation of 0.29 meters in canal reach e3, just upstream of pump station 4. Corrective actions are taken by 8 structures at the same time and water levels are back within a bandwidth of 0.15 meters within 2 hours. The MPC supplies as much water as possible under the structure failure.

7 Conclusions & Recommendations

The conclusions of this study are stated in the first section of this chapter. The second section contains recommendations for further research.

7.1 Conclusions

The conclusions of this thesis are structured around the research- and sub questions formulated in section 1.3. They seek to provide comprehensive answers for meeting the objective of this thesis: **Assess the performance, advantages and disadvantages of Model Predictive Control (MPC) for the South-North Water transfer Project within Jiangsu Province in China.**

This research objective was derived from the hypothesis that a complex, multi-objective water system should preferably be controlled by the more advanced MPC to contribute to meet the desired system behavior and increase the water system's performance. MPC is a control algorithm that makes explicit use of a simplified process model (internal model) of the real system to obtain control actions by minimizing an objective function over the prediction horizon.

1. What is the control problem and what are the control objectives? The answer to this question can be found in section 2.4. The operational water management problem should be considered in a broad context due to the presence of large lakes within the system. These lakes can be used to store large amounts of water months before possible water shortage problems may actually occur. Water managers should provide up to date control objectives throughout the season, since controllers cannot decide on long-term control strategies. With and only with continuous up to date control objectives a controller can really adequate control the Jiangsu water transfer system. The goals of the Jiangsu water system have been provided by JWS. Some of these goals are political or tactical goals and thus have to be translated into control objectives on a regularly base. A first goal is to keep water levels close to target level. A second goal is to deliver the required quantities of water to the right place at the right time (local and SNWTP). A third goal is cost reduction. A fourth goal is to limit the change frequency of change in structure settings. The relative priorities of the goals are debatable and thus assumptions have been made on the relative importance of these goals.

Since the Water Conservancy Department (WCD) is responsible for the water resources within Jiangsu province, close cooperation with WCD is vital for the proper functioning of any real-time controller. The system cannot be controlled by two different institutes, thus a controller will have to facilitate both the provincial requirements and the water transfer of the SNWTP towards the next province.

2. How should the Jiangsu water transfer system be schematized and modeled? The answer to this question is given in chapter 4. The information of the water system that has been used for the schematization can be found in chapter 2 and Appendix A (details). Based on documents from JWS, meetings with members of JWS, internet sources and site visits, an as good as possible representation of the Jiangsu water transfer system has been made as it will be in 2013. The final schematization comprises 27 structures, 18 pools (3 lakes and 15 canal pools) and 4 boundaries. High flow simulations with the hydrodynamic model of the water system showed satisfying correspondence with the projected behavior of the system.

Despite all efforts, some information required for an accurate schematization could not be collected in China. Therefore assumptions needed to be made on some system characteristics. Due to these assumptions, there may be discrepancies between the schematization and the (future) real system. However, these discrepancies will barely affect the results of this research, because the controllers use a rather inaccurate process model of the real system (ID model, see section 3.3.1). Moreover the size of the system is exactly modeled; the assumptions have been made on the bottom roughness and the shape of cross-section profiles of the canals. An improvement in the hydrodynamic model will not lead to an improvement of the controller, because the relative inaccuracies between the internal model and the hydrodynamic model will remain. This implies that the results are very useful for assessing the potential of the controllers on the Jiangsu water transfer project even though assumptions have been made on certain system characteristics. Caution should however be taken when applying a controller one to one to the real system, because of discrepancies between the hydrodynamic model and the real system; retuning might be necessary first.

3. How should a Model Predictive Controller be designed for the Jiangsu water transfer system? The design of the MPC for the Jiangsu water transfer system is presented and clarified in chapter 5. The MPC is designed according to method described in Overloop [2005]. However, the extraordinary size of the lakes made it necessary to come up with a design that includes states and penalties that have not been applied before in a MPC application.

The internal model has been written in compact form in order to keep calculation times short; this is an important condition for real-time implementation, because control actions need to be available fast. However, even in compact form, the simplified internal model of the Jiangsu water system is so large that the computational power of a personal computer (2 Ghz) turned out to be insufficient for real-time control. The use of a commercial solver (TOMLAB) on a 64-bit computer enables real-time control of Jiangsu water transfer system with MPC.

The way in which MPC controls the system can be tuned with penalties on states and inputs that are described in the internal model. The penalties provide a trade-off between water level errors in pools, operational costs and changes in structure settings. The tuning of MPC depends on the relative importance of the system objectives. Two different tuned MPC variants have been tested within this thesis. The results show the performance of a 'normal' tuned MPC and a variant that is strongly tuned for cost reduction. A large range of intermediate settings is possible. It is up to the manager of the water system, what is desirable.

4. How does a Model Predictive Controller perform on the Jiangsu water transfer system? The controllers have been tested under 5 different scenarios, all in the dry season, the period in which water can be transported uphill. The enormous lakes play a determinative role in the operational management of the water system. Therefore the role of the lakes has been described per scenario. For the first scenario data series of an 'average' year have been used in which water demands are relatively low (320 m^3/s on average) and it is assumed that control objectives state that water may unlimited be taken from the lakes. For the second and third scenario data series of a 'dry' year have been used in which water demands within the system are high (1500 m^3/s on average); the two scenarios differ in control objectives for the lakes (save water in one lake and save water in all lakes respectively). In the fourth scenario the disturbance handling is tested and in the fifth scenario the performance during (partial) failure of pumps is tested. Per scenario the performance is shown of 1) a feedback controller 2) a 'normal' MPC and 3) a MPC that aims for reducing the operational costs as much as possible ('MPC cost reduction'). All results can be found in chapter 6.

The 'normal' MPC is able to keep water levels within a bandwidth of 0.01 meters around target level under scenario 1 (low flow conditions), within 0.07 meters under scenario 2 (high and low flow conditions) and within 0.16 meters under scenario 3 (high flow conditions). For comparison, the feedback controller achieves 0.05 meters under scenario 1 and fails under scenarios 2 and 3, which means that the water level in one or more canal pools drops till bottom level (dry bed). MPC never exceeds minimum or maximum allowed water levels. The reason is that the minimum and maximum values range between 0.25 and 1 meter from target level. These large margins can not easily be violated with a good controller.

Regarding the objective of water delivering, the failure of PI control to maintain water levels also implies the failure of water delivery; MPC delivers always all required water quantities.

Regarding the cost reduction, MPC is barely able to reduce any operational costs. The 'MPC cost reduction' is able to significantly reduce operational cost, but only by making large sacrifices on the performance on other goals. The water levels deviate up to 0.18 meters under low flow conditions saving 28% or 4,000 Euro a day. Under high flow conditions water level deviations are up to 0.30 meters saving 7% or 14,000 Euro a day. In year wherein the maximum amount of water has to supplied to Shandong province an estimated maximum of 3 million Euro per year (30 million Yuan) can be saved, by making use of day-variation in the tariff of electrical power.

The simplified description of the storage volume by the ID model did not have a significant impact on the performance of the MPC under low flow conditions. However, under high flow conditions the inaccuracy of the ID model did degrade the performance of the MPC. This degradation is the result of unmodeled dynamics in the underlying process model (internal model) and not by the MPC itself.

In the fourth scenario the disturbance handling has been tested. When disturbances are unpredicted the MPC performs comparable to the feedback controller on the canal pool that the disturbance acts on. For adjacent pools, the MPC has a higher performance, since water levels in adjacent pools are hardly affected. If a disturbance is predicted the feedforward component reacts to the disturbance well in advance and thereby adding significant improvement to the performance of the MPC. Under 'MPC cost reduction' an unpredicted disturbance can be larger then under normal MPC. This depends on the time of the day that a disturbance acts on the system.

A last objective was to limit the change and frequency of structure settings. The change in structure settings should be limited from a control engineering point of view. From a technical point of view JWS has mentioned that the frequency of changes should preferably be limited. The feedback controller required three times as much structure changes than the MPC to achieve the performance described above due to the smaller control time step that has been used.

5. How does a feedback controller perform on the Jiangsu water transfer system? Existing literature on the topic of feedback control of water systems covers irrigation and drainage systems with single in-line canal pools or simple branching networks and thus it is unknown whether it is suitable for the Jiangsu water transfer system. The control tests showed that feedback control on the Jiangsu water transfer system was only capable to successfully control low flow scenarios. If in any part of the water system a high flow is required to maintain water levels, the feedback controller fails to meet the control objectives. The main reason for the Jiangsu water transfer system is the inability of feedback controllers to handle system constraints, since the limits of the system are reached under these conditions.

Under low flow conditions the feedback controller is able to achieve the desired system behavior, as it keeps water level deviations within 0.05 meters. The water level deviation during an unpredicted disturbance is comparable to MPC, though in an adjacent pool also large water level deviations are observed.

All though a rather simple form of feedback has been applied in this research, it should be noted that no single form of feedback would be able to meet the control objectives under high flow conditions, given the fact that feedback control cannot handle systems constraints.

Research Objective

Together the above answers to the research questions provide the comprehensive answer to the research objective. This is summarized below per term used in the research objective (performance, advantages, disadvantages).

Performance The performance of the MPC has been handled extensive in research question 4. In Conclusion MPC is able to meet the system objectives under all circumstances. MPC keeps water levels within a bandwidth of 0.16 meters around target level under all circumstances and therefore never exceeds minimum or maximum allowed water levels. With good disturbance predictions the performance of MPC on water levels is further improved. With increasing flows, it is harder to maintain the water levels. MPC is not able to significantly reduce operational costs without making sacrifices on other objectives. The limits of MPC have been reached; a large time step (1 hour) and a short prediction horizon (1-2 days) are required to enable MPC on a system this large. Almost perfect disturbance predictions have been used, thus performance on the real system might be lower. On the other hand the quality of the process model can be improved in order to achieve a higher performance.

Advantages Besides the known advantages such as less manpower, the most important advantage of MPC is that it is very effective in maintaining the water levels under all circumstances. This can be subscribed to the ability to determine the hydraulic interactions within the whole system in a short period of time. Humans are unable to determine the hydraulic implications within a short time for a complete water system as large as Jiangsu water system. When on any arbitrary location in the system a structure fails or a large disturbance occurs, corrective actions are executed throughout the whole system within one control time step. Due to this characteristic, the MPC is especially suited to maintain water levels under all possible scenarios and inherent to this is that water demands are always satisfied. Though the large control time step of MPC has its disadvantages, an advantage is that it uses two times less changes in structure settings to achieve the results shown in this report.

Disadvantages Known drawbacks of MPC are e.g. the risk of failing communication lines, the limitations of a simplified process model and the required computational power. Previous research showed the limitations of computational power for irrigation and drainage networks. Control of large system as the Jiangsu water transfer system would not be possible with MPC if the computational power was not strongly expanded by the use of a commercial solver on a 64-bit computer. Though this computational power made real-time control of the Jiangsu water transfer project possible, the drawback of computational power still stands. The control time step needed to be chosen as large as 1 hour and the prediction horizon was limited to 2 days at most. The use of the ID model is an advantage and disadvantage at the same time. Though the ID model is compact and therefore very fast, it is only valid at one working point. The very good performance on the water levels under low flow conditions has significant degraded under high flow conditions

7.2 Recommendations

In this research Model Predictive Control has shown to be an appropriate controller for the large, multi-objective Jiangsu water transfer system. Though within the research a number of assumptions have been made, this research gives a good indication of the capabilities of MPC for the Jiangsu water transfer system. This section gives recommendations on how to deal with controllers for the Jiangsu water transfer project, further improvements of the MPC on this water system and further research.

Levels of decision making (tactical vs operational) The first and most important recommendation is to clearly distinguish the political, tactical and operational levels of decision making within operational water management. It is recommended to translate political and tactical defined goals into operational goals (control objectives) on a regularly basis (e.g. every 10 days). With and only with regularly updated control objectives a controller can really adequate control the Jiangsu water transfer system. Responsible authorities/water managers should translate the tactically defined goals into operational goals, so called control objectives.

The seemingly barrier between the two different levels of decision making can be overcome with a user interface. A user interface that allows for easy and fast change in the control objectives , without the need of exact knowledge on the algorithm of MPC, is desirable.

Costs MPC should not be chosen in the first place because of the possible cost reduction (neither should any other real-time controller). In potential the cost reduction on the tactical level (see section 2.4 for definition) is much higher and might well be worth the investments, e.g. investment in better long term predictions models and tools. Having said that, this research has shown that cost reduction on an operational level is very limited and that considerable cost reduction can only be achieved by making large sacrifices on other control objectives. For example, the higher the reduction of operational costs, the higher the water level deviations. This research shows two rather extreme ends of the MPC's possible settings. What would be good (intermediate) settings is up to the water managers of the Jiangsu water transfer system who have to deal with topics as 'to what cost may water levels fluctuate or deviate from target level?' or 'to what costs may structure settings be flexible?'. The results of this thesis can be used in as a guidance on such decisions, since it gives an indication on the possible cost reductions versus the offers that have to be brought on water levels and structures.

Further research For further investigation it is desirable to test the MPC parallel to the real world and feed the MPC with real-time data from the system. There are two main reasons for this. First, the simulations in this thesis have been performed with aggregated data series (time step of 10 days). Simulations with more detailed series would be interesting since this closer resembles the real world disturbances as the real world disturbances are more whimsical then the series used in this thesis. Second the performance of MPC can be compared to the current way of control instead of the feedback controller that failed under a large number of scenarios.

Caution should be taken on one-by-one application of this MPC on the real system, because parameters determination and tuning have been based on the schematization and thus the assumptions made in the schematization. Determining new parameters or retuning might be preferred if certain assumed characteristics turn out to be significant different.

JWS Concrete recommendations can not be given to JWS since no detailed control objectives have been given. It is e.g. not known how a 0.16 meter maximum deviation under all circumstances is valuated by JWS or to what extend water level deviations are allowed in order to lower operational costs, etc. It is up to JWS to judge the results of this research.

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Abbreviations

ID	Integrator Delay
JWS	Jiangsu Water Source Company Ltd.
LQR	Linear Quadratic Regulator
MPC	Model Predictive Control
PI	Proportional Integral
PIF	Proportional Integral Filtered
PIL	Proportional Intergral Lag
SNWTP	Sount-North water transfer project
WCD	Water Conservancy Department

Symbols

$\triangle T$	Time step
A_s	Surface area of a pool
c	costs [€]
C	Output matrix
d	Disturbances
D	Disturbances over prediction horizon n
e	Water level error
e^*	Virtual water level error
e_f	Filtered water level error
E	Energy [kWh]
F_c	Filter constant
J	Objective Function
k	Time index
k_d	Delay time
K	Controller gain matrix
K_p	Proportional gain
K_i	Intergral gain
m	Control horizon
MAE	Maximum absolute error
MAVE	Maximum allowed value estimate
n	Prediction horizon
P	Energy price [€/kWh]
Q	Penalty matrix
q_{lat}	Lateral discharge
Q_{lin}	Linear penalty matrix
R	Penalty matrix
u	Control action
u^*	Virtual control action
U	Control actions over prediction horizon n
x	States of the system
X	States of the system over prediction horizon n