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Polder Flushing: Model Predictive Control of Flushing Operations to Effective and Real Time Control of Salinity in Polders

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Abstract

More than 35% of the world's population live within 100 km of the coast. Groundwater resources in these areas are the main source for domestic, industrial and agricultural use. Worldwide, deltaic areas are under stress due to climate change, sea level increase and decrease in fresh water availability. In addition, in deltaic coastal areas around mean sea level, the saline groundwater will move toward the ground surface and exflitrate to surface water. This saline surface water will not be appropriate for drinking water production, agricultural and industrial use, and therefore, freshwater diverted from rivers is used for flushing the canals and ditches in coastal areas. Due to decreasing fresh water availability and increasing surface water salinization, current saline-fresh water management strategies have to be reviewed, and new sustainable strategies must be developed. Using real time measurements to see the effect of disturbances to the system and updating the control actions in real time will decrease the use of fresh water for flushing operations. Real time control of salinity in polders will result in more effective water management. Control of surface water salinization in a polder is a multi-objective problem such that water quality and quantity have to be considered. Moreover, the constraints of the system and uncertainties must be taken into account. Model Predictive Control (MPC) is a state-of-the-art control technique showing the best performance for these kind of problems. In this study, a MPC configuration for combined water quantity and quality control is discussed on a polder flushing case study for a hypothetical test water course/canal. The exfiltration of saline groundwater to the surface water is also considered and the predictions of saline groundwater exfiltration are used to achieve better control of the local water system.

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1. Introduction

More than 35% of the world's population live within 100 km of the coast [1], which is the result of easy access to transport connections and fish stocks, fertile inlands and mild relief [2]. Groundwater resources in these areas are the main source for domestic, industrial and agricultural use [3]. Due to growing populations, their food demands and economic development, human water consumption is expected to increase [4]. In coastal areas, this increase will cause over-exploitation of aquifers and salinization of extraction wells [5]. Moreover, the intrusion of sea water also increases due to sea level rise in coastal aquifers [6]. In addition to the increase in saline groundwater, in many deltas, the river discharges delivering freshwater to coastal areas will decrease due to changing precipitation patterns [7] and increased water demand for agriculture, both locally and upstream [8].

In low-lying deltaic areas such as; Mississippi delta in Louisiana (USA), the Ganges-Brahmaputra delta (Bangladesh), or the Rhine-Meuse delta (Netherlands), saline groundwater will increasingly move towards the ground surface and exflitrate to surface water [3]. Saline surface water will be less appropriate for agricultural and industrial use, as well as drinking water production. Meanwhile, freshwater diverted from rivers is used for flushing the canals and ditches in coastal areas, to be used for irrigation purposes. The flushing demands varies over time, while the quality is controlled by the salt load entering the system (flushing demands are high during wet periods and low during dry periods) [3].

In The Netherlands, the largest upward groundwater flows (referred to exfiltration of saline groundwater in this study) are found in deep polders [9]. Surface water flushing is one of the larger water users in Netherlands which accounts 15% of the total freshwater demand [3,10]. Freshwater from the rivers Rhine and Meuse are used for flushing of these polders during agricultural growing season [3]. However, decreasing freshwater availability [8] and expected increase of surface water salinization [11] are reasons to question the current water management practise [3].

1.1. Polders

Polders are low-lying and artificially drained areas that are surrounded by dikes. Many water courses or ditches are positioned in the low-lying area, all interconnected through hydraulic structures, such as weirs and sluices [12]. Polders are surrounded by receiving system of storage canals (boezem), which provide extra fresh water to polders during dry periods and provide space for surplus water from polders during wet periods. The polder system, which consists of several ditches, is connected to the storage canals by artificial hydraulic structures (pumps, weirs, sluices). Water levels in polders and surrounding storage canals are maintained within a given margin so that the groundwater levels in the polders are kept close to a target level, to avoid dike failures in storage canals and acceleration of land subsidence is prevented [13]. Salinity of polders is caused by exfiltration of saline groundwater [14]. Land subsidence, climate change and sea level rise accelerate salinization by enhancing the intrusion rate [15]. Saline water threatens the agricultural activities and freshwater ecosystem in a polder. Therefore, salinity control is necessary for both agricultural purposes and maintaining certain fresh water ecosystems [14].

1.2. Model Predictive Control

Model Predictive Control (MPC) is an optimization based control strategy which uses a process model to predict the future process outputs within a specified prediction horizon [16,17]. At each time step, an open loop optimal control sequence is calculated by solving an optimization problem. Only the first element of this sequence is applied to the system and the rest is discarded [18]. This optimization is repeated at every time step by considering most recent measurements. The straightforward implementation of constraints (constraints are directly included in the optimization of the control scheme) on input (for instance, maximum inflow capacity due to the upstream structure and control variables (for instance, maximum salt concentration in a ditch) is also an important feature of MPC, which makes it attractive in practice. In addition, delays (for instance, water and salt transport) and uncertainties (for instance, predictions, measurements) can be explicitly taken into account in MPC [19]. Due to its flexibility and ability, MPC is gaining popularity in multi-variable process control [20], such as operational water management [21–23].

Formulation of a standard MPC has been given in many sources in literature such as [20]. The generic formulation of MPC is formulated such that the control configuration will be a finite horizon, linear time-invariant MPC and the objective function will be configured as a quadratic programming (QP) problem. The objective function that will be solved over the prediction horizon *N*, can be defined as following:

$$
\begin{aligned}
&\min_{u} J = \sum_{i=1}^{\mathrm{N}} \left\{ x^T Q x + u^T R u \right\} \\
&s.t \\
&x_{\min} < x < x_{\max} \\
&u_{\min} < u < u_{u\max}
\end{aligned}
\tag{1}
$$

Where, Q and R are weighting matrices associated with the states, *x*, and inputs, *u*, of the system which penalizes the variables. The constraints can be handled as hard constraint (if violation is not permitted), or soft constraints (if violation is permitted) [24].

2. Salinity Control in Low Lying Polders

Salinity control of polders is a multi-objective problem with constraints (on structures and set points) and uncertainties (on measurements and models used) involved. Possibility of using real time measurements is a necessity for coping with the known/unknown disturbances. Moreover, [12] showed that using a MPC scheme for combined water quality and quality control is superior than using classical control schemes. Therefore, for real time control of salinity of polders, using a MPC scheme which is capable of involving the future predicted disturbances and fulfilling multi-objectives is selected in this study.

The relevant process for real time control of salinity and flushing for controller design are described in [14]. For flushing operations, those processes are water movement and the transfer of dissolved matter (salt in this case). Using this approach, [12] presented a Proportional Integral (PI) and a MPC scheme for real time control of water quantity and quality.

2.1. Internal Model

In order to design a control configuration for the water systems, the essential dynamics of the water system have to be modelled. For salinity control in polders the most important processes are the water movement, the transport of dissolved matter and exfiltration of saline groundwater. If water quality is also effected by the drainage of nutrients to the ditches, exfiltration of nutrients can also be considered. For water movement and transport of dissolved matter, De Saint-Venant equations and the advection-dispersion equations are used respectively [12]. For the exfiltration of saline groundwater, the Rapid Saline Groundwater Exfiltration Model (RSGEM) [3] is used. RSGEM is developed to simulate salinity dynamics of exfiltration groundwater to be used in operational water management of freshwater resources in coastal lowlands. For the sake of simplicity the equations are not given here but interested readers will find the detailed information about the models in [3,12]. The equations are linearized and used to construct discrete time-variant state space model as:

$$
\begin{aligned}
&x(\mathrm{k+1}) = A(\mathrm{k})x(\mathrm{k}) + B(\mathrm{k})u(\mathrm{k}) + B_d(\mathrm{k})d(\mathrm{k}) \\
&y(\mathrm{k}) = \mathrm{C}(\mathrm{k})x(\mathrm{k})
\end{aligned}
\tag{2}
$$

Where *x* is the state vector of the system, *u* is the controlled variable, *d* is the disturbance, *y* is the output of the system and *k* is the time step index. *A, B, B_d*, and C are the matrices associated with system states, control input, disturbance input and output respectively. The outputs of the model are present and future water levels, salt concentrations and discharges. The input can be the change of inflow/outflow (depending on the control configuration) and the disturbances contains all other known/estimated variables. The variables for this test case is discussed in the next section.

2.2. Test Case

As an illustration, the concept of the controller will be given for a hypothetical test canal (Fig. 1). The inflow to the canal is defined as flushing discharge, Q_{flush} [m^3/s], with a certain salt concentration, C_{flush} [g/m^3]. The outflow discharge Q_{out} [m^3/s] and salt concentration C_{out} [g/m^3] are predefined known parameters. The aim of the controller is to keep downstream water level, h_{out} [m], and outflow concentration, C_{out} , at certain set points h_{ref} [m] and C_{ref} [g/m^3].

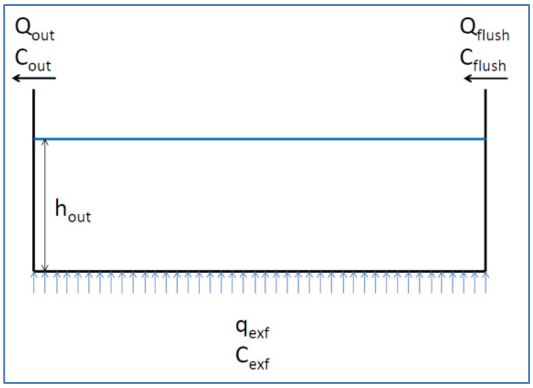

Fig. 1 Simple Canal Section

RSGEM is used to predict the exfiltrating groundwater salinity concentration C_{exf} [g/m^3], and exfiltration discharge q_{exf} [$m^3/s/m$]. In this test case, predicted exfiltration discharge, q_{exf}, and salinity concentration, C_{exf}, is used as a known disturbance to the system. The deviation from the set points of downstream water level and outflow concentration is controlled by manipulating the change of flushing discharge.

For the state space description given in equation 2: the state vector (x) contains the deviations of water level and outflow salt concentration from set points and flushing discharge; controlled variable (u) is the change of flushing discharge; disturbance vector (d) contains the outflow and exfiltration discharges.

3. Conclusion

Salinization of fresh water resources in low lying polders is an important problem in low-lying polders. Flushing the ditches and canals in the polders is necessary for keeping the salt concentration low such that the water is appropriate for different end users. In addition to the salt concentration, water levels in polders must be kept at a certain set point. With its multi objectives and constraints, salinity control in low lying polders by means of flushing operations could be managed by MPC. This study shows the possibility of applying a MPC scheme for salinity control. Necessary equations are given to model the system dynamics. For a hypothetical test canal, the state, input and disturbance variables are discussed and the control configuration is explained.

References

[1] Ioc/Unesco, Imo, Fao, Undp, A Blueprint for Ocean and Coastal Sustainability, Paris, 2011. doi:10.1007/s11999-013-3312-0.
[2] R.J. Nicholls, C. Small, Improved estimates of coastal population and exposure to hazards released, Eos (Washington. DC). 83 (2002) 301 – 305. doi:10.1029/2002EO000216.

[3] J.R. Delsman, Saline groundwater-Surface water interaction in coastal lowlands, IOS Press, Inc., Amsterdam, 2015. doi:10.3233/978-1-61499-518-0-i.

[4] Y. Wada, L.P.H. van Beek, N. Wanders, M.F.P. Bierkens, Human water consumption intensifies hydrological drought worldwide, Environ. Res. Lett. 8 (2013) 034036. doi:10.1088/1748-9326/8/3/034036.

[5] E. Custodio, Aquifer overexploitation: What does it mean?, Hydrogeol. J. 10 (2002) 254–277. doi:10.1007/s10040-002-0188-6.

[6] A.D. Werner, C.T. Simmons, Impact of sea-level rise on sea water intrusion in coastal aquifers, Ground Water. 47 (2009) 197–204. doi:10.1111/j.1745-6584.2008.00535.x.

[7] J. Schewe, J. Heinke, D. Gerten, I. Haddeland, N.W. Arnell, D.B. Clark, et al., Multimodel assessment of water scarcity under climate change., Proc. Natl. Acad. Sci. U. S. A. 111 (2014) 3245–50. doi:10.1073/pnas.1222460110.

[8] G. Forzieri, L. Feyen, R. Rojas, M. Flörke, F. Wimmer, a. Bianchi, Ensemble projections of future streamflow droughts in Europe, Hydrol. Earth Syst. Sci. 18 (2014) 85–108. doi:10.5194/hess-18-85-2014.

[9] P.G.B. De Louw, a. Vandenbohede, a. D. Werner, G.H.P. Oude Essink, Natural saltwater upconing by preferential groundwater discharge through boils, J. Hydrol. 490 (2013) 74–87. doi:10.1016/j.jhydrol.2013.03.025.

[10] F. Klijn, E. Van Velsen, J. Ter Maat, J.C. Hunink, Zoetwatervoorziening in Nederland [in Dutch], (2012).

[11] G.H.P. Oude Essink, E.S. Van Baaren, P.G.B. De Louw, Effects of climate change on coastal groundwater systems: A modeling study in the Netherlands, Water Resour. Res. 46 (2010) 1–16. doi:10.1029/2009WR008719.

[12] M. Xu, P.J. Van Overloop, N.C. Van De Giesen, G.S. Stelling, Real-time control of combined surface water quantity and quality: Polder flushing, Water Sci. Technol. 61 (2010) 869–878. doi:10.2166/wst.2010.847.

[13] A.H. Lobbrecht, M.D. Sinke, S.B. Bouma, Dynamic control of the Delfland Polders and storage basin, The Netherlands, in: Water Sci. Technol., 1999: pp. 269–279. doi:10.1016/S0273-1223(99)00074-8.

[14] A. Hof, W. Schuurmans, Water quality control in open channels, Water Sci. Technol. 42- 153-159. (2000) 153–159.

[15] G.H.P. Oude Essink, Impacts of Climate Change on the Coastal Groundwater Systems in The Netherlands, in: 20th Salt Water Intrusion Meet., Naples, Florida, USA, 2008: pp. 178–181.

[16] C. Camacho, E. F.; Bordons, Model Predictive Control, 2nd ed., Springer, London, 2007. doi:10.1007/978-0-85729-398-5.

[17] M. Breckpot, O. Agudelo, Control of a single reach with model predictive control, River Flow 2012. (2012) 1021–1028. ftp://ftp.esat.kuleuven.ac.be/pub/pub/stadius/mbreckpo/papers/RiverFlow2012.pdf.

[18] U. Maeder, M. Morari, Offset-free reference tracking with model predictive control, Automatica. 46 (2010) 1469–1476. doi:10.1016/j.automatica.2010.05.023.

[19] J.M. Maciejowski, Predictive Control with Constraints, 2002. doi:10.1016/j.compag.2008.03.003.

[20] F. Borrelli, A. Bemporad, M. Morari, Predictive Control for linear and hybrid systems, (2014) 448. http://www.mpc.berkeley.edu/mpc-course-material.

[21] X. Tian, P.-J. van Overloop, R.R. Negenborn, N. van de Giesen, Operational flood control of a low-lying delta system using large time step Model Predictive Control, Adv. Water Resour. 75 (2014) 1–13. doi:10.1016/j.advwatres.2014.10.010.

[22]K. Horváth, E. Galvis, M.G. Valentín, J. Rodellar, New offset-free method for model predictive control of open channels, Control Eng. Pract. 41 (2015) 13–25. doi:10.1016/j.conengprac.2015.04.002.

[23] P.J. van Overloop, K. Horváth, B.E. Aydin, Model predictive control based on an integrator resonance model applied to an open water channel, Control Eng. Pract. 27 (2014) 54–60. doi:10.1016/j.conengprac.2014.03.001.

[24] P.J. van Overloop, S. Weijs, S. Dijkstra, Multiple Model Predictive Control on a drainage canal system, Control Eng. Pract. 16 (2008) 531–540. doi:10.1016/j.conengprac.2007.06.002.