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IFAC PapersOnLine 50-1 (2017) 3160–3164

Model Predictive Control of Salinity in a Polder Ditch Under High Saline Groundwater Exfiltration Conditions: A Test Case

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Abstract: Surface water salinization in deltaic areas due to saline groundwater exfiltration is an important issue. 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. The effects of climate change, sea level increase and fresh water availability increases the stress on deltaic areas resulting in questioning current fresh water management strategies. In this paper, a Model Predictive Control (MPC) scheme is developed and tested for combined salinity and water level control of a polder ditch. The MPC scheme is coupled with Rapid Saline Groundwater Exfiltration Model (RSGEM) developed for fast calculation of exfiltration flux and concentration in a low-lying polder. For the test case presented in this paper, real data from Lissertocht catchment in Netherlands is used for RSGEM to see the performance of the MPC scheme for a real scenario. With open space for further research, results presented on this paper show that MPC of salinity in polders is capable of dealing with saline groundwater exfiltration modeled by RSGEM.

Keywords: Modeling and identification of environmental systems, Real-time control of environmental systems, Hydroinformatics, Climate change impact and adaptation measures, Water quality and quantity management, Water prediction and control.

1. INTRODUCTION

Over 35 % of the world population is living within 100 km of the coastline (Ioc/Unesco et al., 2011) due to easy access to transport connections and fish stocks, fertile inlands and mild relief (Nicholls and Small, 2002). The main source for industrial, agricultural and drinking water use is groundwater resources in these areas (Delsman, 2015). Growing populations, will increase the human water consumption (Wada et al., 2013) and this increase will result in over-exploitation of aquifers and salinization of extraction wells (Custodio, 2002). Meanwhile, sea water intrusion in coastal aquifers due to sea level increase (Werner and Simmons, 2009), decrease of freshwater river discharges due to changing precipitation patterns (Schewe et al., 2014) and increased water demand for agriculture, both locally and upstream (Forzieri et al., 2014) increases the stress on low lying deltaic areas.

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 (Delsman, 2015). 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) (Delsman, 2015). 15 % of the total freshwater demand is used for surface water flushing in The Netherlands (Klijn et al., 2012). However, decreasing freshwater availability (Forzieri et al., 2014) and expected increase of surface water salinization (Oude Essink et al., 2010) results in questioning the current water management practise in The Netherlands.

In this paper, a Model Predictive Control (MPC) scheme for salinity control is developed for a test polder ditch with saline groundwater exfiltration. The MPC scheme is coupled with Rapid Saline Groundwater Exfiltration Model (RSGEM) (Delsman, 2015) to cope with the groundwater exfiltration disturbances. To create a realistic scenario, the controller is tested for consecutive 25 days (20/8/2010 – 13/9/2010) for real data from Lissertocht catchment a low-lying polder in Netherlands. Results presented in this paper shows that the MPC of salinity and water level in polders is effective and decreases the freshwater usage.

1.1 Polders

Polders are low-lying and artificially drained areas that are surrounded by dikes. The water courses or ditches in the polders are connected through hydraulic structures, such as weirs and sluices (Xu et al., 2010). Water levels in polders

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10.1016/j.ifacol.2017.08.335

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 (Lobbrecht et al., 1999). Salinity of polders is caused by exfiltration of saline groundwater (Hof and Schuurmans, 2000). Land subsidence, climate change and sea level rise accelerate salinization by enhancing the intrusion rate (Oude Essink, 2008). 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 (Hof and Schuurmans, 2000).

1.2 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 (Breckpot and Agudelo, 2012; Camacho, E. F.; Bordons, 2007). 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 (Maeder and Morari, 2010). This optimization is repeated at every time step by considering most recent measurements. The straightforward implementation of constraints on input and control variables is also an important feature of MPC, which makes it attractive in practice. In addition, delays and uncertainties can be explicitly taken into account in MPC (Maciejowski, 2002). MPC is gaining popularity in multi-variable process control (Borrelli et al., 2014), such as operational water management (Aydin et al., 2016; Horváth et al., 2015; Tian et al., 2014; van Overloop et al., 2014).

1.3 Rapid Saline Groundwater Exfiltration Model

RSGEM is a lumped water balance model used for determining the saline groundwater exfiltration discharges and salinity concentrations. The model aimed to include the saline groundwater exfiltration dynamics in coastal lowlands and suitable for densely drained polders where fresh rainwater overlies shallow saline groundwater (Delsman, 2015). Interested readers can refer to Delsman (2015) for detailed information about RSGEM which is not included here since it is not the focus of this paper.

2. CONTROLLER DESIGN

The MPC configuration used in this study controls the downstream water level h_{out} (m) and average salinity concentration C_{av} (g/m^3) in the ditch (Fig. 1). To achieve this goal, flushing discharge Q_{flush} (m^3/s) and outflow discharge Q_{out} (m^3/s) are manipulated.

2.1 Simulation Model

The control configuration aims to control the salinity and the water level in the ditch. The dynamics of the system are modelled using the De Saint-Venant (SV) equations for water movement and advection-dispersion (AD) equations for transport of dissolved matter. For the simulation model, these equations are discretized and linearized following (Stelling and Duinmeijer, 2003; Xu et al., 2010). The equations and discretization schemes are not given here for the sake of simplicity. Moreover, the saline groundwater exfiltration in the ditch is modelled with RSGEM (Delsman, 2015). The flow in the ditch is calculated by the linearized SV equations and this is used as the input of the linearized AD equations to simulate the solute transport in the ditch (Xu et al., 2010). The saline groundwater exfiltration flux and the concentration modelled by RSGEM are used by the SV and AD equations as lateral flow flux and concentration.

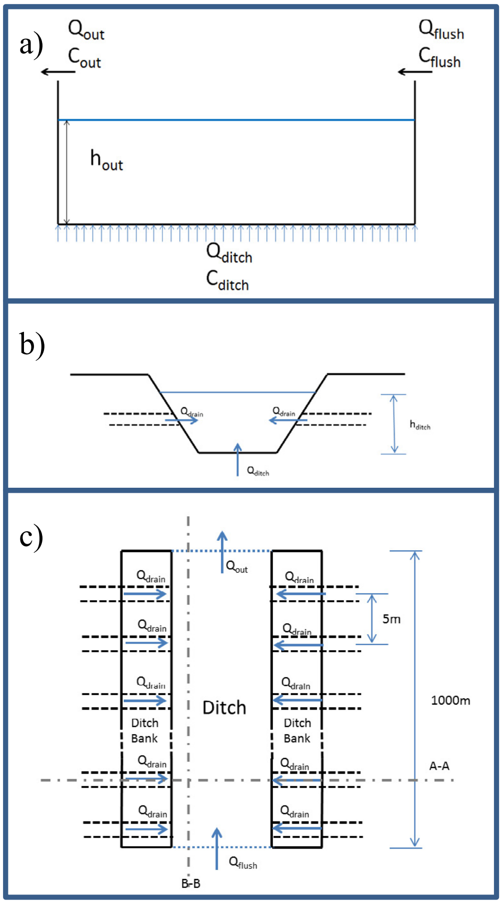

Fig. 1 a) Schematization of ditch (B-B) b) Cross section of the ditch (A-A) c) Plan view of the ditch (not to scale)

2.2. Internal Model and Objective Function

The linearized and discretized SV and AD equations discussed in the previous section are difficult to implement and computationally costly to be used as the internal model of the controller. In this study we used, Integrator Delay (ID) model (Schuurmans et al., 1995) for water transport and a lake model for non-mixed systems (Xu et al., 2010) for salinity control as the internal models of the controller. Since for each control time step of the prediction horizon the linearization is performed at different operating points, the resulting internal model is a discrete time-varying linear system. This system is represented by a discrete time-varying state space model as:

$$x(\mathrm{k}+1) = A(\mathrm{k})x(\mathrm{k}) + B(\mathrm{k})u(\mathrm{k}) + B_d(\mathrm{k})d(\mathrm{k}) \tag{1}$$

$$y(\mathrm{k}) = \mathrm{C}(\mathrm{k})x(\mathrm{k}) \tag{2}$$

Where x is the state vector of the system (Q_{flush}, Q_{out}, e_{h}, e_{c}), u is the controlled variable ($\Delta Q_{\mathrm{flush}}$, ΔQ_{out}, e^*) d is the disturbance which are estimated by RSGEM (Q_{ditch}, Q_{drain}), 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. e_{h} is the deviation of water level from set point, e_{c} is the deviation of average concentration from the set point, e^* is the virtual input as a soft constraint (van Overloop, 2006) to restrict e_{c} (Xu et al., 2010), $\Delta Q_{\mathrm{flush}}$ and ΔQ_{out} are the change of flushing and outflow discharges. The time variant parameters in this state space model are obtained through a forward estimation procedure detailed in Xu et al. (2010).

MPC solves an objective function J, as in (3) over the prediction horizon at each time step.

$$J = \min \sum_{i=1}^{N} \left\{ \begin{array}{l} W_{e_{\mathrm{h}}} \cdot e_{\mathrm{h}}(k)^2 + W_{e_c} \cdot (e_c(k) - e^*(k))^2 \\ + W_{\Delta Q} \cdot \Delta Q(k)^2 + W_{e^*} \cdot e^*(k)^2 \end{array} \right\} \tag{3}$$

$W_{e_{\mathrm{h}}}$, W_{e_c} , $W_{\Delta Q}$ and W_{e^*} are the penalties on e_{h}, e_{c}, ΔQ and e^* respectively. Penalties used in this study are determined by following (van Overloop, 2006; Xu et al., 2010) and are given in Table 1.

Table 1. Weights used in the objective function

i	e_{h}	e_{c}	ΔQ	e^*
$\mathrm{W_i}$	12.75	2.973	3.306	$10^{(-20)}$

3. TEST CASE DESCRIPTION AND SIMULATION

To test the controller, a test ditch (Fig. 1) is used with a length of 1000 m, drainage spacing of 5 m and both upstream and downstream structures are modelled as pumps. For the saline groundwater exfiltration, data from Lissertocht catchment is used. The parameters necessary for running RSGEM for the given case are taken from Delsman (2015). After running RSGEM for a longer period, due to the high daily variation of total exfiltration flux (Fig. 2) and average concentration of the total saline groundwater exfiltration (Fig. 3), 25 days between 20/8/2010 and 13/9/2010 is selected for a real scenario. For this period, total salt load entering the ditch can be seen in Fig. 4.

Assuming that the precipitation and evaporation data is available 18 hours ahead in time, RSGEM is used to calculate the saline groundwater exfiltration discharges and concentrations. Outputs of RSGEM are used as known disturbances to the MPC scheme described in this paper. 1 hour control time step is used to control the system for the objectives; keep the downstream water level, h_{out}, at set point of -0.4 m and keep the average concentration in the ditch, c_{av}, below 0.5 g/m^3.

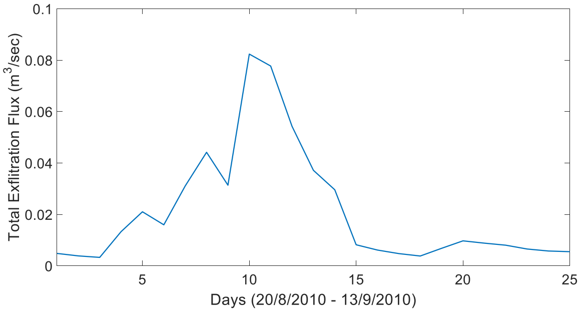

Fig. 2 Total groundwater exfiltration flux to the ditch

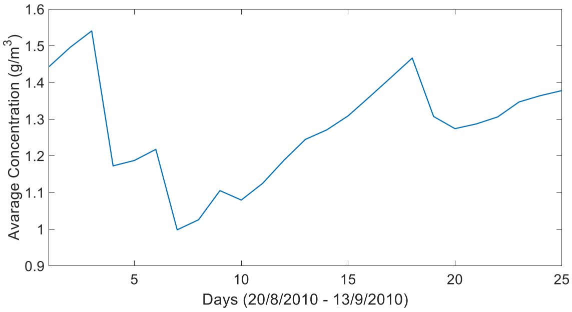

Fig. 3 Average concentration of the total saline groundwater exfiltration to the ditch

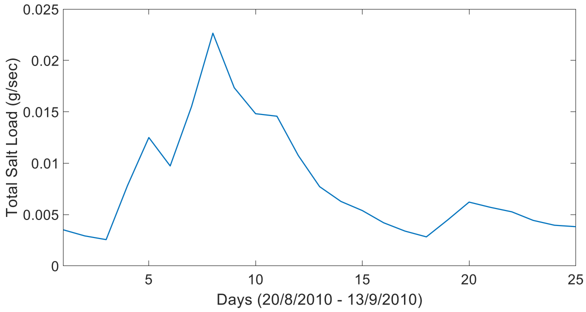

Fig. 4 Total salt load entering the ditch

4. RESULTS

The simulation results of the MPC scheme are given in Fig. 5, Fig. 6 and Fig. 7. Flushing (Q_{flush}) and outflow (Q_{out}) discharges are shown in Fig. 5. Due to the increased groundwater exfiltration flux (Fig. 2) after day 9, controller reacts this by decreasing the inflow to the ditch to keep the downstream water level (h_{out}) at set point (Fig. 6). Meanwhile, controller also reacts to the total salt load entering the ditch (Fig. 4) and keeps the average concentration in the ditch (C_{av}) below the set point (Fig. 7).

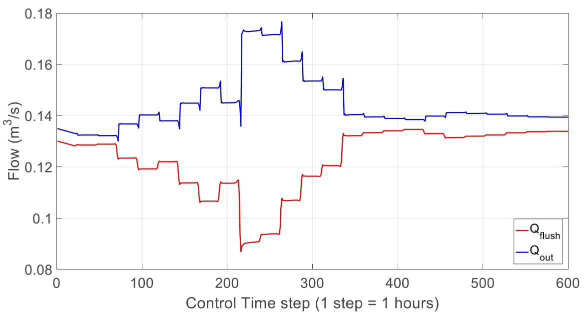

Fig. 5 Flushing and outflow discharges during the simulation

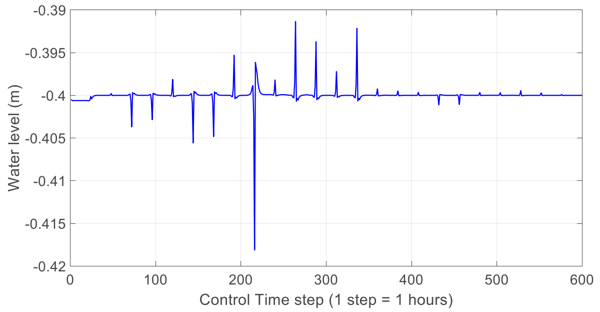

Fig. 6 Downstream water level (h_{out})

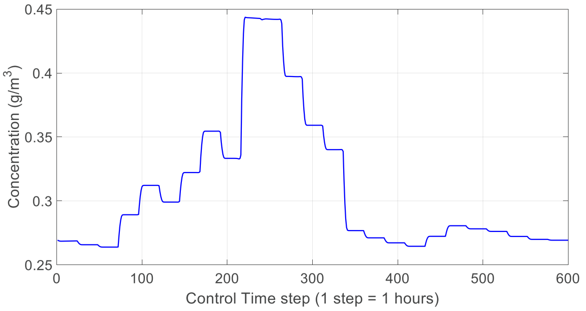

Fig. 7 Average concentration in the ditch (C_{av})

5. CONCLUSIONS

To the knowledge of the authors, this is the first study that couples an MPC scheme with a saline groundwater exfiltration model for salinity control of a polder ditch. Results achieved for a real scenario show that, MPC can be effectively used for salinity control of a polder ditch under saline groundwater exfiltration conditions. Increasing availability of cheaper and reliable sensors for electrical conductivity measurements will enable real-time salinity control using MPC schemes. Measuring the salinity and the water level, for example, at an intake point of a farmer for irrigation and controlling the water level and salinity at that point would be a practical application for an MPC scheme. To achieve this, a transition from an internal model for controlling average concentration to local concentration control is necessary. Moreover, updating the MPC scheme for minimizing the flushing discharge will further improve the performance of the MPC scheme presented here and improve the operational flexibility of the polders.

ACKNOWLEDGEMENT

This research is financed by the Netherlands Organisation for Scientific Research (NWO), which is partly funded by the Ministry of Economic Affairs, and co-financed by the Netherlands Ministry of Infrastructure and Environment and partners of the Dutch Water Nexus consortium.

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