Water quality control in open channels

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Abstract. With the increasing degree of automation in Dutch water management the need for control systems and design procedures for control systems is also evolving. Traditionally these control systems were used for water level and discharge control only. With the measurement equipment that is currently available, improved water quality control also becomes possible. A PhD researcher is currently investigating the theoretical implications. The design of a reliable control system using control theory requires a linear description of the relevant processes. A possible linear description of the relevant processes is presented in this paper.

Keywords. Water quality control; control theory; linear process description

Introduction

The salinity of polders, in the lower parts of The Netherlands is caused by upward seepage of saline groundwater. Nothing can be done to prevent this seepage and the seepage will even increase in the future due to sea level rise and declination of the land. The only way to control the salinity in the polder is by flushing the water system. Salinity control is necessary for agricultural purposes and also for maintaining certain fresh water ecosystems. If chloride concentrations are too high the system is flushed by importing water with a "better" quality from outside the area. Most of the time this is done by importing water of good quality on one side of the system. On the other side of the water system the surplus and saline water is discharged by gravity or pumping stations. Internal structures within the channel system can divide the flushing water throughout the area. Flushing is mostly based on individual knowledge of the operator. Some recent studies (e.g. Lobbrecht 1997) showed that reductions of up to 70% in the amount of flushing water could be achieved if the system could be flushed in the most optimal way. Reducing the amount of flushing water saves energy costs and minimizes adverse effects like the inflow of undesired substances.

Figure 1 shows the layout of a typical Dutch water system. Pumping stations of polder systems charge the boezem with their surplus saline water. The boezem has a function of...
temporary storage of surplus water from polders and also takes care of the transport of surplus water to the sea. In dry periods the boezem supplies water to the polders for irrigation and polder water salinity control. Salinity levels in the boezem thus need to be controlled. One way to control the salinity in the boezem could be by controlling the loads into the boezem. But, especially in the summer time, when there will be hardly any flow in the boezem, it is very likely that all loads from the polders should be reduced to in order to maintain good water quality in the boezem. This, however, leads to unacceptable situations in the underlying polders as these will end up with a surplus of saline water. This might lead to high water levels in the polders but surely the saline water will endanger agricultural activities and fresh water ecosystems in the polder. The most practicable solution is to flush the boezem with fresh water. This fresh water usually originates from the Rhine River.

Control principles
Overview
With the introduction of electronic logic a new, wide range of possibilities arose for water management. The possibilities with this equipment are almost unlimited and within Dutch water management they have been increasingly applied in recent years. A trend that can be found at most of the water districts in The Netherlands is a first stage of automation that is meant for monitoring purposes. Most water boards started with the set up of a telemetry system to monitor water levels and flow rates in their water system. Nowadays the possibilities of determining water quality aspects have increased. Electronic devices can monitor more and more aspects of the water quality. There is a tendency to extend the automated monitoring system with water quality measurements such as electric conductivity (salinity), oxygen levels and phosphate levels. Very often the next step is the automation of structures. Structures are attached to the telemetry system, which offers the opportunity to operate the structures from a distance. The final phase in this automation process is to implement control logic. This control logic should determine control actions based on measurements from the monitoring system and subsequently send these actions to the structures via the telemetry system. In principle a system can be controlled using two main techniques i.e. feedback control and feedforward control.

Feedback control
Feedback control is based on measuring actual system variables and comparing them to the desired ones. Based on the difference between the actual value and the desired one, a control algorithm generates a signal to adjust the systems input(s). In the case of water quality control the actual chloride concentration might be measured and compared to the desired one. Based on this comparison a controller can adjust the inflow at an inlet structure. In control engineering quite a few control algorithms for feedback control have been developed for a wide range of applications. These algorithms vary from a simple local proportional controller to a more (centralized) linear quadratic optimal controller or even more complex controllers.

Feedforward control
Disturbances in a water system, such as waste loads, can sometimes be predicted in advance or can be measured before entering the system. In those cases a feedforward control system can be applied to anticipate. Experiences with feedforward control on other systems showed very good performance and it is always worthwhile to implement a feedforward controller if possible. If a waste load occurs, corrective actions start immediately to minimize its effects. Feedforward control should preferably be combined with feedback control, as it is impossible to measure all disturbances and to know the system behavior perfectly.
Example

To illustrate the possibilities of the control principles, a simple case of water quality control in a canal was considered. The canal of this example consists of one single reach with a length of 1500 metres. A pumping station of an adjacent polder is situated in the middle of the canal. This pumping station charges the canal with 0.15 m³/s with a dissolved matter concentration of 700 g/m³. At a distance of 250 metres downstream of this pumping station an irrigation water turnout is situated and the concentration at that specific location should not exceed 200 g/m³. The canal can be flushed by means of the inlet structure at the upstream end of the canal. The dissolved matter concentration of the flushing water equals 150 g/m³. At time \( t=0 \) the flow rate in the canal equals 0.5 m³/s and the chloride concentration in the whole canal equals 150 g/m³. Figure 2 shows some simulation results at the turnout location. The following simulations were made: in the first test no controller (OL) was applied. In the second test a so-called proportional feedback controller (FB) was applied. The third test used a feedforward controller (FF). The example clearly shows that control techniques can be applied effectively to this type of water quality problem.

Experiences

So far there has been no experience with the application of these kinds of control systems in relation to water quality control as discussed in this paper. The tuning of such control systems is therefore based on trial and error. For a systematic design method for controllers, a suitable model of the (most) relevant processes is required. In the case of water quality there are among others the water movement and the transport of dissolved matter. To obtain simple reliable control systems, systematic design methods have been developed in linear control theory (e.g. Åström et al., 1984). These design methods require a model that consists of linear ordinary differential equations or linear difference equations. One way to obtain such a model is by approximating only the "essential" dynamics of the system that should be controlled. The following section will discuss the derivation of such a model.

Modeling

For flushing the most important processes are the water movement and the transport of dissolved matter. These processes are usually modeled by the St. Venant equations and the convection–diffusion equation, respectively (e.g. French, 1986; Booij, 1978). These equations are:

\[
T \frac{\partial H}{\partial t} + \frac{\partial Q}{\partial x} = 0
\]

\[
\frac{\partial Q}{\partial t} = -2\beta Q \frac{\partial Q}{A} + \beta Q^2 \frac{\partial A}{A^2} - \frac{|Q|Q^n}{AR^{3/2}} + gA \left( I - \frac{\partial H}{\partial x} \right)
\]

\[
\frac{\partial QC}{\partial x} + \frac{\partial AC}{\partial t} = \frac{\partial}{\partial x} \left( AK \frac{\partial C}{\partial x} \right) = P
\]
Here $T =$ width of water surface [m], $H =$ water level [m], $Q =$ flow rate [$m^3/s$], $A =$ cross-sectional area [$m^2$], $R =$ hydraulic radius [m], $I =$ bottom slope [--], $K =$ dispersion coefficient [$m^2/s$], $C =$ concentration of dissolved matter [$g/m^3$], $P =$ production of dissolved matter per unit length [$g/m \cdot s$], $\beta =$ Boussinesq coefficient, $x =$ horizontal distance, $g =$ gravitational acceleration and $t =$ time.

The first two equations are the Saint Venant equations that describe the water movement. The last one represents the convection–diffusion equation describing the transport of dissolved matter in water. It is noted that the production term can be left out when studying salinity problems. The set of equations consists of all nonlinear partial differential equations, which makes it hard to solve and analyze these equations analytically. If the equations are linearized around a working point, however, a solution can be found analytically. Linearization is a legitimate action as, for small deviation from the working point, the linearized equations are valid. After linearization, Laplace transformation and rewriting the following set of equations can be obtained:

$$\begin{align*}
\frac{\partial q}{\partial x} + T_0 sh_{(x,s)} & \\
\frac{\partial h}{\partial x} = \frac{\beta_0 - s}{(c_0^2 - V_0^2)} q_{(x,s)} + \frac{2V_0 T_0 s + \gamma_0 h_{(x,s)}}{(c_0^2 - V_0^2) T_0} & \\
\frac{\partial f}{\partial x} = -C_0 T_0 s h_{(x,s)} - A_0 sc_{(x,s)} & \\
\frac{\partial c}{\partial x} = -\frac{1}{A_0 K} f_{(x,s)}
\end{align*}$$

Here $T =$ width of water surface [m], $h =$ water level deviation from working point [m], $q =$ flow rate deviation from working point [$m^3/s$], $c =$ deviation in concentration of dissolved matter with respect to working point [$g/m^3$]. The subscript zero denotes the value at steady state or working point. The variable $f$ denotes the variation of flux due to dispersion, where flux is defined as the transport of dissolved matter. The variable $s$ is the Laplace operator. The final solution is shown in the block diagram of Figure 3.

Figure 3 Transport of dissolved matter in an open-channel
Mathematically the solution is given by:

\[
\begin{pmatrix}
q(x,s) \\
h(x,s) \\
f(x,s) \\
c(x,s)
\end{pmatrix} = c_1(s) \begin{pmatrix}
\frac{1}{-\alpha_1} & \frac{1}{-\alpha_2} & 0 & 0 \\
T_0 s & T_L s & 0 & 0 \\
0 & 0 & 1 & 1 \\
0 & 0 & 0 & 0
\end{pmatrix} \begin{pmatrix}
\alpha_1(s)x + c_2(s) \\
\alpha_2(s)x + c_3(s) \\
\frac{1}{A_0 K_2 \alpha_3} \\
\frac{1}{A_0 K_3 \alpha_4}
\end{pmatrix} + c_4(s) \begin{pmatrix}
0 \\
0 \\
1 \\
1
\end{pmatrix}
\]

with,

\[
c_1(s) = \frac{q(L,s) - e^{-\alpha_2 L} q(0,s)}{e^{\alpha_1 L} - e^{-\alpha_2 L}}; \quad c_2(s) = \frac{q(L,s) - e^{-\alpha_1 L} q(0,s)}{e^{\alpha_2 L} - e^{-\alpha_1 L}};
\]
\[
c_3(s) = \frac{f(L,s) - e^{-\alpha_1 L} f(0,s)}{e^{\alpha_2 L} - e^{-\alpha_1 L}}; \quad c_4(s) = \frac{f(L,s) - e^{-\alpha_2 L} f(0,s)}{e^{\alpha_2 L} - e^{-\alpha_2 L}}.
\]

Here \(q(0, s), q(L, s)\) denote the flow rates at the respective boundaries and \(f(0, s), f(L, s)\) denote the flux due to dispersion at the respective boundaries.

Analysis

The first thing that can be noted is that the shape of the solution is the same for both the water movement and the transport of dissolved matter. This may seem strange at first but sounds more plausible if we realize that the convection–diffusion equation is sometimes used as an approximation for describing the water movement (e.g. French, 1986). The results concerning the water movement part have been described in detail by Schuurmans (1995). The spreading of the dissolved matter over the reach is described by the terms \(e^{\alpha_1(s)x}\) and \(e^{\alpha_2(s)x}\). These are transcendental functions that are hard to analyze. Useful information, however, can be obtained by evaluating these terms for \(s \to 0\). The spreading of dissolved matter at \(s=0\) is given by:

\[
e^{\alpha_1(0)x} = 1; \quad e^{\alpha_2(0)x} = \frac{Q_0}{A_0 K_2} = e^{K_2 x}.
\]

This means that a change in the amount of dissolved matter will always reach the downstream end of a canal. A change in the amount of dissolved matter at the downstream end will dampen exponentially with the distance in the upstream direction. Most of the time this damping will be strong and it will be unlikely that the disturbance will reach the upstream end of the canal. Only for low flows and large dispersion coefficients will a disturbance reach the upstream end of the canal. In general, however, this will not be the case.

Substitution of \(\lim_{s \to 0} \alpha_3 = \frac{O}{AK}\) and \(\lim_{s \to 0} \alpha_4 = 0\) leads to: \(c(x) = a \cdot f(0) + b \cdot f(L)\)

With \(a\) and \(b\) defined by:

\[
a = \frac{1}{1 - e^{-\frac{QL}{AK}}} \left( \frac{1}{Q_0} - \frac{\frac{O}{AK}(L-x)}{2Q_0} \right) \quad b = \frac{1}{1 - e^{-\frac{QL}{AK}}} \left( \frac{\frac{O}{AK}(L-x)}{2Q_0} - \frac{O}{QL} \right)
\]

For \(x = 0\) and for \(x = L\) the following is found (assuming \(L \gg 1\)):

\[
c(0) = \frac{1}{Q_0} f^*(0, s); \quad c(L) = \frac{1}{Q_0} f^*(0, s)
\]

It was found that the concentration of dissolved matter is usually not affected by the downstream boundary. So the major dynamics are described by \(e^{\alpha_4x}\). The diffusive flux variation at location \(x\), as a function of a diffusive flux variation at \(x=0\) is described by:

\[
\frac{f(x,s)}{f(0,s)} = e^{\alpha_4(s)x}
\]
One way to obtain an approximate model is to assume a model structure and match terms in the power series expansion of the approximation to that of the “accurate” model. This method is known as moment matching (Davidson et al., 1988). Here we will use plug flow as the approximating model structure. Plug flow is a common approximation describing transport of dissolved matter (Tchobanoglous, 1985). It uses a pure delay time. The first two terms of the expansion of the plug flow model match those of \( \exp(\alpha_4(s)x) \) expanded about \( s=0 \). Therefore, the following model is suggested for control systems design:

\[
c(x,s) = \frac{1}{Q_0} e^{-\tau s} f(0,s)
\]

In case of flushing a water system, water of good quality is let into the system. By doing so a concentration gradient is introduced at \( s=0 \). This is a front between the water of good and bad quality. After a time \( \tau = (A/Q) \cdot x \) the front will have moved to a location \( x \) metres downstream.

The phenomenon of mixing when two flows come together is not incorporated in the model above (see also Figure 4). At location \( x \) two flows come together. When applying a 1-D approach both flows will mix instantaneously according to the following mass balance:

\[
Q_1 C_1 + Q_d C_d(t) = Q_{\text{tot}} C_{\text{ongoing}}(t) \quad \text{with} \quad C_1 = C_{\text{upstream}}(t-T) \quad \text{and} \quad Q_{\text{tot}} = Q_1 + Q_d
\]

It is now obvious that an increase of \( Q_1 \) at the upstream boundary will dilute the waste load resulting in lower concentrations downstream of the waste load. Based on this simple mass balance it is possible to define a transfer function that relates the concentration in the ongoing canal to an increase in flow rate at the upstream boundary.

\[
c_3 = \left( \frac{c_{1,e} - c_{3,e}}{Q_{\text{tot},e}} \right)
\]

In this case the delay time between the upstream boundary and the location \( x \) is not equal to the delay time of the transport of dissolved matter but to the delay time due to the water movement. Expressions for this delay time can be found in Schuurmans (1995). As these delay times are much smaller, mixing of flows should be considered an option when designing control systems for water quality as it will lead to faster responses.

Conclusion

Salinity in open channels is a problem in the lower part of The Netherlands. An example has shown that possibilities exist to control salinity by applying standard control techniques. The design of standard control systems requires a linear description of the relevant processes. A linear description was presented in this paper. Based on the knowledge presented in this paper the research can now continue with the design of control systems.
References


