Analysis of Hydraulic Delays in Cascade Reservoir Systems: A State-Space Control Approach

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***Abstract*— This work analyses the effect of hydraulic delays on water level regulation in cascade reservoir systems. A previously proposed state-space control strategy is extended by incorporating delay in the flow propagation between reservoirs. The delay is interpreted as an additional perturbation, and a bound on the tracking error is derived.**

Simulation results under different delay values and disturbance uncertainty show that the delay leads to performance degradation while preserving closed-loop stability.

I. Introduction

The operation of controlled water systems requires maintaining reservoir levels within predefined limits while coping with uncertain inflows. In applications such as flood mitigation and drainage management, deviations from the desired water levels may lead to severe operational and safety issues. As a result, the design of reliable control strategies for reservoir systems remains a relevant and challenging topic.

Numerous control strategies have been proposed in the literature for water level regulation in reservoir systems. An adaptive control approach is considered in [1]. Model predictive control (MPC) methods have also been widely applied, as in [2], [3], due to their ability to handle constraints in a systematic way. However, MPC approaches are typically computationally demanding and highly dependent on the accuracy of weather forecasts. Classical control approaches have also been explored, including proportional integral derivative (PID) controllers [4], [5]. Despite their simplicity, PID-based methods may lead to oscillatory behaviour and require careful tuning of the integral action, which can be time-consuming in practice.

In [6], a control strategy based on a state-space formulation was proposed for water level regulation in cascade reservoir systems. The approach combines a simple structure with low computational requirements, while allowing reference changes and adjustable convergence rates. The results obtained showed effective performance under disturbance uncertainty, making it a suitable candidate for real-time applications.

However, in practical implementations, the interaction between reservoirs is not instantaneous. The transport of water between upstream and downstream units introduces hydraulic delays, which depend on physical characteristics such as channel length and flow conditions. These delays may affect the closed-loop dynamics, particularly in cascade configurations, where downstream reservoirs rely on upstream actions.

The main objective of this work is to analyse the impact of hydraulic delays on the control strategy proposed in [6]. The delay is introduced in the flow propagation between reservoirs and interpreted as an additional perturbation acting on the downstream dynamics. Based on this formulation, a bound on the tracking error is derived, providing a quantitative measure of the effect of the delay.

The proposed analysis is supported by simulation studies under different operating conditions, including varying delay values and different levels of disturbance uncertainty. For clarity, the study is conducted on a two-reservoir cascade system, which captures the essential behaviour while allowing a straightforward interpretation of the results.

The remainder of the paper is organised as follows. Section 2 presents the system model, Section 3 describes the control strategy, Section 4 analyses the effect of hydraulic delays, and Section 5 presents the simulation results. Finally, conclusions are drawn in Section 6.

II. System Model

In this work, we consider a cascade system composed of two interconnected reservoirs. The water level of reservoir i at discrete time k is denoted by $h_i(k)$, for $i = 1, 2$, and is measured with respect to a reference datum.

The control input $Q_{c,i}(k)$ represents the pumping or discharge flow, while $Q_{d,i}(k)$ denotes the disturbance inflow associated with rainfall-runoff effects.

*This work is funded by national funds through the FCT – Foundation for Science and Technology, I.P., under the project "WaterPLAAN – Stop Water Pollution: Plan Agriculture Now", reference 2023.13840.PEX (https://doi.org/10.54499/2023.13840.PEX). This work was also supported by the FCT – Foundation for Science and Technology, I.P., through national funds within the scope of the R&D Unit Centre for Territory, Environment and Construction (CTAC), reference UID/4047/2025 (https://doi.org/10.54499/UID/04047/2025). The authors also acknowledge the support of the R&D Unit SYSTEC – Systems and Technologies Center (UID/00147) and the Associated Laboratory ARISE – Advanced Production and Intelligent Systems (ref. LA/P/0112/2020), funded by FCT/MECI through national funds.

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The system dynamics are obtained from a discretized mass balance equation and are given by

$$h_1(k+1) = h_1(k) - B_1 Q_{c,1}(k) + B_1 Q_{d,1}(k), \tag{1}$$

$$h_2(k+1) = h_2(k) + B_2 Q_{c,1}(k) - B_2 Q_{c,2}(k) + B_2 Q_{d,2}(k), \tag{2}$$

where

$$B_i = \frac{T_c}{A_{s,i}}, \quad i = 1, 2,$$

with $A_{s,i}$ denoting the storage area of reservoir i and T_c the sampling time.

This model assumes that the outflow from the upstream reservoir instantaneously affects the downstream reservoir.

For simplicity, the analysis in this paper is presented for a system with two reservoirs. The extension to larger cascade systems follows similar reasoning but is omitted for clarity.

III. Control Strategy

The control objective is to regulate the water levels of both reservoirs towards predefined reference values h_1^* and h_2^*.

The control strategy follows the approach proposed in [6].

In practice, the disturbance inflow $Q_{d,i}(k)$ is not exactly known. Therefore, an estimate $\widehat{Q}_{d,i}(k)$ is used in the control law.

The control inputs are defined as

$$Q_{c,1}(k) = \max\left\{0,\ \min\left(Q_{c,1}^{\max},\ \begin{matrix}\widehat{Q}_{d,1}(k) - \\ \dfrac{1-\alpha}{B_1}\left(h_1^* - h_1(k)\right)\end{matrix}\right)\right\}. \tag{3}$$

$$Q_{c,2}(k) = \max\left\{0,\ \min\left(Q_{c,2}^{\max},\ \begin{matrix}Q_{c,1}(k) + \widehat{Q}_{d,2}(k) - \\ \dfrac{1-\alpha}{B_2}\left(h_2^* - h_2(k)\right)\end{matrix}\right)\right\}. \tag{4}$$

The quantities $Q_{c,i}^{\max}$ denote the maximum admissible control flows, reflecting physical limitations of the actuators.

Assuming perfect disturbance estimation, i.e., $\widehat{Q}_{d,i}(k) = Q_{d,i}(k)$, it has been shown in [?] that the closed-loop system converges to the desired reference levels h_i^*, even in the presence of input constraints.

More precisely, the tracking error $e_i(k) = h_i(k) - h_i^*$ satisfies

$$e_i(k+1) = \alpha e_i(k), \quad i = 1, 2, \tag{5}$$

with $0 < \alpha < 1$, ensuring exponential convergence.

IV. Model Extension with Hydraulic Delay

In practical cascade reservoir systems, the flow propagation between consecutive reservoirs is not instantaneous. Therefore, the outflow from an upstream reservoir may affect the downstream reservoir only after a finite travel time.

A discrete-time delay $\tau \in \mathbb{N}$ is introduced in the hydraulic connection between the reservoirs.

A. Delayed Model

The dynamics of the first reservoir remain unchanged:

$$h_1(k+1) = h_1(k) - B_1 Q_{c,1}(k) + B_1 Q_{d,1}(k). \tag{6}$$

For the second reservoir, the upstream flow is delayed:

$$h_2(k+1) = h_2(k) + B_2 Q_{c,1}(k-\tau) - B_2 Q_{c,2}(k) + B_2 Q_{d,2}(k). \tag{7}$$

When $\tau = 0$, the original delay-free model is recovered.

B. Delay-Induced Perturbation

Let $h_2^0(k+1)$ denote the delay-free evolution:

$$h_2^0(k+1) = h_2(k) + B_2 Q_{c,1}(k) - B_2 Q_{c,2}(k) + B_2 Q_{d,2}(k). \tag{8}$$

The delayed model gives:

$$h_2^\tau(k+1) = h_2(k) + B_2 Q_{c,1}(k-\tau) - B_2 Q_{c,2}(k) + B_2 Q_{d,2}(k). \tag{9}$$

The difference induced by the delay is therefore

$$r_\tau(k) = h_2^\tau(k+1) - h_2^0(k+1) = B_2\left(Q_{c,1}(k-\tau) - Q_{c,1}(k)\right). \tag{10}$$

C. Bound on the Delay Effect

Assume that the variation of the upstream control input is bounded. That is, there exists a constant $\Delta Q > 0$ such that

$$|Q_{c,1}(j) - Q_{c,1}(j-1)| \le \Delta Q, \quad \forall j \in \mathbb{N}. \tag{11}$$

To analyse the effect of the delay, consider the difference between the current and delayed control input:

$$Q_{c,1}(k) - Q_{c,1}(k-\tau). \tag{12}$$

This difference can be expressed as a telescopic sum:

$$Q_{c,1}(k) - Q_{c,1}(k-\tau) = \sum_{m=0}^{\tau-1}\left[Q_{c,1}(k-m) - Q_{c,1}(k-m-1)\right]. \tag{13}$$

Taking absolute values and applying the triangle inequality yields

$$\begin{aligned} &|Q_{c,1}(k) - Q_{c,1}(k-\tau)| \\ &\le \sum_{m=0}^{\tau-1}\left|Q_{c,1}(k-m) - Q_{c,1}(k-m-1)\right|. \end{aligned} \tag{14}$$

Using the bounded variation assumption, each term in the sum is upper bounded by ΔQ. Since the sum contains τ terms, it follows that

$$|Q_{c,1}(k) - Q_{c,1}(k-\tau)| \le \tau \Delta Q. \tag{15}$$

Recalling that the delay-induced perturbation is given by

$$r_\tau(k) = B_2\left(Q_{c,1}(k-\tau) - Q_{c,1}(k)\right), \tag{16}$$

we obtain

$$|r_\tau(k)| \le B_2\tau\Delta Q. \tag{17}$$

Remark: This result shows that the effect of the hydraulic delay depends on both the delay length τ and the rate of variation of the control input. In particular, if the control signal evolves smoothly (i.e., small ΔQ), then the delay-induced perturbation remains small even for moderate values of τ.

D. Effect on the Tracking Error

Let the tracking error of the second reservoir be defined as

$$e_2(k) = h_2(k) - h_2^*. \tag{18}$$

In the delay-free case, the closed-loop dynamics satisfy

$$e_2(k+1) = \alpha e_2(k). \tag{19}$$

In the presence of hydraulic delay, the additional term $r_\tau(k)$ appears in the system dynamics. Therefore, the error evolves as

$$e_2(k+1) = \alpha e_2(k) + r_\tau(k), \tag{20}$$

which shows that the delay acts as an additive perturbation.

Using the bound obtained in the previous subsection, we have

$$|r_\tau(k)| \le B_2\tau\Delta Q, \tag{21}$$

and therefore

$$|e_2(k+1)| \le \alpha|e_2(k)| + B_2\tau\Delta Q. \tag{22}$$

By iterating this inequality, it follows that

$$|e_2(k)| \le \alpha^k|e_2(0)| + B_2\tau\Delta Q\sum_{j=0}^{k-1}\alpha^j. \tag{23}$$

Since $0 < \alpha < 1$, the geometric sum satisfies

$$\sum_{j=0}^{k-1}\alpha^j = \frac{1-\alpha^k}{1-\alpha}, \tag{24}$$

and therefore

$$|e_2(k)| \le \alpha^k|e_2(0)| + \frac{B_2\tau\Delta Q}{1-\alpha}(1-\alpha^k). \tag{25}$$

Consequently,

$$\limsup_{k\to\infty}|e_2(k)| \le \frac{B_2\tau\Delta Q}{1-\alpha}. \tag{26}$$

E. Discussion

The hydraulic delay introduces a bounded perturbation that depends on the delay τ and on the variation of the upstream control input.

As a consequence, exact asymptotic convergence is no longer guaranteed. However, the water levels remain within a neighbourhood of the desired reference value, whose size increases with the delay and with the control variability.

V. Simulation Results

In this section, several simulation scenarios are considered in order to assess the performance of the proposed control strategy under different operating conditions.

A cascade system composed of two reservoirs is analysed, subject to disturbance inflows associated with rainfall-runoff processes. The actual disturbance Q_d is obtained by adding Gaussian white noise to each component of $\widehat{Q}_d$, with zero mean and standard deviation $\sigma = 0.5$. This perturbation is introduced to emulate the uncertainty typically present in rainfall-runoff forecasts when the controller is applied in a predictive water management framework.

The reference water level for the first reservoir is set to $h_1^* = -0.40\,\mathrm{m}$ (MSL) during the first 5 hours, and is then changed to $h_1^* = -0.44\,\mathrm{m}$ (MSL). The reference for the second reservoir is kept constant at $h_2^* = -0.30\,\mathrm{m}$ (MSL).

The maximum admissible control flows are $Q_{c,1}^{\max} = 100\,\mathrm{m}^3/\mathrm{s}$ and $Q_{c,2}^{\max} = 70\,\mathrm{m}^3/\mathrm{s}$, while the minimum control flow is fixed at $0\,\mathrm{m}^3/\mathrm{s}$ for both reservoirs.

The storage areas are given by $A_{s,1} = 7.3\times10^6\,\mathrm{m}^2$ and $A_{s,2} = 7\times10^5\,\mathrm{m}^2$. The control sampling period is set to $T_c = 900\,\mathrm{s}$.

Once these parameters are fixed, the behaviour of the closed-loop system depends only on the tuning parameter $\alpha \in (0,1)$, which determines the convergence rate to the reference levels. In this work, $\alpha = 0.1$ is considered.

As a starting point, the performance of the proposed control strategy is evaluated in the delay-free case, i.e., $\tau = 0$. This scenario corresponds to the nominal conditions considered in the original formulation of the controller and is used as a reference for comparison with the delayed cases analysed later. The objective is to verify the ability of the controller to track the desired water levels in the presence of disturbance uncertainty.

The results for the delay-free case, shown in Figures 1 and 2, demonstrate that the proposed control strategy ensures accurate tracking of the desired reference levels for both reservoirs.

For Reservoir 1, the water level initially follows the reference $h_1^* = -0.40\,\mathrm{m}$. At $t = 5$ h, a change in the reference to $h_1^* = -0.44\,\mathrm{m}$ is introduced. The controller reacts immediately by increasing the control input $Q_{c,1}$, which reaches its maximum admissible value for a short period. This transient behaviour enables a rapid adjustment of the water level, leading to a fast convergence to the new reference with no significant steady-state deviation.

For Reservoir 2, the reference is kept constant at $h_2^* = -0.30\,\mathrm{m}$. The water level remains close to the desired value throughout the simulation, despite the presence of rainfall-runoff disturbances and the mismatch between the real disturbance Q_d and its estimate $\widehat{Q}_d$. The control input $Q_{c,2}$ adapts to both the disturbance inflow and the upstream dynamics, reflecting the cascade structure of the system.

Overall, the results confirm the expected closed-loop behaviour in the absence of delay, showing that the controller is able to compensate for disturbance uncertainty and ensure satisfactory tracking performance. This case provides a reference for assessing the impact of hydraulic delays in the following simulations.

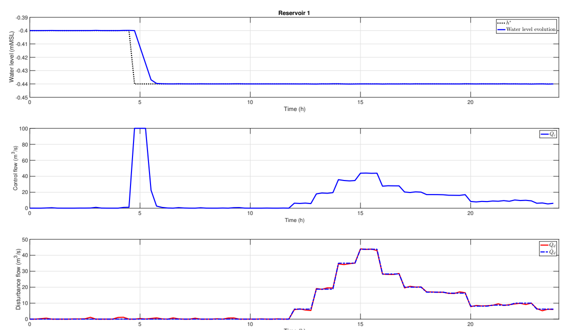

Fig. 1. Reservoir 1 response in the delay-free case ($\tau = 0$). Water level h_1, control input $Q_{c,1}$ and disturbance inflow.

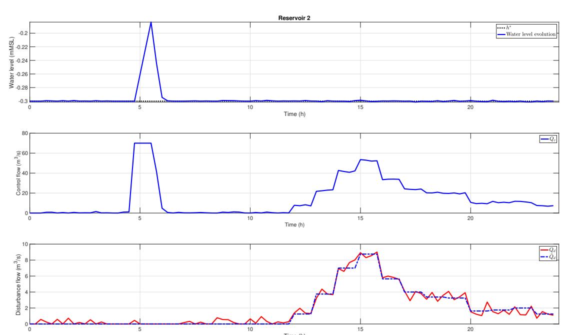

Fig. 2. Reservoir 2 response in the delay-free case ($\tau = 0$). Water level h_2, control input $Q_{c,2}$ and disturbance inflow.

The results obtained for $\tau = 1$ (see Figures 3 and 4) show the impact of a small hydraulic delay on the closed-loop performance.

For Reservoir 1, the behaviour remains essentially unchanged when compared with the delay-free case. Since the delay affects only the flow propagation between reservoirs, the dynamics of the upstream reservoir are not directly influenced. As a result, the water level follows the reference trajectory with similar transient characteristics, including the response to the reference change at $t = 5$ h.

For Reservoir 2, the effect of the delay becomes noticeable. The response of the water level to variations in the upstream control input is no longer immediate, leading to a slight deviation from the reference value during transient periods. This effect is particularly visible following the reference change in Reservoir 1 and during periods of increased disturbance inflow.

The control input $Q_{c,2}$ exhibits a delayed reaction to changes in $Q_{c,1}$, reflecting the propagation delay introduced in the system. Despite this, the controller is still able to regulate the water level and maintain it close to the desired reference.

Overall, the results illustrate that a small delay introduces a degradation in performance, mainly affecting the downstream reservoir, while preserving the overall stability and tracking capability of the closed-loop system.

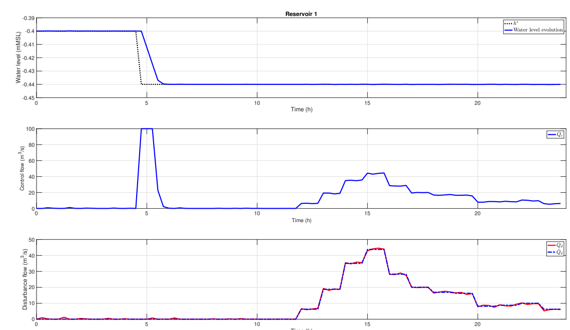

Fig. 3. Reservoir 1 response with hydraulic delay $\tau = 1$ and reference change at $t = 5$ h ($\alpha = 0.1$).

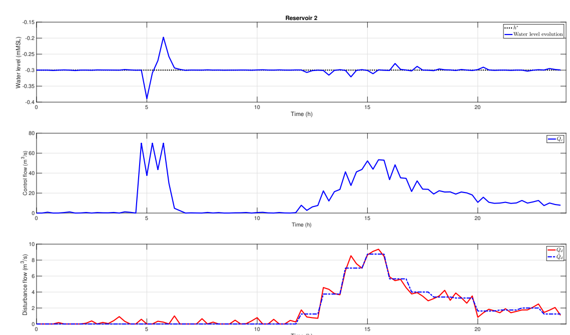

Fig. 4. Reservoir 2 response with hydraulic delay $\tau = 1$ and constant reference level ($\alpha = 0.1$).

The results obtained for different values of the hydraulic delay τ (see Figures 5, 6, and 7) illustrate the impact of the delay on the closed-loop behaviour of the system.

From the water level evolution, it can be observed that the dynamics of Reservoir 1 are not significantly affected by the delay. The response remains practically identical for all considered values of τ, as the delay is introduced only in the flow propagation towards the downstream reservoir. The water level follows the reference trajectory with similar transient behaviour, including the response to the reference change at $t = 5$ h.

In contrast, the behaviour of Reservoir 2 is clearly influenced by the delay. As τ increases, the response becomes slower and larger deviations from the reference are observed during transient periods. This effect is particularly noticeable following the reference change in Reservoir 1, where the delayed propagation of the control action leads to a lagged response in the downstream reservoir.

The control inputs reflect this behaviour. The control signal $Q_{c,1}$ remains essentially unchanged for all delay values, while $Q_{c,2}$ exhibits increasing variability as the delay grows. In particular, higher values of τ lead to more pronounced oscillations and delayed control actions, as the controller reacts to outdated information.

The disturbance profiles remain identical for all simulations, ensuring that the observed differences in performance are solely due to the effect of the hydraulic delay.

Overall, the results show that increasing the delay degrades the closed-loop performance in the downstream reservoir without compromising stability, while the upstream reservoir remains largely unaffected.

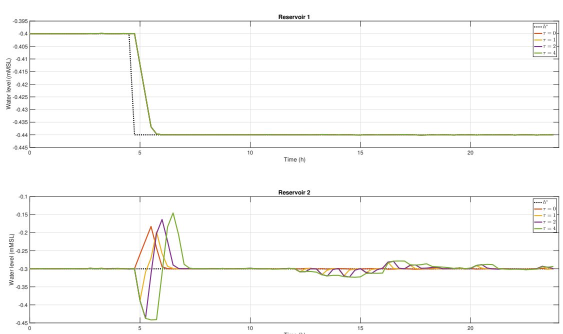

Fig. 5. Control of the water level of the reservoirs considering different values of the hydraulic delay $\tau \in \{0, 1, 2, 4\}$ and a change in the reference level during the control period ($h_1^* = -0.40$ m from the beginning until $t = 5$ hours, and $h_1^* = -0.44$ m from $t = 5$ hours onwards, while $h_2^* = -0.30$ m (MSL) is kept constant), for $\alpha = 0.1$. The evolution of the water levels h_1 and h_2 is illustrated in the top and bottom graphs, respectively. The dashed black line represents the desired reference values, while the coloured lines correspond to the different delay values.

The results obtained for $\tau = 4$ under increased disturbance uncertainty (Gaussian white noise with zero mean and standard deviation $\sigma = 10$) highlight the robustness of the proposed control strategy under more demanding operating conditions (see Figures 8 and 9).

For Reservoir 1, the overall behaviour remains similar

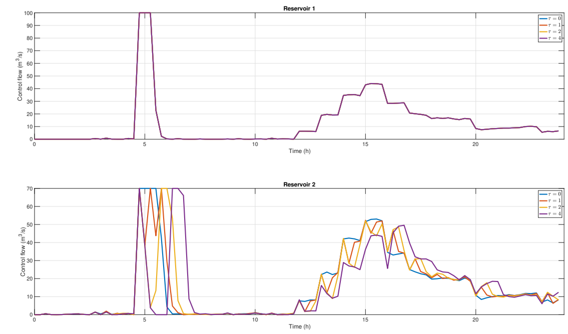

Fig. 6. Control inputs $Q_{c,1}$ and $Q_{c,2}$ for different values of the hydraulic delay $\tau \in \{0, 1, 2, 4\}$, for $\alpha = 0.1$. The control flow applied to Reservoir 1 is shown in the top graph, while the control flow applied to Reservoir 2 is shown in the bottom graph. The different coloured lines represent the control actions corresponding to each delay value.

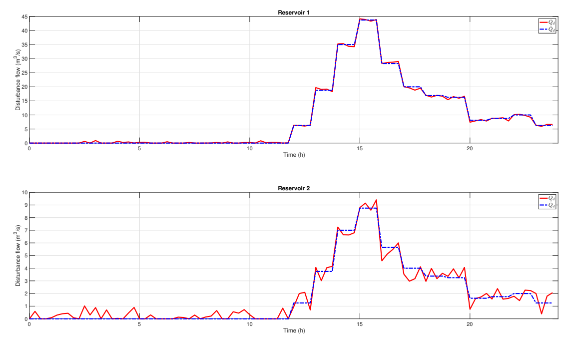

Fig. 7. Rainfall-runoff disturbance inflows for the two reservoirs. The disturbance inflow $Q_{d,1}$ and its estimate $\widehat{Q}_{d,1}$ are shown in the top graph for Reservoir 1, while $Q_{d,2}$ and $\widehat{Q}_{d,2}$ are shown in the bottom graph for Reservoir 2. The real disturbance is represented by the solid red line, whereas the estimated disturbance is represented by the dashed blue line.

to the previous cases. The water level follows the reference trajectory and responds to the reference change at $t = 5$ h, although small fluctuations around the reference are now visible due to the increased disturbance uncertainty. The control input $Q_{c,1}$ reflects this behaviour, exhibiting higher variability as it compensates for the noisy disturbance signal.

For Reservoir 2, the combined effect of the hydraulic delay and the increased disturbance uncertainty becomes more pronounced. The water level shows larger deviations from the reference and increased oscillatory behaviour, particularly during periods of higher disturbance inflow. The delayed propagation of the upstream control action, together with the inaccurate disturbance estimation, leads to a more irregular response.

The control input $Q_{c,2}$ also exhibits significant variability, with more frequent and abrupt changes when compared to the previous scenarios. This reflects the increased difficulty in regulating the downstream reservoir under both delayed information and high disturbance uncertainty.

Overall, these results show that the performance degradation observed for larger delays is further amplified when the disturbance estimation becomes less accurate. Nevertheless, the system remains stable and the controller is able to maintain the water levels within a bounded region around the desired reference values.

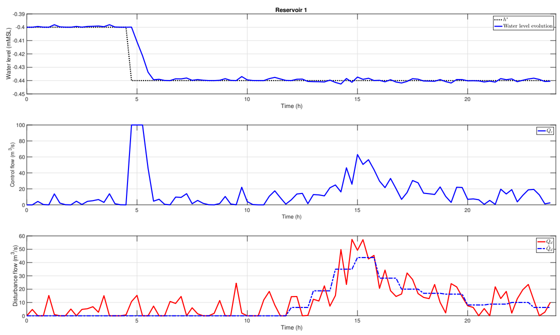

Fig. 8. Control of the water level of Reservoir 1 assuming a hydraulic delay $\tau = 4$ and a change in the reference level during the control period ($h_1^* = -0.40\,\mathrm{m}$ from the beginning until $t = 5$ hours, and $h_1^* = -0.44\,\mathrm{m}$ from $t = 5$ hours onwards), for $\alpha = 0.1$. The evolution of the water level is illustrated in the top graph, where the dashed black line corresponds to the desired reference value. The pump control flow $Q_{c,1}$ is represented in the second graph. In the bottom graph, the rainfall-runoff inflow $Q_{d,1}$ is shown in solid red line, while the estimated disturbance $\widehat{Q}_{d,1}$ is shown in dashed blue line. The disturbance is affected by increased Gaussian white noise with standard deviation $\sigma = 10$.

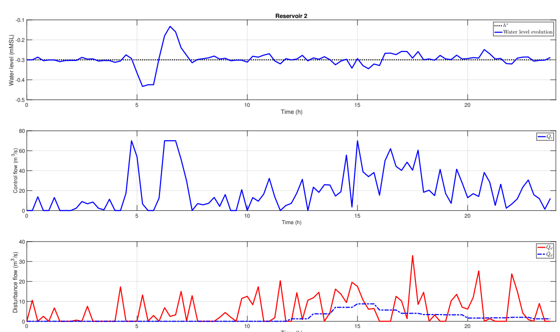

Fig. 9. Control of the water level of Reservoir 2 assuming a hydraulic delay $\tau = 4$ and a constant reference level $h_2^* = -0.30\,\mathrm{m}$ (MSL), for $\alpha = 0.1$. The evolution of the water level is illustrated in the top graph, where the dashed black line corresponds to the desired reference value. The pump control flow $Q_{c,2}$ is represented in the second graph. In the bottom graph, the rainfall-runoff inflow $Q_{d,2}$ is shown in solid red line, while the estimated disturbance $\widehat{Q}_{d,2}$ is shown in dashed blue line. The disturbance is affected by increased Gaussian white noise with standard deviation $\sigma = 10$.

VI. Conclusion

In this work, the effect of hydraulic delays in a cascade system of reservoirs was analysed within a state-space control framework. For simplicity, the study focused on a two-reservoir configuration, which allows a clear interpretation of the delay impact while preserving the essential dynamics of the system.

A delayed model was introduced to account for the transport time between reservoirs, and its effect was characterised as an additive perturbation in the closed-loop dynamics. A bound on the induced error was derived, showing that the deviation from the desired reference depends on both the delay magnitude and the variation of the control input.

The simulation results confirm the theoretical analysis. In the absence of delay, the controller ensures accurate tracking of the reference levels despite disturbance uncertainty. When a delay is introduced, the performance degradation becomes evident, particularly in the downstream reservoir, while the upstream reservoir remains largely unaffected. Increasing delay values lead to slower responses and larger deviations from the reference, although stability is preserved. Additional simulations with increased disturbance uncertainty illustrate the behaviour of the closed-loop system under more demanding conditions, showing that the system remains stable and the water levels are kept within a bounded region around the desired references.

Overall, the proposed approach provides a simple and effective way to analyse and handle hydraulic delays in cascade reservoir systems. Future work will focus on extending the methodology to larger networks and on improving the compensation of delay effects under limited disturbance information.

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