



# Seasonally Adjustable Reservoir Modeling Algorithm

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**ABSTRACT:** The article presents the work on the development of an algorithm for modeling hydraulic structures in the construction of a remote-control system under conditions of data uncertainty. In this case, a mathematical model of hydraulic structures using modern software systems is developed based on the experience of designing and optimizing such structures as an individual structure. The proposed mathematical model and algorithms were tested for adequacy to the object.

## I. INTRODUCTION

In the development strategy for the further development of the Republic of Uzbekistan in 2022-2026, "fundamental reform of the water resources management system and water economy, reduction of electricity consumption in water management facilities, the introduction of energy-saving technologies in production, information and communication in the economy, social sphere, management system tasks are defined in connection with the introduction of technologies. In order to implement these tasks, new intelligent systems that remotely control the technological parameters of water reservoirs must be developed in conditions where the information is unclear.

Water resources systems, water storage, flows, and outflows can also be expressed using vague quantities due to their uncertain and varying classifications. The level and consumption of water in reservoirs change, as does the demand for water in the cultivation of various types of crops. This dynamic situation underscores the urgent and critical need for the efficient use of water in hydraulic engineering facilities without allowing excessive wastage, even in conditions where the information is not clear.

Therefore, it is crucial to consider and implement methods of regularizing the state of dynamic systems in hydraulic engineering facilities and to create methods and algorithms for solving unclear issues. This need to regularize dynamic systems is a crucial aspect of our proposal.

It is known that a high-precision mathematical model is necessary to create a high-quality control system. However, obtaining a mathematical model of any process has significant limitations. In many cases, the obtained models are linear, which creates some inaccuracies in the model. This complexity underscores the challenges we face in developing our proposed system.

In this regard, this feature also exists for hydro-technical structures; the resulting uncertainties are as follows:

- models of reservoir structures need to be clarified.
- uncertainty of water level and consumption.
- sensor errors.
- errors in the management process.
- due to using microcontrollers, errors that occur due to quantization, etc.

Several foreign scientists have researched the management of hydrotechnical facilities. In [34], research was carried out on managing hydrotechnical structures in dams. The control is carried out by cable from the operator point, and the control signal is sent in analog form. Their disadvantage is that excessive costs occur when data is transmitted via cable.

In [1], the SCADA system was used to control hydro-technical facilities. The system achieves data collection, processing, analysis, and facility management. SCADA is an open system, which means that the software system is open, and the interface allows external communication if data is passed to it in the required format. This link depends on the component it is designed for. Its primary disadvantage is that this system is expensive, and a system with hydraulic structures cannot pay for itself in a year or two.

[2] worked on automatic control of hydraulic valves. The proposed method is optimal, convenient, and effective. Its disadvantage is that it needs to focus on the cryptographic security of the transmitted data.



In the study in [3], a large-scale encryption key algorithm for remote control systems was developed. The main drawback is that it cannot be used in large objects due to SMS encryption's small memory and mobile phones' low performance.

In [4], a control system for hydraulic structures, particularly dams in channels, is proposed. The main drawback is that feedback on the state of the dam based on the transmitted data is needed.

[5] also developed a system for decoding hydraulic engineering in shoots, which used nonsymmetric encryption to encrypt short messages to decode objects. Because this system deploys elliptic curves and a symmetric encryption algorithm, it has excellent computational advantages over the previously proposed public key solution while providing as many security services as possible. The main disadvantage of this system is that data processing is prolonged, which causes excessive waste in hydrotechnical facilities.

A system of automatic control of water reservoirs was developed in [6]; the authors should have considered water consumption and level changes in the lower and upper reservoirs in their work.

[7] proposes a wireless water level monitoring system that uses an ultrasonic remote sensing system. At this time, the stations connected to the base station could operate in the base station, and the blocks of the allocation interface were removed. Mechanical detailing is an advantage of this system. The disadvantage is that the water level control is carried out slowly, and cryptography issues for remote control have yet to be developed.

[8] proposed using microcontrollers for automatic water control in a dam. In this work, the DSPIC30F4011 microcontroller-based terminal (MAT) installed at a distance is mainly designed for accurate measurements, storage, and transmitting equipment output to the computer server (CS).

[9] used a GSM system for water level monitoring in a reservoir. The valve control mechanism in the dam is implemented using manual and computer systems (CT). However, both the manual and CT-based control methods were prone to errors. The developed system is extensive and complex, suitable for large dams. Large systems like CT are optional for medium and small dams.

In [10], fuzzy clustering and standard data analysis are presented for controlling non-linear systems. Under certain conditions, these methods are better than general computation and functional decomposition methods.

In [11], the use of the GSM system for remote monitoring of the effect of water on the reservoir dam through piezometric sensors in the effective use of hydro-technical facilities is proposed. This method is effective for dams mainly made of local soils but only sometimes practical for dams made of special concrete.

A system for automatic shutter control in channels was developed in [12]. The system uses the method of synthesizing non-linear systems with a delay, which is considered somewhat more effective in controlling shutters than other methods under certain conditions.

In [13], a system for remote control of objects in pumping stations is proposed. Data transmission in the system uses open-key algorithms, including the elliptic curve cryptography method.

Based on the information presented in [14], the issue of synthesizing the system based on the use of the prediction method in control while observing the object's output, taking into account the delay time for the control of the object, was considered. In solving the control problem, the restrictions on the control and condition of the object based on the model built with the help of the prediction method are considered.

[15] used a GSM module to measure and control the velocity of flows in the upper and lower reaches. This system transmits the flow rate measured by measuring devices, i.e., sensors, to the operator via GSM.

In [16], the problem of reference model control in controlling hydraulic power lines was solved. Variables and auxiliary contour trackers were used in this work.

In [17], attention is paid to eliminating the delays in the entry of the object to a certain extent in controlling the hydraulic valves and stabilizing the non-precision parametric fuzzy systems.

[18] proposed using a GSM module to remote control the amount of electricity consumed at pumping stations. This system is more convenient and effective than the previous ones.

[19] Also, fuzzy logic was used to measure and control the pressures in the reservoir dam. In this system, the author considered the pressure difference in the dam based on low, medium, and high ratios. Genetic algorithms and an adaptive neuro-fuzzy inference system were used in the optimization.

In [20], the identification problem in automatic shutter control was considered. To solve this problem, the method of moments was used, and the parameters of the object transfer function were determined.

## **II. MATERIALS AND METHODS**

The hydraulic structure is unique from the point of view of the relief of the land where the hydraulic complex is located, the calculated load, and construction. The individual construction of the mathematical model of hydraulic structures using modern software systems is based on the experience of designing and optimizing such structures.

The dynamics of the water level in the reservoir over time can be described by the difference equation in the following form:

$$x(k+1) = f(x(k), u(k), \theta, k) + g(\theta, x(k))w(k), \quad x(k_0) = x_0, \quad (1)$$

where  $x(k) \in R^2$  – vector position, ( $x_1(k)$  – the volume of water in the reservoir,  $x_2(k)$  – the water level in the reservoir);  $u(k) \in R^3$  – control effect vector ( $u_1(k)$  – consumption of water input to the reservoir;  $u_2(k)$  – the amount of water output from the reservoir;  $u_3(k)$  – the amount of water consumption);  $\theta \in R^s$  – unknown vector of parameters;  $x_0$  – of time  $k_0$  the initial volume of the reservoir at the instant of time;  $f$  and  $g$  – some functions;  $w(k)$  – the average value and is a sequence of Gaussian random variables with zero mean and covariance

$$E\{w(k)w^T(j)\} = Q(k)\delta_{kj}.$$

The initial state  $x_0$  – the average  $\bar{x}_0$  and covariance  $P_0$  random variable with mean and covariance.

The optimization of the operating modes of the reservoir consists of selecting such control impacts on the water intake structure that ensure the implementation of the water supply schedule while minimizing water losses due to evaporation and filtration from the reservoir surface [21].

The control functions during the reservoir filling process include the inflow of water  $u_1(t)$ , its outflow  $\eta(k)$ , and water consumption during the operation of the reservoir  $u_3(t)$ .

Constraints on the state of the object:

$$H_{\min} \leq h(t) \leq H_{\max},$$

$$dh(t)/dt \leq U_{kp},$$

appear as follows, where  $h(t)$  is the water level in the reservoir;  $H_{\min}$ ,  $H_{\max}$  are respectively, the minimum and maximum values of the free water surface ordinate in the reservoir;  $V_{\text{crit}}$  is the critical value of the reservoir's filling and operation speed.

Due to the nonlinearity of the differential equation (1) and the complexity of the various changes in the operating modes of water intake and hydraulic structures during the water resource management process, exact analytical solutions to these equations do not exist. Therefore, approximate solution methods based on numerical techniques are used [22].

(1) To linearize equation, we use the extended Kalman filter [23], which results in the following:

$$x(k+1) = A(\theta, k)x(k) + B(\theta, k)u(k) + G(k)w(k) \quad (2)$$

$$y(k) = C(\theta, k)x(k) + \eta(k)$$

Here,  $A(\theta, k)$ ,  $B(\theta, k)$ , and  $C(\theta, k)$  are linear functions of the unknown parameter vector  $\theta$ , which has a dimension of  $s$ , and  $\eta(k)$  is a sequence of Gaussian random variables with a mean value and covariance equal to zero.

$$E\{\eta(k)\eta^T(j)\} = R(k)\delta_{kj}$$

We assume that the parameters change over time as correlated random variables.

$$\theta(k+1) = F(k)\theta(k) + \xi(k), \quad \theta(0) = \theta_0$$

Here, the known matrix  $F(k)$  reflects the interdependence of the parameter sequence,  $\xi(k)$  is a random vector representing the independent variations in the parameter sequence, and  $\theta_0$  is a random vector that expresses the initial uncertainty of the parameters [24].

If we assume that  $w(k)$  and  $\xi(k)$  are uncorrelated Gaussian random variables with a mean of zero and positive definite covariances  $Q(k)$  and  $R(k)$ , respectively, then equation (2) can be rewritten as a function of the parameters.

$$x(k+1) = A(k, \theta)x(k) + B(k, \theta)u(k) + G(k)w(k) = D(k)u(k) + G(k)w(k) \quad (3)$$

Here,  $D(k)$  is a function consisting of  $x(k)$  and  $u(k)$  [25]. Given  $X^k$ , if we assume that the estimate of  $k$  at time  $\theta$  is  $\hat{\theta}(k/k)$ , then standard estimation procedures can be applied to obtain one-step estimates of  $x$  and  $\theta$ , along with the covariances of their associated Gaussian random variables [26]:

$$\hat{x}(k+1/k) = \hat{A}(k/k, \hat{\theta})x(k) + \hat{B}(k/k, \hat{\theta})u(k)$$

$$\hat{\theta}(k+1/k) = \hat{F}(k)\hat{\theta}(k/k)$$

$$P(k+1/k) = D^T(k)\Gamma(k/k)D(k) + G(k)Q(k)G^T(k)$$

$$\Gamma(k+1/k) = F(k)\Gamma(k/k)F^T(k) + K(k)$$

Here:

$$\hat{A}(k/k, \hat{\theta}) = A(k, \theta)|_{\theta=\hat{\theta}(k)}, \quad \hat{B}(k/k, \hat{\theta}) = B(k, \theta)|_{\theta=\hat{\theta}(k)},$$

$$x(k+1) - \hat{x}(k+1/k) = D(k)[\theta(k) - \hat{\theta}(k)] + G(k)w(k).$$

The recursive parameter estimation and error covariance  $\Gamma(k+1/k+1)$  are determined by the following expressions [27]:

$$\hat{\theta}(k+1/k+1) = \hat{\theta}(k+1/k) + K(k+1)P^{-1}(k+1/k)[x(k+1) - \hat{x}(k+1/k)]$$

$$K(k+1) = F(k)\Gamma(k/k)D^T(k)$$

$$\Gamma(k+1/k+1) = \Gamma(k+1/k) - K(k+1)P^{-1}(k+1/k)K^T(k+1)$$

Now, to minimize the average value of the quality criterion, we can express the management algorithm using the method of synthesizing an optimal system [28] in the following form:

$$J(U_k^{N-1}) = E \left\{ \frac{1}{2} \sum_{i=k}^{N-1} x^T(i+1)M(i)x(i+1) + u^T(i)N(i)u(i) \middle| Z^k, U^k \right\} \quad (4)$$

Here:  $M(i) = M^T(i) \geq 0$  and  $N(i) = N^T(i) > 0$ .

Taking (3) into account, we will use the dynamic optimization method to find the sequence in the minimization equation  $U_{k+1}^{N-1}$  (4) [29]:

$$u^*(j/k) = -C(j/k)x(j), \quad j = k+1, \dots, N-1 \quad (5)$$

$$C(j/k) = [E\{B^T(j, \theta)S(j+1/k)B(j, \theta) + R(j)\}]^{-1} \times E\{B^T(j)S(j+1/k)A(j, \theta)\} \quad (6)$$

$$S(j/k) = E\{[A(j, \theta) - B(j, \theta)C(j/k)]^T (M(j) + S(j+1/k)) \times [A(j, k) - B(j, \theta)C(j/k)] + C(j/k)N(j)C^T(j/k)\}$$

## II. RESULTS AND DISCUSSION

The most time-consuming operation in the considered multistage control algorithm is the  $\Theta = [E\{B^T(j, \theta)S(j+1/k)B(j, \theta) + R(j)\}]$  calculation of the inverse of the matrix [30]. The accuracy and computational stability of the control algorithm are significantly dependent on the quality of this procedure.

The matrix in expression (6) is  $\Theta$  a symmetric, non-negative definite matrix and has an incomplete rank [31]. If the matrix is ill-conditioned or non-invertible, it is advisable to use regularization procedures in the following forms to improve the stability of the pseudoinverse procedure in (6):

$$\Theta^+ = T^T (TT^T + \alpha I)^{-2} T$$

Here,  $T$  is determined from the factorization of the matrix,  $\Theta = T^T T$  is the regularization parameter, and  $\alpha > 0$  is the identity matrix.

Here, it is advisable to determine the regularization parameter  $\alpha$  based on the method of model examples [32]. The formalization of the process above allows for the selection of the mathematical model's structure in the following form:

$$x_{k+1} = A_k x_k + B_k u_k + w_k, \quad x_{k_0} = x_0$$

$$y_k = C_k x_k + \eta_k$$

Here:

$$A_k = \begin{bmatrix} a_{11,k} & a_{12,k} \\ a_{21,k} & a_{22,k} \end{bmatrix}, \quad B_k = \begin{bmatrix} b_{11,k} & b_{12,k} & b_{13,k} \\ b_{21,k} & b_{22,k} & b_{23,k} \end{bmatrix}, \quad C_k = \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix},$$

$$M[x_0] = 0, \quad M[x_0 x_0^T] = X_0, \quad M[\eta_k] = 0, \quad M[x_0 \eta_k^T] = 0, \quad M[x_0 w_k^T] = 0,$$

$$M \left[ \begin{pmatrix} w_k \\ \eta_k \end{pmatrix} \begin{pmatrix} w_l^T & \eta_l^T \end{pmatrix} \right] = \begin{bmatrix} W & G \\ G^T & V \end{bmatrix} \delta_{k-l}$$

$$\theta^T = [a^T \quad b^T]$$

We assume that the process of changing the parameter vector  $\theta^T$  forms a Markov process in the

form  $\theta_{k+1} = \theta_k + w_k^\theta$  where  $a^T = (a_{11}, a_{12}, a_{21}, a_{22})$ ,  $b^T = (b_{11}, b_{12}, b_{13}, b_{21}, b_{22}, b_{23})$ ,  $w_k^\theta$  is the implementation of a random function.

In that case, the process and observation equations can be written in the following form:

$$x_{k+1} = A_k x_k + B_k u_k + w_k, \quad x_{k_0} = x_0 \quad (7)$$

$$\theta_{k+1} = \theta_k + w_k^\theta \quad (8)$$

$$y_k = C_k x_k + \eta_k$$

Here  $w_k, w_k^\theta$  ( $k = 0, 1, \dots$ )-Gaussian sequences:

$$M[w_k, w_l^T] = Q_k^x \delta_{kl}, \quad M[w_k^\theta, w_l^{\theta T}] = Q_k^\theta \delta_{kl}, \quad Q_k^x = R_k,$$

Here  $\delta_{kl}$  is the Kronecker symbol.

By introducing the augmented state vector  $x^p = [x^T \mid \theta^T]^T$ , we rewrite equations (7) and (8) in the following form:

$$x_{k+1}^p = f^p[x_k^p, u_k, k] + w_k^p,$$

$$z_{k+1} = c[x_k^p, u_k, k] + w_k,$$

Here

$$x_k^p = \begin{bmatrix} x_k \\ \theta_k \end{bmatrix}, \quad f^p = \begin{bmatrix} f[x_k, \theta_k, u_k, k] \\ \theta_k \end{bmatrix}, \quad w_k^p = \begin{bmatrix} w_k \\ w_k^\theta \end{bmatrix}$$

or in the augmented form:



$$\begin{aligned}
 x_{1,k+1} &= x_{3,k}x_{1,k} + x_{4,k}x_{2,k} + x_{7,k}u_{1,k} + x_{8,k}u_{2,k} + x_{9,k}u_{3,k} + w_{1,k} \\
 x_{2,k+1} &= x_{5,k}x_{1,k} + x_{6,k}x_{2,k} + x_{10,k}u_{1,k} + x_{11,k}u_{2,k} + x_{12,k}u_{3,k} + w_{2,k}, \\
 x_{3,k+1} &= a_{11,k+1} = a_{11,k} + w_{a_{11,k}}; & x_{4,k+1} &= a_{12,k+1} = a_{12,k} + w_{a_{12,k}}, \\
 x_{5,k+1} &= a_{21,k+1} = a_{21,k} + w_{a_{21,k}}; & x_{6,k+1} &= a_{22,k+1} = a_{22,k} + w_{a_{22,k}}, \\
 x_{7,k+1} &= b_{11,k+1} = b_{11,k} + w_{b_{11,k}}; & x_{8,k+1} &= b_{12,k+1} = b_{12,k} + w_{b_{12,k}}, \\
 x_{9,k+1} &= b_{13,k+1} = b_{13,k} + w_{b_{13,k}}; & x_{10,k+1} &= b_{21,k+1} = b_{21,k} + w_{b_{21,k}}, \\
 x_{11,k+1} &= b_{22,k+1} = b_{22,k} + w_{b_{22,k}}; & x_{12,k+1} &= b_{23,k+1} = b_{23,k} + w_{b_{23,k}}, \\
 z_{1,k} &= x_{1,k} + w_{1,k}; & z_{2,k} &= w_{2,k}.
 \end{aligned}$$

To obtain the model of the reservoir, an experiment was conducted under the conditions of the object's normal operation. During the experiment, monitoring was carried out continuously and discretely using the express analysis method, depending on the observability of certain technological parameters.

In the implementation of process variables, the time of registration of T parameters and the data search interval  $\Delta t$  are selected taking into account the characteristics of measuring known parameters. The required values of registration and discretization time for the implementation of observed random processes are: T = 30 hours,  $\Delta t$  = 20 min. A total of 90 measurements were taken. Test sequences were performed for different modes of the considered process, the results are included in Table 1.

1- Table

№	$u_1,$ M <sup>3</sup> /sec	$u_2,$ M <sup>3</sup> /sec	$u_3,$ M <sup>3</sup> /sec	$y_1,$ M <sup>3</sup>	$y_2,$ M	№	$u_1,$ M <sup>3</sup> /sec	$u_2,$ M <sup>3</sup> /sec	$u_3,$ M <sup>3</sup> /sec	$y_1,$ M <sup>3</sup>	$y_2,$ M
1.	175,70	62,70	41,60	130,60	105,24	46.	191,30	81,26	132,81	136,80	110,32
2.	176,10	62,85	42,44	130,85	105,53	47.	201,48	91,87	143,74	136,67	110,22
3.	176,98	63,31	52,86	131,07	105,70	48.	192,02	82,16	134,24	136,59	110,15
4.	177,88	73,75	63,00	131,22	105,82	49.	182,29	72,93	124,81	136,53	110,11
5.	188,39	84,06	63,48	131,37	105,94	50.	172,40	73,31	115,20	136,47	110,06
6.	188,68	84,30	63,88	131,51	106,06	51.	163,21	64,04	115,70	136,41	110,01
7.	189,03	75,20	63,91	131,69	106,21	52.	163,96	54,83	116,48	136,39	109,99
8.	179,88	75,51	64,75	131,84	106,32	53.	164,06	55,43	116,60	136,36	109,97
9.	180,28	65,67	65,22	132,01	106,46	54.	164,98	56,12	116,65	136,33	109,94
10.	170,88	56,22	65,71	132,19	106,61	55.	165,33	56,66	117,53	136,30	109,92
11.	171,83	56,83	55,80	132,40	106,78	56.	155,85	57,01	118,20	136,23	109,86
12.	172,59	57,24	46,20	132,65	106,98	57.	146,18	57,30	109,13	136,16	109,80
13.	182,78	57,43	46,62	132,94	107,21	58.	146,35	57,92	109,13	136,08	109,74
14.	183,37	67,88	56,63	133,15	107,38	59.	157,32	57,96	109,92	136,04	109,71
15.	194,30	78,25	67,62	133,32	107,52	60.	168,20	58,56	110,24	136,04	109,71
16.	205,13	79,00	77,89	133,50	107,66	61.	168,86	58,59	110,39	136,04	109,71
17.	205,18	79,10	88,40	133,63	107,77	62.	169,18	58,92	121,06	136,00	109,68
18.	215,43	89,27	88,41	133,77	107,88	63.	169,31	59,23	131,83	135,92	109,62
19.	225,76	89,89	98,56	133,90	107,99	64.	169,32	70,01	132,33	135,80	109,52
20.	226,36	79,95	99,22	134,07	108,12	65.	170,30	80,94	142,72	135,61	109,36



21.	217,24	80,44	99,95	134,20	108,23	66.	181,26	81,68	142,93	135,46	109,24
22.	217,38	70,86	100,70	134,37	108,36	67.	191,99	92,28	143,04	135,30	109,11
23.	208,14	61,05	91,64	134,57	108,52	68.	192,64	92,87	133,59	135,18	109,01
24.	198,67	51,33	92,24	134,77	108,68	69.	182,89	93,08	123,70	135,06	108,92
25.	188,80	41,75	93,00	134,96	108,84	70.	173,07	83,36	124,29	134,93	108,82
26.	189,75	52,28	93,04	135,12	108,97	71.	173,32	73,58	114,42	134,88	108,77
27.	200,27	62,50	93,38	135,28	109,10	72.	173,74	74,46	105,12	134,86	108,76
28.	200,52	72,67	103,48	135,37	109,17	73.	163,99	65,46	96,05	134,87	108,76
29.	200,54	72,86	103,85	135,46	109,24	74.	154,97	66,18	96,45	134,84	108,74
30.	201,04	73,45	104,75	135,54	109,30	75.	155,57	56,50	96,87	134,85	108,75
31.	191,78	64,32	95,30	135,65	109,40	76.	156,47	57,45	87,47	134,89	108,78
32.	191,99	64,50	96,17	135,77	109,49	77.	157,01	68,44	87,72	134,89	108,78
33.	182,81	65,35	87,06	135,88	109,58	78.	167,47	69,25	98,04	134,89	108,78
34.	183,62	55,71	88,02	136,02	109,69	79.	178,34	79,47	108,15	134,86	108,76
35.	173,94	45,75	78,08	136,20	109,84	80.	188,94	80,25	118,71	134,82	108,73
36.	164,37	46,64	78,38	136,34	109,95	81.	198,96	91,25	118,82	134,78	108,70
37.	165,27	36,85	68,99	136,56	110,13	82.	199,31	91,36	129,53	134,71	108,63
38.	175,97	47,54	79,28	136,73	110,27	83.	200,09	91,89	139,53	134,59	108,54
39.	176,52	48,02	89,37	136,87	110,38	84.	200,15	101,92	139,87	134,44	108,42
40.	177,36	48,60	99,74	136,98	110,47	85.	200,72	102,68	130,12	134,33	108,33
41.	178,08	58,83	110,18	137,01	110,49	86.	200,74	102,93	120,80	134,24	108,26
42.	179,06	69,55	110,58	137,01	110,49	87.	201,52	103,06	111,50	134,20	108,22
43.	189,90	80,02	111,52	137,00	110,48	88.	191,76	93,42	112,30	134,15	108,18
44.	190,63	80,25	122,29	136,96	110,45	89.	191,84	84,27	102,33	134,17	108,20
45.	191,05	80,68	132,39	136,88	110,39	90.	192,07	75,13	92,51	134,25	108,27

### III.CONCLUSION

This study presents a comprehensive algorithm for simulating seasonally regulated reservoirs under data uncertainty using a control-oriented mathematical framework. The model incorporates nonlinear dynamic equations, stochastic disturbances, and control strategies tailored for hydraulic structures. The estimation results show that the state variables such as reservoir volume and water level can be accurately estimated using regularization algorithms, achieving fast convergence and stability in the estimation process.

The empirical analysis based on the trajectories of the estimated parameters (e.g.,  $\hat{x}_1, \hat{x}_2, \hat{x}_3, \dots, \hat{x}_8$ ) confirms the effectiveness of the proposed method in observing the critical dynamics of the system. Notably, the empirical correlation value for the residuals remained well below the critical threshold, confirming the adequacy of the model assumptions and the estimation process.

The matrices  $A_k, B_k,$  and  $C_k$  obtained from the system identification further strengthen the robustness of the model for implementation in real-time control systems. These results not only demonstrate the viability of the algorithm for accurate modeling, but also suggest its potential for integration into SCADA and IoT-based smart water management systems.

Future development will focus on refining the model's scalability, incorporating AI-enhanced prediction mechanisms, and conduction field validation across multiple reservoir configurations. The application of this algorithm could significantly improve the efficiency of water use, reduce losses in agricultural systems and support Uzbekistan's national goals for sustainable hydrotechnical infrastructure



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