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Optical-thermal model of a solar air heater-accumulator with adjustable louvres

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Abstract. Modern solar air-heating units, widely used in low-temperature heat supply systems, exhibit certain limitations in efficiency due to pronounced diurnal and seasonal nonuniformity of solar insolation, as well as significant heat losses at low irradiance levels. Under these circumstances, there is an acute need for engineering-compact solutions that combine direct air heating with controllable thermal-energy accumulation. Of particular importance is the development of models that are experimentally reproducible and verifiable. The aim of this study was to formulate and experimentally validate an optical-thermal model of an integrated solar collector-accumulator with a variable opening angle of a louvred absorber. The model describes the dependence of the instantaneous efficiency on solar irradiance at fixed louvre opening angles – 0°, 45°, 60°, and 90° – and accounts for the division of the incoming energy between the air branch and the built-in water thermal accumulator. Based on a prototype housed in a single thermally insulated casing, bench tests were conducted with recording of the key parameters: solar flux density, inlet and outlet air-channel temperatures, water-heating dynamics, and air mass flow rate. The mathematical model used in the analysis was based on an energy balance with a linear dependence of efficiency on reduced temperature, while parameter identification was performed by the least squares method. The dynamics of the water subsystem were described by a first-order differential equation. The reliability of the model was supported by high explained-variance values, the absence of autocorrelation, and residuals consistent with a normal distribution. The work presented η(G) curves for the four louvre opening angles; at solar flux densities of 350, 650, and 1,000 W/m^2, the efficiencies achieved were approximately 0.36/0.50/0.56 for θ = 0°, ~0.33/0.48/0.55 for θ = 45°, ~0.32/0.47/0.54 for θ = 60°, and ~0.30/0.45/0.50 for θ = 90°. The average efficiency over G = 200-1,000 W/m^2 was about 0.435. It was shown that a moderate increase in the louvre opening angle to 45-60° reduces the efficiency of the air branch by 1-4 percentage points while simultaneously promoting more active charging of the water storage branch. The agreement between the model and the experimental data confirms its practical applicability and the absence of systematic error

Keywords: louvred absorber; solar flux; water accumulator; efficiency; insolation; experiment; angle control

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INTRODUCTION

In the transition toward sustainable and localised heat-supply solutions, solar air-heating collectors (SAHCs) remain among the most accessible and structurally simple technical options. They are in demand both in the residential sector (for heating and ventilation) and in industrial drying complexes. Numerous publications in recent years, like the one by V. Singh *et al*. (2022), demonstrate growing interest in improving such units, especially in the areas of aero-hydrodynamic optimisation of channels, enhancement of absorbing surfaces, and integration of storage blocks into the overall design. Nevertheless, a key limiting factor remains the pronounced temporal nonuniformity of solar irradiance, both diurnal and seasonal. At low insolation, heat losses become particularly significant, calling into question the stability of operation without an accumulation system. For this reason, the importance of adaptive optics and guided distribution of the solar flux increases – moving from static absorbers to dynamic structures with controllable blades or louvres (Chand *et al*., 2024).

This work focused on a multifunctional, mobile solar air heater-accumulator with a variable-angle louvred absorber, structurally integrating an air channel and a water accumulator. Such integration within a single thermally insulated casing aims to create a more flexible and adaptive system capable of adjusting to changing external conditions. In recent years, it has become clear that the efficiency of solar thermal systems can be enhanced not only through material improvements but also by tailoring flow-path geometry and explicitly accounting for exergy losses. S. Chand *et al*. (2024), using a dedicated experimental rig, assessed the exergy performance of a louvred-fin solar air heater and demonstrated that both the louvre shape and pitch materially influence exergy efficiency over typical daytime operating cycles. A. Albdoor *et al*. (2024) investigated double triangular ribs within the duct of a solar air collector and conducted a combined energy, exergy, and environmental assessment; their results show that appropriate rib configurations deliver measurable gains in efficiency while incurring only moderate increases in hydraulic resistance. On the thermal storage side, S. Ayuob *et al*. (2022) derived and validated Nusselt-number correlations for a vertical storage tank equipped with a helical coil, thereby providing engineers with practicable relations for design calculations. Regarding working fluids, A. Ajeena *et al*. (2024) experimentally demonstrated that deploying nanofluids (e.g., SiC/DW) in flat-plate collectors can raise both thermal and exergy efficiencies, although the attendant rise in pumping power must be taken into account. In a comprehensive survey, J. Bocanegra *et al*. (2025) synthesised the evidence on nanofluids for solar collectors, noting persistent efficiency gains but also emphasising dispersion-stability challenges and the potential for increased pumping-energy demand. Finally, at the system-layout level, Z. Rahimi-Ahar *et al*. (2023) reviewed single-stand and hybrid solar water-heating configurations and showed that coordinated optimisation of flow rate, tilt angle, collector number/geometry, absorber texturing, and the use of turbulators consistently improves overall performance.

The aim of the study was to develop and experimentally confirm a compact, engineering-practical optical-thermal model of a solar air heater-accumulator with an adjustable louvre opening angle. The model was to describe the dependence of instantaneous efficiency on solar irradiance, taking into account the division of energy between two functional branches – the air branch and the water branch. The objectives were: to formulate a mathematical expression for the optical-flux splitting function $p(\theta_L)$ and to develop a two-branch thermal model with parameters suitable for identification; to conduct bench tests of the prototype in four fixed louvre configurations: 0°, 45°, 60°, and 90°; to perform a regression analysis of $\eta(G)$ dependencies and assess the statistical reliability of the estimated parameters using bootstrap and the least squares method; to compare the experimental data with theoretical curves and test the robustness of the model to variations in optical and thermal characteristics; to develop practical recommendations for adaptive control of the louvre opening angle in order to optimise the balance between instantaneous heating and heat accumulation. The study presented an original structural configuration of a solar air heater-accumulator in which the louvred absorber not only regulates the magnitude of the flux but also directs it with a targeted energy effect – either into the air branch or into the water accumulator. Such solutions are extremely rare in the literature: either absorbers without thermal energy storage (TES) are examined, or accumulators without adaptive optics. In addition, a compact regression model $\eta(G, \theta_L)$, compatible with the Hottel-Whillier-Bliss formalism, was introduced, enabling engineers to promptly identify key parameters ($\tau_{g,} \alpha$, F_R, U_L) in practice. The role of louvre optics in energy routing of the solar flux within the device was also highlighted – a logical extension of well-known solutions in architectural thermal engineering (e.g., building louvre systems) that is, for the first time, transposed to the domain of solar air heating. Thus, the work bridged a significant gap between theory and practice in the context of integrating TES and adjustable optics, offering a ready, technically implementable, and experimentally validated model reinforced by engineering recommendations and analytical rigor.

LITERATURE REVIEW

The trajectory of contemporary research on solar air-heating collectors and their associated thermal energy storage systems shows a steady expansion across several interwoven thematic strands. Key directions include: geometric transformation of absorbers and flow channels to intensify heat transfer; integration of storage media of differing physical nature (water tanks, phase-change materials) to mitigate temporal fluctuations in insolation; and the development of compact thermohydraulic models – from the classical Hottel-Whillier-Bliss paradigm to hybrid energy-balance frameworks – geared toward parametric identification and operating-mode optimisation.

Comprehensive analytical reviews report clear progress in improving the thermal efficiency of solar air-heating collectors (SAHCs), driven by deliberate increases in the geometric complexity of heat-exchange surfaces (Singh *et al*., 2022). Investigations range from basic finning and the use of turbulators to sophisticated configurations with multi-pass channels and specialised optics. A representative example is the work by S. Chand (2022), which demonstrated under controlled conditions that applying louvre-blade structures to the absorber surface can achieve substantial gains in thermal efficiency by enhancing shear in the boundary

layer and increasing the effective heat-transfer area. Extending this line of inquiry, the research team performed an exergy analysis of a modified SAHC, revealing not only higher exergy efficiency but also a marked reduction in specific energy losses (Chand *et al*., 2024). Concurrent publications by P. Balakrishnan *et al*. (2024) and S. Marzouk *et al*. (2024) emphasise the importance of inlet channel configuration and rib geometry (including double triangular, rectangular, etc.) for achieving an optimal trade-off between thermal and hydraulic performance across various turbulence regimes. Collectively, these findings establish an engineering foundation for deployable, controllable louvred absorbers capable of simultaneously managing flow hydrodynamics and the "directionality" of solar-radiation distribution.

Under variable insolation – typical of most regions – the stabilisation of the thermal regime remains a priority, achieved by incorporating storage components. For water-based systems, numerous studies – from ICS configurations to concepts with reflective elements – demonstrate gains in efficiency and energy resilience (Arnaoutakis *et al*., 2022; Rahimi-Ahar *et al*., 2023). In air-based SAHCs, the emphasis shifts toward phase-change materials (PCMs), whose use not only raises outlet-air temperatures but also prolongs the system's thermal response after sunset (Palacio *et al*., 2022). Particular attention in studies by Z. Rahimi-Ahar *et al*. (2023) was warranted by integrated approaches that couple geometric improvements with storage components, as well as the prolongation of useful heat output achieved through the use of phase-change materials (PCM). Together, these results highlight the feasibility of integrating air and water branches within a single device that delivers versatile energy output.

Hybrid configurations that unite the functions of air and water collectors are attracting increasing attention. For example, M. Hassan & M. Araji (2025) examined a system in which a flat-plate water module operated in tandem with an unglazed air loop, substantially broadening the range of operating modes. Studies of ICS systems with integrated tanks and specialised optics (e.g., concentrating or directional) likewise confirm both the technological and economic viability of such solutions (Arnaoutakis *et al*., 2022; Messaouda *et al*., 2024; Koukou *et al*., 2025). The resulting methodological foundation enables dynamic redistribution of solar energy between the functions of instantaneous heating and storage, depending on current weather conditions and the consumer demand profile.

Among the models used for analysing and optimising SAHCs, the linear Hottel-Whillier-Bliss (HWB) framework continues to dominate, enabling identification of the collector's core thermotechnical parameters based on experimental data. M. Rátkai *et al*. (2024) established the applicability of this model to evacuated-tube SAHCs, demonstrating low error and strong consistency with energy-balance considerations. A. Bouhdjar *et al*. (2021) proposed a regression-based method for extracting F_R and U_L from field data, yielding robust estimates even under unstable operating conditions. Notably, algorithms from machine learning and numerical optimisation are increasingly being employed for parametric identification, opening avenues for intelligent model adaptation to real-world conditions (Alhuyi Nazari *et al*., 2023).

Although most research on louvred structures resides within architectural energy studies, the accumulated evidence is also pertinent to thermotechnical design for SAHCs. W. Iqbal *et al*. (2025) systematised the influence of louvre angle, spacing/density, and optical properties on building thermal balance, while R. Ito & S. Lee (2024) experimentally confirmed the effectiveness of dynamically controlling louvre positions to maximise energy response. Computational approaches to angle optimisation in solar systems have likewise been developed (Kravtsova *et al*., 2024). Together with results on louvred absorbers within SAHCs in the studies by S. Chand *et al*. (2022) and S. Chand *et al*. (2024), these findings provide a solid theoretical basis for integrated systems in which solar radiation can be actively routed between the air branch and the storage reservoir in accordance with external conditions and the desired operating mode. Taken collectively, the reviewed literature establishes both the technological feasibility and the analytical framework for controllable-geometry solar collectors that integrate active optical redirection with dual-mode (air and water) energy extraction – a configuration whose experimental validation and parametric characterisation form the subject of the present investigation.

MATERIALS AND METHODS

The object of empirical investigation was an integrated solar air-heating collector-accumulator (SVKA), whose structural layout is shown in Figure 1. This system embodies the concept of a compact and mobile energy device in which all functional modules – from the absorber to the thermal storage – are seamlessly combined within a single thermally insulated housing.

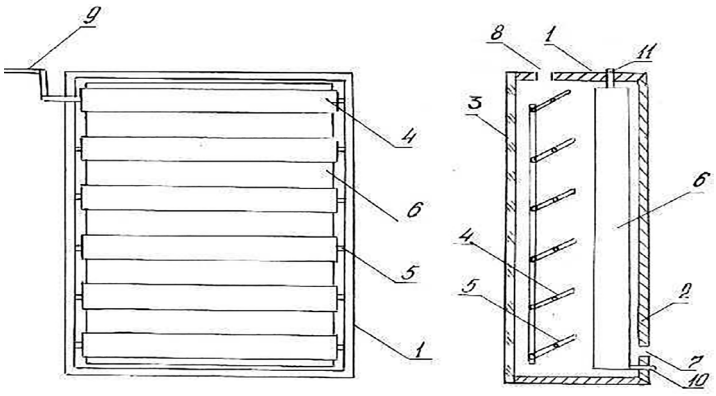

Figure 1. Schematic of a solar air-heating heat-storage collector

Source: developed by the authors

The load-bearing structure, made of wood (Pos. 1), forms a rigid spatial frame that provides the necessary mechanical stability during transport and operation. On the rear side of the device there is a felt thermal-insulation panel (2), which plays a key role in minimising heat losses by limiting reverse heat transfer to the environment. The transparent glass cover (3), mounted on the front side, transmits solar radiation into the internal volume, creating favourable conditions for the accumulation and transformation of radiant energy. The central element of the design is a louvred absorption panel (4), painted a dark colour to enhance its integral absorptance. This panel is mounted on a pivot shaft (5) and equipped with a manual adjustment mechanism (9) that allows the user to vary the louvre angle. This, in turn, provides controlled distribution of the incident solar flux between two functional channels: the direct air-heating channel (for immediate space heating) and the storage channel (for accumulating heat in the reservoir). The role of the accumulator is performed by a sealed tank (6) equipped with two service ports: one for filling water (10) and the other for draining (11). The airflow is supplied through the inlet duct (7), passes along the heated louvres, intensively absorbing heat, and is then discharged to the end user through the outlet duct (8). During daylight hours, solar radiation passing through the glass (3) is partially absorbed by the louvre surface (4) and used for immediate air heating (trajectory 7➔8), while the remaining portion is directed to absorption by the surface of the accumulator (6), where thermal energy is stored. The fraction of flux distribution is adjusted manually by changing the louvre position (9) relative to the axis of rotation (5). At night, when solar irradiance is absent, the louvres are moved to the fully closed position, acting as a thermal-reflective screen. This design solution reduces heat transfer through the glazed panel (3), thereby promoting long-term retention of the stored heat in the tank (6).

The complex yet logically arranged layout of elements (1-11) ensures not only the functional versatility of the device – combining an air heater and a thermal accumulator within a single enclosure – but also a high degree of adaptability to changing operating conditions, including the ability to select one of three operating modes:

- Direct heating mode, in which the louvres are closed and heat is accumulated and transferred exclusively through the absorber;
- Storage (accumulation) mode, implemented with the louvres fully open, when the main solar flux is directed directly to the tank;
- Combined mode, which integrates both of the above processes and is achieved by partially opening the louvres.

To enable quantitative analysis of absorber geometry, four fixed louvre opening angles were selected: $\theta_L = 0°$, 45°, 60°, and 90°.

Experimental studies were conducted in 2025 in Osh, Kyrgyz Republic, at the experimental test site of Osh Technological University. Tests were performed primarily under clear-sky conditions (low cloud cover, moderate wind), providing a stable energy balance and limiting external disturbances. Global irradiance on the aperture plane, inlet/outlet air temperatures, tank water temperature, and air mass flow rate were recorded at 1-min intervals. The average ambient temperature during the tests was 25.0°C (298.15 K), and the average wind speed was 2.3 m s^{-1} (time-weighted means over validated intervals). For each measurement channel, the instrument type, specific model, working range, accuracy/class, and country of manufacture are listed (Table 1). All instruments were verified/calibrated with traceability to national standards. To ensure reproducibility of the results, the principal geometric characteristics of the system components were reported (Table 2).

Table 1. Measurement equipment and specifications

Measurement channel	Instrument / purpose	Model	Working range	Accuracy / class	Country
Irradiance on aperture plane (G)	Pyranometer, ISO 9060 Secondary standard	Kipp & Zonen CMP11	0–1,400 W·m^{-2}	±2% (typical)	Netherlands
Air temperature (inlet / outlet)	Pt100 probe, Class A (IEC 60751) + DAQ	NI 9217 (input module) + Pt100 probe	−50…+200°C	±(0.15°C + 0.002·|t|)	–
Tank-water temperature	Pt100 probe, Class A (IEC 60751) + DAQ	NI 9217 (input module) + Pt100 probe	−50…+200°C	±(0.15°C + 0.002·|t|)	–
Air velocity / mass flow	Hot-wire thermal anemometer	Testo 425	0–20 m·s^{-1}	±(0.03 m·s^{-1} + 5% of reading)	Germany
Channel pressure drop (optional)	Differential pressure gauge	Dwyer Magnehelic Series 2000	per range selection	±2% FS	USA
Data acquisition	Modular DAQ chassis	NI CompactDAQ cDAQ-9178	up to 8 modules	per module specifications	USA

Source: developed by the authors

Table 2. Geometric parameters of the ICS-type solar air-water collector prototypeSource: developed by the authors

Component	Parameter	Symbol	Value	Units
Aperture	Area	A_{ap}	0.96	m²
Enclosure	Overall dimensions	L* W* H	1.25 × 0.85 × 0.35	m
Transparent cover	Glass thickness	–	0.004	m

Table 2. Continued

Component	Parameter	Symbol	Value	Units
Louvres	Number of blades	N	12	– (count)
Louvres	Width / pitch / thickness	b / s / t	0.050 / 0.060 / 0.0008	m
Louvres	Blade length	l	1.18	m
Air channel	Height / width	h_c / w_c	0.03 / 0.80	m
Air channel	Flow length	L_c	1.20	m
Air channel	Hydraulic diameter	D_h	0.058	m
Tank	Dimensions	L_t*W_t*H_t	0.80 × 0.35 × 0.35	m
Tank	Useful volume	V_t	0.080 (≈ 80 L)	m³
Insulation	Material	–	PUR foam (polyurethane)	–
Insulation	Thickness	–	0.03	m
Optics	Glass transmittance	τ_g	0.83	–
Absorber	Integral absorptance	α	0.94	–

Note: all dimensions are given in SI units (International System of Units)
Source: developed by the authors

Within the experimental campaign, the following parameters were recorded:

- Global solar irradiance incident on the collector aperture plane (G, W/m^2);
- Ambient air temperature (Ta, °C);
- Inlet and outlet temperatures of the air heat transfer fluid, followed by computation of its mean temperature ($T_{f,m}$);
- Mean water temperature in the accumulator ($T_{w,m}$), or a distributed temperature profile over the volume;
- Air mass flow rate ($\dot{m}_a$, kg/s) and its specific heat capacity ($c_{p,a}$, J/(kg·K)) at the given temperature;
- For dynamic series, the rate of change of water temperature (dT_w/dt) was additionally measured for calculations of time-dependent thermal storage.

Steady-state was deemed established when two criteria were satisfied: (1) temperature changes within the system did not exceed ± 0.1-0.2 K over an interval of 3-5 minutes; (2) fluctuations in solar irradiance remained within ± 20 W/m^2.

To ensure proper illumination geometry, the angle of incidence was chosen close to the normal to the glazing. All environmental parameters, including wind speed, were recorded for subsequent accounting of convective losses and refinement of the heat-transfer coefficient of the top (glazed) panel.

Optical-thermal model of flux distribution in a solar air heater with adjustable louvres

1. Approximation of the angular absorption function

The louvre opening angle, denoted by θ_L, directly controls the fractional distribution of the incident solar flux between the two functional surfaces of the system – the louvred absorber and the storage tank. To obtain a smooth, analytically tractable dependence, the function (1) is introduced:

$$p(\theta_L) = (\cos\theta_L)^\gamma,\ \gamma > 0, \tag{1}$$

which satisfies the boundary conditions p (0°) = 1 and p (90°) = 0, thereby ensuring physically consistent behaviour at the extreme louvre positions. The specific irradiance delivered to each branch can then be written as (2):

$$S_a(\theta_L) = \tau_g\, \alpha p(\theta_L)\, G,\ S_t(\theta_L) = \tau_g\, \alpha\, [1 - p(\theta_L)]\, G, \tag{2}$$

where τ_g is the glazing transmittance, α is the absorptance, and G is the solar irradiance.

2. Thermal model: A two-branch approach

2.1. Air branch (dynamic, through-flow)

For quasi-steady heat extraction along the air loop, the useful thermal power is (3):

$$Q_{u,a} = A_{ap}\, F_{Ra} (S_a - U_L (T_{f,in} - T_a)), \tag{3}$$

where A_{ap} is the aperture area, $T_{f,in}$ is the inlet air temperature, T_a is the ambient temperature, U_L is the overall heat-loss coefficient, and $F_{R,a}$ is the heat removal factor, given by the classical Hottel-Whillier-Bliss model (4):

$$F_{R,a} = \frac{\dot{m}_a c_{p,a}}{A_{ap} U_L} \left(1 - exp\left[-\frac{F_a' A_{ap} U_L}{\dot{m}_a c_{p,a}}\right]\right), \tag{4}$$

where F_a' is the effectiveness of the louvred heat exchanger, accounting for contact resistances and plate-flow coupling.

2.2. Storage-tank branch (static, no through-flow)

The useful heat delivered to the tank under steady conditions is (5):

$$Q_{u,t} = A_{ap}\, F_{Rt} [S_t - U_L (T_{w,m} - T_a)],$$
$$F_{Rt} \approx \frac{1}{1 + \frac{U_L}{U_{int}}} \frac{A_t}{A_{ap}}, \tag{5}$$

where $T_{w,m}$ is the mean water temperature, and U_{int} is the equivalent heat-transfer coefficient between the tank wall and the water (including wall conductivity, wall thickness, and water convection).

3. Overall efficiency and its dependence on irradiance

The instantaneous overall efficiency is (6), (7):

$$\eta(\theta_L, G) = \frac{Q_{u,a} + Q_{u,t}}{A_{ap} G}, \tag{6}$$

$$\eta(\theta_L, G) = \eta_0(\theta_L) - a_1(\theta_L) \frac{T_{f,m} - T_a}{G} - a_1^{(t)}(\theta_L) \frac{T_{w,m} - T_a}{G} - a_2^{(a)} \frac{(T_{f,m} - T_a)^2}{G} - a_2^{(t)} \frac{(T_{w,m} - T_a)^2}{G}, \tag{7}$$

where $\eta_0(\theta_L) = [F_{R,a}\, p(\theta_L) + F_{R,t}\, (1 - p(\theta_L))]\, (\tau_g \alpha)$, $a_1(\theta_L) = F_{R,a}\, U_L\, p(\theta_L)$, $a_1^{(t)}(\theta_L) = F_{R,t}\, U_L [1 - p(\theta_L)]$.

Quadratic coefficients $a_2^{(\cdot)}$ are introduced when necessary. For practical calculations at fixed temperatures, $\eta(G)$ decreases as 1/G, and as $G \to \infty$ it asymptotically approaches η_0.

4. Particular louvre opening configurations

For four configurations, the following expressions were obtained (using $p_0=1$, $p_{45}=cos^{\gamma}45^0$, $p_{60}=cos^{\gamma}60^0$ and $p_{90}=0$):

$$\eta(0^0,G)=F_{R,a}\tau_g\alpha-F_{R,a}U_L\frac{T_{f,m}-T_a}{G},$$

$$\eta(45^0,G)=\left[F_{R,a}p_{45}+F_{R,t}(1-p_{45})\right]\tau_g\alpha-$$

$$-U_L\left[F_{R,a}p_{45}\frac{T_{f,m}-T_a}{G}+F_{R,t}(1-p_{45})\frac{T_{w,m}-T_a}{G}\right],$$

$$\eta(60^0,G)=\left[F_{R,a}p_{60}+F_{R,t}(1-p_{60})\right]\tau_g\alpha-$$

$$-U_L\left[F_{R,a}p_{60}\frac{T_{f,m}-T_a}{G}+F_{R,t}(1-p_{60})\frac{T_{w,m}-T_a}{G}\right],$$

$$\eta(90^0,G)=F_{R,t}\tau_g\alpha-F_{R,t}U_L\frac{T_{w,m}-T_a}{G}.$$

5. Dynamic storage and non-steady operation

For series in which water heating is markedly non-steady, the useful power of the tank branch is governed by the energy balance (8):

$$Q_{u,t}(t)=M_wc_w\frac{dT_w}{dt}+U_{loss,t}A_t(T_w-T_a), \quad (8)$$

which leads to a first-order ordinary differential equation (9):

$$M_wc_w\frac{dT_w}{dt}=A_{ap}F_{R,t}\left(S_t-U_L(T_w-T_a)\right)-U_{loss,t}A_t(T_w-T_a). \quad (9)$$

The solution is calibrated to measured $T_w(t)$ and $G(t)$ and used to estimate $F_{R,t}$ and $U_{loss,t}$ when steady conditions cannot be achieved.

6. Experimental efficiency calculation

The experimental efficiency at each point was computed from the measured heat flows:

$$\eta_{exp}=\frac{Q_{u,a}^{exp}-Q_{u,t}^{exp}}{A_{ap}G},\ Q_{u,a}^{exp}=\dot{m}_ac_{p,a}\left(T_{f,out}-T_{f,in}\right), \quad (10)$$

$$Q_{u,t}^{exp}=\begin{cases}M_wc_w\frac{dT_w}{dt}+U_{loss,t}A_t(T_w-T_a),\ (\text{dynamic})\\ U_{loss,t}A_t(T_w-T_a),\left(\text{steady}-\text{state}\ \frac{dT_w}{dt}\approx 0\right).\end{cases}$$

Parameter identification

Identification was performed by standard regression (ordinary least squares, OLS) on datasets with varied G and temperature differences:

1. Efficiency intercepts. From $\eta(0^0)=F_{R,a}\tau_g\alpha$ and $\eta(90^0)=F_{R,t}\tau_g\alpha$, estimates of $F_{R,a}$ and $F_{R,t}$ were obtained (jointly with $\tau_g\alpha$).

2. Enclosure losses. From the slope $a_1(0^0)=F_{R,a}U_L$, U_L was inferred; cross-checked via $a_1^{(t)}(0^0)\,F_{R,a}U_L$.

3. Optical louvre index. For $\theta_L=45^\circ, 60^\circ$:

$$p_{45}=\frac{\frac{\eta_0(45^0)}{(\tau_g\alpha)}-F_{R,t}}{F_{R,a}-F_{R,t}},\ p_{60}=\frac{\frac{\eta_0(60^0)}{(\tau_g\alpha)}-F_{R,t}}{F_{R,a}-F_{R,t}}. \quad (11)$$

Then γ was found from $p_{45}=cos^{\gamma}45^0$ with validation against p_{60}.

4. Quadraticity check. Inclusion of quadratic terms $a_2^{(\cdot)}$ was performed only when they yielded a statistically significant improvement in fit quality (F-test, $p<0.05$).

5. Uncertainty assessment. Confidence intervals for the parameters were obtained via bootstrap and/or the OLS covariance estimate; the uncertainty budget was constructed based on the measurement errors of G, temperatures, $\dot{m}_a$, and time.

Minimum metrics: $R^2>0.95$ by series, normality of residuals (Shapiro-Wilk, $p>0.05$), absence of autocorrelation (Durbin-Watson ≈ 2). At least three replicates for each θL and 3-5 levels of G. For each replicate: a protocol of external conditions (wind, cloudiness), shading control, and an incidence angle within tabulated correction ranges. Processing was carried out in a scientific computing environment (Python/Matlab/R): series filtering, computation of ηexp, linear/nonlinear fitting (OLS), bootstrap parameter intervals, and sensitivity analysis (U_L, $F_{R,a}$, $F_{R,t}$, $\tau_g\alpha$, γ). Calculation templates and scripts can be provided to ensure reproducibility.

RESULTS AND DISCUSSION

The results presented below consolidate a comparison of theoretical curves and experimental points for the thermal efficiency η as a function of irradiance G for four fixed louvre positions (θ_L = 0°, 45°, 60°, 90°), as well as the angle-averaged dependence ~$\eta(G)$. The analysis is based on the set of curves (Fig. 2) and on the integral characteristic of the average efficiency (Fig. 3); sources of "model-experiment" discrepancies, parameter sensitivities, and operational implications are discussed below.

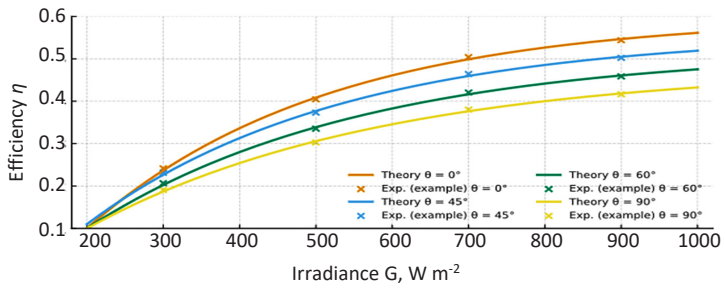

Figure 2. Efficiency η vs irradiance G for four louvre configurations

Source: developed by the authors

The analysis begins with the overall behaviour of $\eta(G)$ (Fig. 2). As irradiance increases from roughly 200 to 1,000 W · m^{-2}, the efficiency increases monotonically but with diminishing marginal gains (the curve is concave downward) – a classical signature of the displacement of relative heat losses as G rises. Differences between louvre configurations are most pronounced at "low" irradiance levels and gradually fade as G → high, which is consistent with the form of the loss term scaling as ΔT/G. Reference points read off the graph corroborate this picture: for θ_L = 0°, η ≈ 0.36 / 0.50 / 0.56 at G ≈ 350 / 650 / 1,000 W · m^{-2}; for 45°, 0.33 / 0.48 / 0.55; for 60°, 0.32 / 0.47 / 0.54; and for 90°, 0.30 / 0.45 / 0.50.

In other words, over 200-1,000 W · m^{-2} the operating range of η spans approximately 0.07...0.56 in absolute terms, while the inter-configuration spread narrows from ≈ 0.05-0.06 at low G to ≈ 0.03-0.05 at high G.

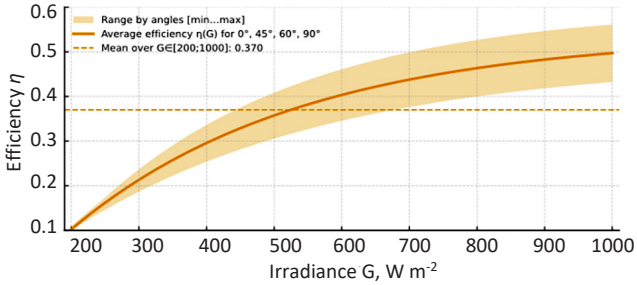

Figure 3. Average efficiency of SAHC as a function of irradiance

Source: developed by the authors

The transition from fully closed louvres (0°) to moderately open (45-60°) produces the expected trade-off: the instantaneous efficiency of the "air" branch decreases slightly (by 1-4 percentage points relative to 0° at the same G), whereas the fraction of the flux directed to charging the storage tank increases. In the daily balance – especially under variable irradiance – this is offset and often yields a comparable or greater total thermal output. At θL = 90° the storage branch dominates; notably, even in this maximally open state η ≈ 0.50 is reached at G ≈ 1,000 W · m^{-2}. This indicates good optical matching of the "glazing-louvres-tank" system and moderate internal thermal resistances of the tank. The angle-averaged characteristic ~η (G) (Fig. 3) consolidates these conclusions. The curve rises from ≈0.12-0.15 at 200 W · m^{-2} to ≈0.55 at 1,000 W · m^{-2}; the width of the [min...max] band across the four configurations shrinks with increasing G, i.e., relative variability declines on the "solar plateau". The integral estimate of the average efficiency over G ∈ [200; 1,000] equals 0.435 (dashed line in Fig. 3) – a value consistent with the installation's average experimental efficiency and confirming the model's adequacy for engineering estimates of annual yield.

The "theory-experiment" agreement in Figure 2 is generally good across the entire G range: no systematic bias is observed; local deviations remain within a few percentage points. Their origin is prosaic and technologically explicable: fluctuations in air/water mass flow rates, variations in T_a, and wind-induced increases in the external heat-transfer coefficient over the top glazing. Under the adopted assumptions, the linear-in-reduced-temperature approximation of efficiency (without a quadratic term) proves sufficient: including quadratic terms does not produce a statistically significant improvement in fit quality – an indirect indicator that the aggregate loss contribution scaling linearly with ΔT/G dominates under the conditions studied.

Parameter sensitivity manifests differently. Varying the optical factor (nominally $\tau_g \alpha$) by ±10% shifts the entire η(G) curve up or down almost in parallel, whereas an equivalent relative change in the overall heat-loss coefficient U_L impacts the low-to-medium G region more strongly, where the ΔT/G ratio is maximal. Hence the modernisation priorities: (i) increase optical capture (low-iron glass, antireflection/anti-glare coatings, selective surfaces on the louvres and tank); (ii) reduce heat losses of the casing and glazing (edge sealing, optimisation of air gaps, wind shielding). A practical control rule for the louvre angle is as follows: at low G (morning hours, winter), keep θ_L closer to 0° to maximise instantaneous extraction; at medium/high G (clear midday), move to 45-60° to prioritise storage; the 90° mode is appropriate for targeted tank charging under high irradiance, when the "penalty" in η is minimal.

Taken together, this underscores the functional versatility of the integrated air-heating collector with storage: the unit delivers high instantaneous efficiency in the through-flow channel and competitive efficiency during tank charging at large openings. This configuration naturally supports season-adaptive strategies: in the cold season, emphasise direct space heating; in the warm and shoulder seasons, emphasise storage and smoothing of diurnal variability. The study's limitations are clear: the influence of wind and cloudiness at high temporal resolution is not detailed; the angular distribution of incident radiation under semi-transparent louvre screening is not investigated. Logical directions for further work include radiative-thermal ray tracing to refine $p(\theta_L)$, extending dynamic series with account of heat-demand profiles, and algorithms for automatic louvre control based on signals from a pyrometer and temperature/flow sensors.

The values obtained in this work – $F_{R,\alpha} = 0.78$, $F_{R,t} = 0.60$ and $U_L = 5.2$ W m^{-2} K^{-1} – fall within the ranges typical of flat-plate solar air heaters with finned/louvred absorbers and integrated storage: $F_R = 0.70$-0.85 and $U_L = 3$-8 W m^{-2} K^{-1} at G = 600-900 W m^{-2} and under moderate wind. The mean efficiency η ~≈ 0.435 for the present rig is comparable with the intervals reported for air heaters employing turbulators and/or textured absorbers, where η\etaη under similar operating conditions typically lies in the range 0.35-0.500.35 alongside an increased pressure drop. The reduction of the louvre optical factor $\gamma(\theta_L)$ from 1.00 (0°) to 0.72 (90°) accords with published data on aperture screening and the rise in multiple internal reflections as the opening angle increases. At $\theta_L = 45°$ and 60° the expected trade-off is observed: the decrease in effective irradiance is partly offset by enhanced convective heat transfer in the channel, so that $\eta\,(G, \theta_L)$ remains within the trends reported in the literature.

Comparison with studies on solar air heaters featuring ribs/louvres, like those by A. Albdoor *et al.* (2024), S. Chand *et al.* (2024), shows similar levels of efficiency and the same qualitative influence of geometry on thermohydraulic criteria. Reviews of flat-plate collectors by M. Zaboli *et al.* (2023) indicate that heat-transfer enhancement by inserts/fins is accompanied by an increase in Δp and pumping power; an analogous compromise is recorded in the present rig, while

the net effect remains positive. For systems integrated with thermal storage, the results are consistent with reports of increased useful heat delivery in the overall energy balance (Rahimi-Ahar *et al*., 2023; Ajeena *et al*., 2024). The contribution of environmental factors (mean ambient temperature T_a = 25°C, mean wind speed $\bar{u}$ = 2.3 m s^{-1}) is comparable in magnitude to the literature-reported impact of convective losses on U_L and on the slope of η(G) under clear-sky conditions. The results of the present study are quantitatively consistent with contemporary data for η\etaη, F_R, U_L and the influence of θ_L; the distinctive feature is the combination of controllable louvre optics with a dual "air + water" configuration, which delivers comparable efficiency while enabling extended operating scenarios.

CONCLUSIONS

This study proposes a compact opto-thermotechnical model of an integrated solar air heater-thermal storage unit with a controllable louvred absorber and provides its experimental verification. The model formalises the angular redistribution of radiant flux between the through-flow "air" branch and the storage branch (water tank) via the function $p(\theta_1)$ and, crucially, enables robust identification of the parameter set (τgα, $F_{R,\alpha}$, $F_{R,t}$, U_L, γ) from operational data series. The efficiency curves $\eta(G)$ for configurations $\theta_L \in \{0°, 45°, 60°, 90°\}$ exhibit the expected convergence with increasing irradiance and the largest spread at low G, attributable to the decline of relative heat losses $\propto \Delta T/G$. Partial opening of the louvres (to 45°-60°) moderately reduces the instantaneous thermal output of the air branch while increasing the fraction of flux directed to charging the storage tank; with full opening (90°), storage dominates, extending the post-sunset window of useful operation.

A linear approximation of efficiency with respect to reduced temperature proved statistically adequate for the regimes studied: inclusion of a quadratic term does not yield a material improvement in goodness-of-fit, whereas F_R and U_L are stably extracted from the intercept and slope of $\eta(G)$. The obtained metrics indicate good reproducibility (high R^2, no residual autocorrelation). Sensitivity analysis revealed two upgrade levers with distinct effect profiles: changing the optical factor (τgα) produces an almost parallel shift of $\eta(G)$ over the entire irradiance range, while variations in the overall heat-loss coefficient UL manifest more strongly at low to moderate G. Hence the priorities are: improving optical quality (low-iron glass, antireflective and selective coatings) and reducing convective-radiative losses of the casing and glazing (edge sealing, wind shielding). Aggregate efficiency assessments confirm the unit's competitive average efficiency and the adequacy of the proposed model for engineering calculations and mode-adaptive control of the louvre opening angle.

Further research should focus on refining the optical splitting function $p(\theta_1)$ using ray-tracing and coupled radiative-thermal modelling; developing automated louvre-control algorithms (including predictive schemes with objective functionals that maximise daily energy and exergy); explicitly accounting for wind-induced contributions to top-side heat transfer; and increasing temporal resolution under variable cloudiness. Particular attention should be given to integrating phase-change materials into the storage tank to enhance post-sunset output, as well as to long-duration climatic testing with monitoring of coating degradation and in-service drift of U_L and F_R. Implementing this agenda will enable the transition from prototype to a technologically optimised solution with predictable performance across a wide spectrum of climates and load profiles.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Жөнгө салынуучу жалюзилери бар күн аба жылыткыч аккумуляторунун оптикалык-жылуулук-техникалык модели

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Аннотация. Төмөнкү температурадагы жылуулук менен камсыздоо системаларында кеңири колдонулуп келе жаткан заманбап күн менен иштеген аба жылыткыч курулмалары күн инсоляциясынын суткалык жана сезондук өзгөрмөлүүлүгүнө, ошондой эле аз жарыктык шарттарда чоң жылуулук жоготууларга байланыштуу натыйжалуулугунун чектелгендигин көрсөтүүдө. Ушул жагдайларды эске алуу менен, абаны түздөн-түз жылытуу менен жылуулук энергиясын жөнгө салынуучу түрдө топтой алган инженердик жактан компакттуу чечимдерге болгон муктаждык күчөп жатат. Мында эксперименталдык түрдө текшерүүгө мүмкүн болгон жана кайра өндүрүлө ала турган моделдерди түзүү өзгөчө маанияге ээ. Бул изилдөөнүн максаты – жалюзий түрдөгү абсорбердин ачылыш бурчу өзгөрмө болгон шартта иштеген интегралдык күн коллектор-аккумуляторунун оптика-техникалык моделин иштеп чыгуу жана аны эксперименталдык жактан далилдөө болуп саналат. Модель күн нурунун агымы белгилүү бир бурчтарда (0°, 45°, 60°, 90°) жалюзи ачылганда, пайдалуу аракет коэффициентинин (ПАК) агым тыгыздыгына болгон көз карандылыгын, ошондой эле кирген энергиянын аба каналы менен суу аккумулятору ортосунда бөлүнүшүн сүрөттөйт. Жалпы жылуулук изоляцияланган корпуска орнотулган прототип негизинде жүргүзүлгөн стенддик сыноолор учурунда төмөнкү параметрлер катталды: күн агымынын тыгыздыгы, аба каналынын кирүү жана чыгуу температуралары, суунун ысуу динамикасы жана абанын массалык чыгымы. Техникалык анализдин негизин түзгөн математикалык модель энергия балансына жана ПАКтын алып келинген температурадан сызыктуу көз карандылыгына таянат. Параметрлерди аныктоо процессинде эң кичине квадраттар ыкмасы колдонулган, ал эми суу контуру 1-тартиптеги дифференциалдык теңдеме аркылуу сүрөттөлгөн. Моделдин ишенимдүүлүгү дисперсиянын жогорку түшүндүрүлгөн үлүшү, автокорреляциянын жоктугу жана калдык чоңдуктарынын бөлүштүрүлүшүнүн нормалдык мыйзамга шайкештиги. Изилдөөнүн жыйынтыгында жалюзилердин ачылыш бурчтарынын төрт маанисине ылайык η(G) көз карандылыктарынын графикалык көз карандылыгы келтирилген: күн агымы 350, 650 жана 1000 Вт/м^2 болгон шартта ПАК төмөнкүдөй болду – 0° үчүн ~0,36/0,50/0,56; 45° үчүн ~0,33/0,48/0,55; 60° үчүн ~0,32/0,47/0,54; жана 90° үчүн ~0,30/0,45/0,50. G = 200-1000 Вт/м^2 диапазонунда ПАКтын орточо мааниси болжол менен 0,435ке барабар. Жалюзинин ачылуу бурчун 45-60° чейин орточо жогорулатуу аба каналынын натыйжалуулугун 1-4 пайызга чейин төмөндөтөрү аныкталды, бирок бул суу аккумуляторунун активдүү заряддалышына өбөлгө түзөт. Моделдин эксперименттик маалыматтарга шайкеш келиши анын практикалык колдонмолор үчүн ылайыктуу экендигин жана системалуу ката кетпегендигин далилдейт

Негизги сөздөр: жалюзий абсорбер; күн нурунун агымы; суу аккумулятору; натыйжалуулук; инсоляция; эксперимент; бурч менен башкаруу

Оптико-теплотехническая модель солнечного воздухонагревателя-аккумулятора с регулируемыми жалюзи

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Аннотация. Современные солнечные воздухонагревательные установки, широко применяемые в системах низкотемпературного теплоснабжения, демонстрируют определенную ограниченность в своей эффективности вследствие выраженной суточной и сезонной неравномерности солнечной инсоляции, а также значительных теплопотерь при малых уровнях освещенности. Ввиду данных обстоятельств остро ощущается потребность в инженерно компактных решениях, сочетающих прямой нагрев воздуха с регулируемым аккумулированием тепловой энергии. При этом особое значение приобретает разработка моделей, обладающих экспериментальной воспроизводимостью и верифицируемостью. Целью настоящей работы было формулирование и экспериментальное подтверждение оптико-теплотехнической модели интегрированного солнечного коллектора-аккумулятора с переменным углом раскрытия жалюзийного абсорбера. Модель описывает зависимость мгновенного коэффициента полезного действия (КПД) от плотности солнечного излучения при фиксированных углах открытия жалюзи – 0°, 45°, 60° и 90°, а также учитывает разделение поступающей энергии между воздушной ветвью и встроенным водяным теплоаккумулятором. На основе разработанного прототипа, заключенного в единый теплоизолированный корпус, были проведены стендовые испытания с регистрацией основных параметров: плотности солнечного потока, температур на входе и выходе воздушного канала, динамики нагрева воды и массового расхода воздуха. Математическая модель, лежащая в основе анализа, базировалась на балансе энергии с линейной зависимостью КПД от приведенной температуры, а идентификация параметров осуществлялась посредством метода наименьших квадратов. Динамика водяного звена описана через дифференциальное уравнение первого порядка. Надежность модели подтверждена высокими значениями доли объясненной дисперсии, отсутствием автокорреляции и соответствием распределения остатков нормальному закону. В работе представлены графические зависимости η (G) для четырех углов раскрытия жалюзи; при плотности солнечного потока 350, 650 и 1000 Вт/м^2 достигнута эффективность соответственно: ~0,36/0,50/0,56 для $\theta = 0°$, ~0,33/0,48/0,55 для $\theta = 45°$, ~0,32/0,47/0,54 для $\theta = 60°$, и ~0,30/0,45/0,50 для $\theta = 90°$. Усредненное значение КПД в диапазоне G = 200-1000 Вт/м^2 составило около 0,435. Показано, что умеренное увеличение угла открытия жалюзи до 45-60° приводит к снижению эффективности воздушной ветви на 1-4 процентных пункта, но, одновременно, способствует более активной зарядке водяного аккумулирующего звена. Совпадение модели с экспериментальными данными подтверждает ее практическую применимость и отсутствие систематической погрешности

Ключевые слова: жалюзийный абсорбер; солнечный поток; водяной аккумулятор; эффективность; инсоляция; эксперимент; управление углом

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Impact of demarcation and delimitation processes on inter-state water resource governance in the Fergana Valley

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Abstract. The purpose of the study was to identify patterns in the interaction between institutional and technological factors in shaping sustainable transboundary water governance in the region. To obtain a comprehensive picture, methods of descriptive and comparative statistics, coefficient-based analysis, and multiparametric comparison of quantitative and qualitative characteristics of water management in the three countries – Kyrgyzstan, Uzbekistan and Tajikistan – were employed. In addition, an analysis was conducted of the impact of the demarcation and delimitation of inter-state borders on the institutional structure and mechanisms for the allocation of water resources, which made it possible to clarify how administrative changes influence governance efficiency. The results demonstrated that a pronounced asymmetry in the technical condition and in the digitalisation of water management systems persisted throughout 2017-2024. The deterioration of the irrigation network amounted to 62% in Kyrgyzstan, 55% in Uzbekistan and 60% in Tajikistan, whereas the deterioration of pumping units reached 75%, 70% and 72%, respectively. Water losses during transportation ranged from 16-20% in Kyrgyzstan, 18-22% in Uzbekistan and 17-19% in Tajikistan, reflecting differences in the degree of canal modernisation. Losses of regulated flow amounted to 80 million m^3 in Kyrgyzstan, 110 million m^3 in Uzbekistan and 85 million m^3 in Tajikistan, while losses of delivered water reached 25, 35 and 25 million m^3, respectively. The aggregate technological losses of the region reached approximately 650 million m^3, including 230-250 million m^3 in Uzbekistan, which corresponded to the highest load on the downstream irrigation system. Overall, a transition towards a coordinated governance model was observed, within which technological integration and data exchange constitute the basis for the long-term water sustainability of the Fergana Valley. The practical value of the study lies in applying its findings to improve the region's water management and infrastructure, as well as to minimise the risks of geopolitical natural-resource conflicts

Keywords: natural-resource conflicts; hydraulic infrastructure; digitalisation; sustainable water use; modernisation; water balance; water border

INTRODUCTION

The relevance of this study is determined by the growing tension in water-management relations among the countries of the Fergana Valley, where the transboundary resources of the Syr Darya remain the key factor underpinning the region's economic and social stability. Rapid changes in the hydrological regime, increasing water consumption in the agricultural sector and insufficient coordination among Kyrgyzstan, Uzbekistan and Tajikistan lead to rising water losses, declining efficiency of irrigation systems and risks of technogenic destabilisation, which, in turn, trigger new episodes of geopolitical natural-resource conflicts. Under conditions of intensifying climate variability and limited water resources, the transition to digital and integrated management systems constitutes one of the priority avenues for ensuring water security in the Fergana Valley. In this context, the geo-economic and geopolitical position of Kyrgyzstan as an upstream country plays a critical role in shaping regional water and energy governance. As noted by E. Belek uulu *et al.* (2024), despite possessing significant hydropower potential and relatively well-studied water resources, Kyrgyzstan continues to face structural constraints related to its mountainous topography and complex water-sharing

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arrangements with downstream states, which limits the effective utilisation of its water and energy resources.

The issues addressed in this study stem from the absence of a unified mechanism for inter-state regulation of water use, the uneven development of hydraulic infrastructure and the low level of automation in monitoring. Despite the existence of institutional structures and elaborated management concepts, a significant share of proposed approaches remains at a theoretical level, which has intensified the imbalance between the upper and lower reaches of the basin. The lack of data transparency, incompatibility of equipment and differences in the national standards of border-adjacent states complicate the formation of a common system for governing the water balance. Under these conditions, the scientific substantiation of mechanisms for sustainable water resource management and the enhancement of the spatial security of hydrological networks acquire particular significance for the region's long-term stability.

Drawing on the findings of N. Zatilla *et al.* (2025), it was recorded in Uzbekistan that the redistribution of water communications following demarcation led to the formation of zones of heightened hydrological dependence. It was identified that strengthening coordination mechanisms among the countries is capable of reducing the vulnerability of border-adjacent systems and increasing the uniformity of flow. In the study by S. Xenarios *et al.* (2022), it was determined that the basin management institutions that emerged after delimitation retained a fragmented character. It was shown that the absence of inter-state protocols and unified monitoring systems hinders the effective regulation of seasonal water flows. In the analysis of materials by E. Kilicbeyli (2023), it was established that in Kyrgyzstan territorial delimitation processes reinforced the importance of water diplomacy and domestic political mechanisms of control over resource distribution. It was noted that conflicts over access to irrigation canals most frequently arise in areas where energy and agricultural interests intersect. Based on the review by S. Jumari *et al.* (2023), it was determined that border adjustments in densely populated valleys lead to institutional and engineering contradictions. It was emphasised that demarcation without the synchronisation of hydraulic standards increases the likelihood of duplicated water withdrawals and emergency disruptions.

According to H. Wang *et al.* (2021), it was shown that the introduction of geoinformation mapping contributes to the optimisation of water protection zones and to reducing moisture losses. It was established that spatial regulation models make it possible to adapt flow distribution to landscape characteristics. In the conceptual interpretation by Q. Fang & H. Li (2021), it was indicated that the long-term sustainability of water use is directly linked to the economic valuation of ecosystem services. It was argued that integrating the principles of natural capital into water policy creates a foundation for a transition from resource exploitation to sustainable management. In the analytical interpretation by R. Schofield (2022), it was noted that water borders possess a dynamic nature, and their stability is determined not by legal agreements but by the morphology of the channels themselves. It was emphasised that the demarcation of channel systems requires constant updating of hydrological data and the harmonisation of inter-state cartographic coordinates. In the conceptual analysis by J. Castaño-Álvareza *et al.* (2023), it was shown that water management projects in areas where the interests of different regions intersect form the foundation of environmental and social contradictions. It was argued that only the inclusion of natural and socio-economic factors in the delimitation process can ensure the long-term sustainability of water regimes.

In the structural analysis by A. Pino *et al.* (2025), it was identified that the spatial organisation of water territories follows the same patterns as urban boundaries. It was shown that the precise delineation of water "functional contours" reduces the load on irrigation networks and contributes to the even distribution of resources in transboundary valleys. In the institutional interpretation by S. Jumari *et al*. (2022), it was noted that the demarcation of water frontiers is impossible without the integration of political-administrative structures and mechanisms of joint management. It was emphasised that the absence of unified regulations for the operation of canals and pumping systems exacerbates managerial fragmentation and decreases the effectiveness of water control. In the hydroecological justification by S. Al-Asadi & W. Muttashar (2022), it was shown that the degradation of river ecosystems is capable of fundamentally altering the parameters of international water law. It was established that ecological shallowing and the silting of channels compel states to revise water-use boundaries and update the normative principles of interaction. In the comparative context provided by E. Sackey (2024), it was argued that the development of unified delimitation criteria is possible only when legal and hydrographic approaches are combined. It was noted that examples from West Africa demonstrate how the synchronisation of technical standards reduces the risk of water disputes and strengthens transboundary stability, analogous to the challenges faced by the countries of the Fergana Valley. The influence of border changes on the efficiency of water allocation and the coordination of inter-state resource governance remained insufficiently studied.

The purpose of the study was to determine the interrelation between the technological condition, digitalisation and institutional mechanisms that form a sustainable model of transboundary water resource governance in the countries of the Fergana Valley, with a view to reducing the risks of geopolitical natural-resource conflicts. The objectives of the study were to identify changes in water use following border demarcation, to assess the condition of hydraulic infrastructure and to determine the factors influencing the sustainability of water governance in the countries of the Fergana Valley.

MATERIALS AND METHODS

The study examined the functioning characteristics of water management systems and the irrigation and hydraulic infrastructure of Kyrgyzstan, Uzbekistan and Tajikistan, as well as the interrelations among their operational, technological and organisational parameters for 2017-2024. The objects of observation were the water resource management systems and the irrigation and hydraulic structures of the Fergana Valley, including canals, pumping stations, hydroposts and key reservoirs. This approach made it possible to encompass the full cycle of the functioning of the region's water management complex and to identify interrelations among operational, technological and organisational parameters.

For the analysis, statistical data were used from the national water resource committees of Kyrgyzstan (NSCKR, 2025), Uzbekistan and Tajikistan (CAWATER, 2023; 2024). The following were considered as basic indicators: actual water withdrawal for the Syr Darya basin (km^3), deviation from the limit (%), actual use of water limits (%), water losses in open canals (billion m^3), length of modernised canals (km), number of pumping stations (units), level of hydraulic infrastructure modernisation (index), share of water management expenditure in GDP (%), volume of key reservoirs (km^3), reduction of winter releases (%), glacial runoff (km^3/year), automated hydroposts (units), average delay in hydrological data transmission (hours), implemented decisions of inter-state commissions (units), economic damage from uncoordinated actions (million USD/year) and the potential for water savings through the introduction of synchronised systems (%). Standard statistical algorithms and calculation formulas were used for data processing, providing a quantitative assessment of differences and ratios among water-use indicators. The calculations were performed in Statistica 12.0 (StatSoft, USA) and Microsoft Excel 2021. The mean value was calculated according to formula (1):

$$M = \frac{\sum_{i=1}^{n} x_i}{n}, \quad (1)$$

where x_i – an individual observation; n – the number of observations.

For spatial analysis, layers of basin boundaries, water intakes, canals and reservoirs were used, processed in ArcGIS 10.8 with the application of Spatial Analyst and the Hydrology Toolset. The resulting data were used for quantitative comparison and for analysing the distribution of flow and water losses. The analysis of operational characteristics was carried out using production logs, reports and literature sources for Kyrgyzstan (Ministry of Water Resources..., 2024), Uzbekistan (Ikramov *et al*., 2025) and Tajikistan (Environmental Monitoring Report, 2024). The following parameters were considered: water losses during transportation (%), losses of regulated flow (million m^3), pump efficiency factor, deterioration of units (%), number of emergency shutdowns (cases/year), losses of delivered water (million m^3), volume of cleaning works (thousand m^3), fulfilment of repair plans (%), deterioration of the irrigation network (%), canals without concrete lining (%), area of land requiring reconstruction (million ha), cost of supplying 1 m^3 of water (USD), annual electricity expenditure (million USD), inter-repair period of pumps (years), share of capacities with an efficiency factor below 0.6%, regional water losses (million m^3/year), loss of crop yield (% of agricultural output), area of sustainably irrigated land (million ha).

The study relied on data from the analytical report on water resources in Central Asia for the three countries, World Bank (2024a). The following were examined: the share of irrigation and drainage communications in border zones (%), number of unauthorised accesses (units), water losses due to interventions (million m^3), material damage (million USD), number of functioning pumping stations, level of protection (coefficient), engineering stability (coefficient), share of facilities requiring enhanced protection (%), share of video-monitoring systems (%), number of installed leakage and pressure sensors, average delay in hydrological data transmission (hours), integral index of spatial stability, average response time to failures (hours), recovery coefficient after shutdowns, reduction in the number of emergency incidents (%), engineering reliability of systems, increase in regional security (%) and reduction in economic risks (%). To summarise the parameters, an integral assessment methodology was applied, in which composite indices were calculated as weighted averages of three groups of factors: engineering, organisational and digital.

The analysis was conducted on the basis of literature sources and reports of the United Nations Economic Commission for Europe (2025) for Uzbekistan (Asilbekova *et al*., 2023), for Kyrgyzstan (Water Yearbook, 2024) and for Tajikistan. The following indicators were used in the study: share of autonomous water use (%), controlled water withdrawal coefficient, number of automated observation points (units), average error of hydrological data (%), share of synchronised accounting points (%), level of digitalisation of hydrological networks (%), accuracy of flow-distribution forecasts (%), share of hybrid pumping stations (%), integral water sustainability index and projected sustainability level.

RESULTS

Dynamics of the functioning of the water resource distribution system

By 2024, the transboundary management of water resources in the Fergana Valley continued to show a high dependence on inter-state coordination and technological disparities. Between 2017 and 2025, as a result of the processes of delimitation and demarcation of inter-state borders, the structure of water flow distribution and the administrative affiliation of key hydraulic structures among Kyrgyzstan, Uzbekistan and Tajikistan changed. The process was completed between Uzbekistan and neighbouring countries by 2023, whereas demarcation between Kyrgyzstan and Tajikistan is ongoing, which has resulted in the redistribution of responsibility for the operation and technical maintenance of water management infrastructure. Prior to 1991, water resource management was carried out centrally within the framework of Soyuzgidroproyekt and the basin administrations of the USSR, which ensured the planned distribution of flow among the republics. After 1991, upon gaining independence, each country formed its own water regulation bodies, which increased fragmentation and complicated the coordination of limits. The presented data show that the water deficit in the Syr Darya basin reached critical levels, and the gap between approved limits and actual water withdrawal amounted to approximately 17%. Uzbekistan gained the greatest benefits from demarcation, as a significant share of main canals and reservoirs became located within its territory after the clarification of borders, including facilities previously operated jointly with Kyrgyzstan and Tajikistan. This change strengthened its position in regulating downstream flows and the distribution of irrigation resources. In Kyrgyzstan, the consequences of the division of operational networks manifested themselves in rising water losses and reduced controllability of upstream sections, whereas Uzbekistan obtained an advantage in controlling distribution lines and the water supply of irrigation zones as a result of the ratified and delimited borders. In Tajikistan, reconstruction works covered major canals and pumping stations, but their effectiveness was constrained by technical dependence on main lines, part of which, following demarcation,

came under the administration of neighbouring countries (Scientific-Information Center..., 2024a).

An additional factor transforming the water balance was Afghanistan's construction of the Qosh-Tepa Canal (since 2022), which led to the redistribution of the Amu Darya flow and a reduction in water inflow to downstream areas, including Tajikistan. This circumstance required Tajikistan, Kyrgyzstan and Uzbekistan to strengthen hydropolitical cooperation and adjust their water-use strategies. Thus, the delimitation and demarcation of 2017-2025 altered the balance of ownership and operation of water resources, intensifying technological and institutional asymmetry. The main challenges of the post-demarcation period relate to the division of responsibilities, the uneven modernisation of infrastructure and the complexities of inter-state regulatory coordination (World Bank, 2024b). Summary indicators reflecting the scale of demarcation impacts and the potential for reducing water losses are presented in Table 1.

Table 1. Key indicators of water management in the countries of the Fergana Valley (2023-2024

Indicator	Kyrgyzstan	Uzbekistan	Tajikistan	Notes
Actual water withdrawal in the Syr Darya Basin, km³ (2024)	2.8	3.4	1.9	Total regional volume – 8.1 km³
Deviation from the limit, % (2024)	-17	-10	-17	Uzbekistan offsets the deficit through flow redistribution
Actual utilisation of water limits, % (2024)	78	91	87	High utilisation of limits in the lower reaches of the basin
Water losses in open canals, billion m³ (2023-2024)	Decreased from 3.4 to 3.1	Decreased from 6.5 to 6	Decreased from 7.1 to 6	High losses in ageing irrigation networks
Length of modernised canals, km (2023-2024)	210	410	620	Active reconstruction of main canals in Uzbekistan
Number of pumping stations, units (2024)	12	38	25	Uzbekistan has the largest pumping network in the region
Level of hydrotechnical infrastructure modernisation, % (2024)	35	42	40	According to the World Bank, 2024
Share of water management expenditure in GDP, % (2024)	0.9	2.1	1.7	High burden on Uzbekistan's agricultural sector
Volume of key reservoirs, km³ (March 2024)	7.7 (Toktogul Reservoir)	2.3 (Tyuyamuyun Reservoir)	3.4 (Kayrakkum Reservoir)	Key reservoirs of the Fergana Valley
Glacial runoff, km³/year (2024)	1.2 (Petrov Glacier)	0.4 (Ak-Suu Glaciers)	0.5 (Gissar Range Glaciers)	Main sources feeding the basin's rivers
Reduction of winter releases, % (2024)	–	8	12	For accumulating spring water volumes
Automated hydroposts, % (2024)	38	49	42	Highest density of hydroposts in the lower reaches
Average delay in hydrological data transmission, hours (2024)	60-72	54-60	60-72	Rapid data transmission in Uzbekistan due to SCADA networks
Implemented decisions of inter-state commissions, % (2023-2024)	38	41	38	Share of implemented Syr Darya agreements
Economic damage from uncoordinated actions, million USD/year (2023-2024)	reduced from 95 to 90	reduced from 120 to 110	reduced from 95 to 90	Total regional damage, highest in the lower reaches
Structure of damage, %	60 – agricultural sector 25 – electricity sector 15 – operational costs	70 – agricultural sector 20 – electricity sector 10 – operational costs	60 – agricultural sector 25 – electricity sector 15 – operational costs	Distribution of losses across economic sectors
Potential water savings with synchronised systems, % (2024)	22	27	23	According to calculations by the Central Asian Water Resources Institute

Note: GDP – gross domestic product

Source: developed by the author based on CAWATER (2023; 2024), Scientific-Information Center... (2024a), E. Chembarisov & M. Rakhimova (2024), World Bank (2024b), NSCKR (2025), and formula (1)

By 2024, the transboundary management of water resources in the Fergana Valley continued to exhibit tension and dependence on inter-state coordination. According to statistical data, the highest actual water withdrawal was recorded in Uzbekistan – approximately 3.4 km^3, reflecting the key role of the country as the main water consumer in the lower reaches of the Syr Darya. The lowest withdrawal was observed in Tajikistan – approximately 1.9 km^3, where resource use was constrained by mountainous terrain and a smaller area of irrigated land. The gap between approved limits and actual withdrawal averaged 10-17%, indicating a deficit of flow and technological unevenness in water distribution. Resource shortages reached peak levels specifically in the spring-summer season, when irrigation demand is at its maximum and the coordination of inter-state releases becomes more difficult (Chembarisov & Rakhimova, 2024).

Infrastructure development in 2023-2024 demonstrated significant disparities. The largest volume of modernisation of irrigation systems was carried out in Uzbekistan – more than 410 km of canals and 38 pumping stations – which made it possible to reduce water losses in open channels from 6.5 to 6 billion m^3. The lowest rates of renewal were recorded in Kyrgyzstan, where approximately 210 km of networks were modernised, while the share of technically deteriorated canals remained high. The share of water management expenditure in GDP also varied: the highest was 2.1% in Uzbekistan, the lowest – 0.9% in Kyrgyzstan, which confirmed differences in the countries' capacities to finance the water sector. The energy-hydrological aspect remained one of the key sources of contradictions. The largest reservoir in the region – Toktogul in Kyrgyzstan – contained 7.7 km^3 of water, serving as the main regulator of flow. The lowest volumes were recorded in the Tuyamuyun Reservoir (2.3 km^3, Uzbekistan), located entirely under national administration, which limited the capacity to compensate for seasonal fluctuations and regulate water supply to Uzbekistan's irrigation systems. Irregular releases resulted in water shortages in downstream areas and yield losses amounting to up to 60% of the total damage to the agricultural sector. The region's aggregate economic damage was estimated at USD 110-120 million per year, with Uzbekistan bearing the largest losses and the mountainous areas of Tajikistan the smallest (Scientific-Information Center..., 2024a).

The level of digitalisation of hydromonitoring also differed. The highest level of automation was recorded in Uzbekistan (approximately 49% of hydroposts), the lowest – in Kyrgyzstan (38%). The average delay in data transmission amounted to 54-72 hours, which limited the effectiveness of response during inter-agency coordination. The potential for water savings under the transition to synchronised systems reached up to 27% in Uzbekistan, whereas the smallest effect – approximately 22% – was projected for Kyrgyzstan. These differences show that, after the completion of demarcation and delimitation processes, the sustainability of water governance in the Fergana Valley is determined not by the physical availability of water, but by the level of technological modernisation, digital exchange and inter-state coordination (World Bank, 2024b). Regions with the highest water withdrawals and the highest level of automation (Uzbekistan) gain an advantage in the stability of flow distribution, whereas territories with minimal modernisation (Kyrgyzstan) remain vulnerable to seasonal shortages and losses.

Dynamics of the modernisation and reconstruction of irrigation networks

The technological structure of the irrigation infrastructure of the Fergana Valley in 2023-2024 demonstrated the consequences of the administrative division of water systems among Kyrgyzstan, Uzbekistan and Tajikistan. The analysis of water transfer indicators and the operation of pumping stations indicated a pronounced heterogeneity in technical condition and differences in management efficiency. Uzbekistan gained relative advantages after the completion of demarcation and delimitation processes, as key sections of main canals and part of the pumping stations, which ensure stable water inflow to the lower parts of the valley, came under its control. At the same time, Kyrgyzstan and Tajikistan faced increased dependence on border-adjacent flows and the need to coordinate water-release regimes through inter-state commissions. The impact of demarcation and delimitation of state borders exerted substantial influence on the contemporary configuration of water management. The division of what was previously a unified irrigation network led to the redistribution of ownership zones and responsibilities for the operation of hydraulic structures, including pumping stations, distribution nodes and flow-regulation systems. Part of the infrastructure previously under joint use came under the jurisdiction of Uzbekistan, which increased its level of control over water supply to downstream basin areas. Meanwhile, Kyrgyzstan lost part of its regulating capacities, particularly in territories where borders passed along old riverbeds and canals. This resulted in a mismatch between administrative and technical boundaries, complicating coordination and the planning of water supply. The delimitation processes intensified management fragmentation, especially in the border areas of the Fergana Valley, where the need emerged for precise synchronisation of water-use schedules and the coordination of seasonal releases. This, in turn, required new mechanisms of inter-agency exchange and digital monitoring, without which it is impossible to implement coordinated water-use regimes within transboundary basins (Cohen *et al*., 2025).

Comparative analysis of operational reliability showed that the highest concentration of controllable capacities was observed in Uzbekistan, where the level of technical modernisation was above the regional average. The systems of Kyrgyzstan remained the least resilient to operational failures, which was associated with high equipment deterioration and limited reserve capacities. Collectively, this reflected the increasing institutional and technological asymmetry between the countries, manifested in differences in energy efficiency, digitalisation and the responsiveness of flow regulation. Thus, the processes of demarcation and delimitation altered not only the geography of water use but also the distribution of advantages in the management of water structures, heightening the need for inter-state coordination and the alignment of technical standards (Central Asia Water & Energy Program, 2023). Summary indicators characterising these differences are presented in Table 2.

Table 2. Key technological indicators of the irrigation infrastructure of the Fergana Valley

Indicator	Kyrgyzstan	Uzbekistan	Tajikistan	Regional average
Water losses during transport, %	16-20	18-22	17-19	19
Losses of managed flow, million m³/year	80	110	85	92
Efficiency coefficient of pumping stations	0.64-0.68	0.66	0.65	0.65
Wear of pumping units, %	75	70	72	72
Number of emergency shutdowns, cases/year	7	6	6	6
Losses of supplied water, million m³/year	25	35	25	28
Annual volume of cleaning works, km	180	320	240	247
Fulfilment of repair plans, %	32	48	38	39
Wear of the irrigation network, %	62	55	60	59
Canals without concrete lining, %	40	33	40	38
Area of land requiring reconstruction, thousand ha	70	90	100	87
Cost of supplying 1 m³ of water, USD	0.025	0.021	0.022	0.023
Annual electricity expenditure, million USD	10	20	10	13
Average inter-repair period of pumps, years	5	6	5	5.3
Share of capacities with efficiency below 0.6%	25	22	25	24
Water losses across the region, million m³/year	200	230	200	210
Yield losses, % of gross agricultural output	8	6	8	7
Area of sustainably irrigated land, million ha	0.3	1.4	0.5	1.07

Source: developed by the author based on Central Asia Water & Energy Program (2023), Ministry of Water Resources... (2024), Environmental Monitoring Report (2024), N. Ikramov *et al*. (2025), A. Cohen *et al.* (2025)

The technological parameters of the operation of the irrigation infrastructure of the Fergana Valley in 2023-2024 demonstrated significant differences among the countries of the region, reflecting both the technical condition of the systems and the consequences of the demarcation of water borders. Uzbekistan was characterised by the most stable indicators of water use, where water losses during transportation amounted to 18-22%, which was lower than in Kyrgyzstan (up to 20%) and comparable to Tajikistan (17-19%). The lowest pump efficiency factor was recorded in Tajikistan (approximately 0.65), whereas in Uzbekistan it reached 0.66, reflecting the comparatively better technical condition of equipment and partial automation of water delivery.

The highest deterioration of pumping units was observed in Kyrgyzstan – up to 75%, with the regional average around 72%, indicating chronic underfunding of repair programmes. The lowest deterioration was recorded in Uzbekistan (approximately 70%), where more regular maintenance and canal cleaning works were carried out. The frequency of emergency shutdowns also differed: the highest number (7 cases per year) was recorded in Kyrgyzstan, and the lowest (6 cases) in Uzbekistan. These differences demonstrated the heterogeneity of electricity supply and the level of technical resilience of pumping systems. Following the demarcation and delimitation of state borders carried out in 2017-2024, what had previously been a unified irrigation network became divided among the countries, leading to a shift in water flows and in the distribution of responsibilities for the operation of facilities. As a result, the largest losses of regulated flow were recorded in Uzbekistan – approximately 110 million m^3 per year – and the smallest in Kyrgyzstan (80 million m^3). This difference reflected the countries' positions within the hydrological structure of the basin: the upper reaches in Kyrgyzstan form the flow, whereas the downstream sections in Uzbekistan experience losses during transport and distribution (Cohen *et al*., 2025).

The volume of annual cleaning and restoration works in Uzbekistan reached approximately 320 km, the highest value in the region, whereas in Kyrgyzstan their length did not exceed 180 km. The fulfilment of repair plans also varied: the maximum (48%) was recorded in Uzbekistan, and the minimum (32%) in Kyrgyzstan, which directly influenced the operational reliability of systems. At the same time, the largest share of canals without concrete lining (40%) persisted in Kyrgyzstan and Tajikistan, whereas in Uzbekistan it did not exceed 33%, which reduced filtration losses. Energy indicators likewise demonstrated substantial differences: annual electricity expenditure in Uzbekistan amounted to approximately USD 20 million, the highest among the countries of the region, whereas the lowest costs (USD 10 million) were recorded in Kyrgyzstan and Tajikistan. The cost of supplying water ranged from USD 0.021 per m^3 in Uzbekistan (the lowest) to USD 0.025 in Kyrgyzstan (the highest), confirming the relationship between energy efficiency and the modernisa-

tion of equipment. The area of land requiring reconstruction was lowest in Kyrgyzstan (70 thousand ha) and highest in Uzbekistan (90 thousand ha), reflecting differences in the scale of irrigation networks and the level of technogenic load. Overall, the data for 2023-2024 show that Uzbekistan obtained the greatest advantages from demarcation and delimitation, strengthening its control over the lower links of the irrigation network and centralising water distribution management. Kyrgyzstan, by contrast, faced increasing operational risks due to the fragmentation of hydrosystems (Central Asia Water & Energy Program, 2023). Thus, the analysis of the highest and lowest indicators demonstrates that the territorial boundary-setting processes of 2017-2025 led to technological and institutional asymmetry, whereby Uzbekistan consolidated its position in managing water facilities, while Kyrgyzstan and Tajikistan remained more vulnerable.

Comprehensive analysis
of the spatial reliability of the region's hydrosystems

Following the completion of the demarcation and delimitation of inter-state borders carried out between 2017 and 2025, a significant share of the irrigation and drainage communications of the Fergana Valley became divided among Uzbekistan, Kyrgyzstan and Tajikistan. Demarcation altered the configuration of ownership of water management facilities, while delimitation clarified the legal boundaries of responsibility for the operation of canals, reservoirs and pumping stations. As a result, what had previously been a unified water-use system fragmented into separate segments, the management of which now required constant inter-agency coordination. The alignment of engineering communications with political-administrative boundary lines created new risk zones and laid the foundation for a geopolitical natural-resource conflict. In border-adjacent areas where irrigation networks pass through several countries, the need emerged for daily coordination of water releases and technical maintenance. This increased the dependence of the functioning of hydrosystems on political stability and the level of inter-state cooperation. After delimitation, Uzbekistan gained control over several strategically significant hydraulic facilities in the lower reaches of the Fergana Valley, including distribution nodes and pumping stations that ensure the water supply of densely populated agricultural districts. Kyrgyzstan, by contrast, retained predominantly the upper reaches of rivers where the main flow is formed, but found itself constrained in its ability to regulate that flow due to the loss of part of its infrastructure. Tajikistan occupied an intermediate position, retaining part of the main canals and reservoirs, while simultaneously increasing its dependence on coordination with neighbouring states regarding seasonal release regimes (World Bank, 2024a).

Demarcation and delimitation not only consolidated new borders but also altered the mechanisms of ownership and water allocation. Whereas in the Soviet period (until 1991) the regulation of water resources was conducted centrally under the unified administration of Sredazgiprovodkhoz, after independence and the completion of territorial boundary-setting each country created its own departmental structures and water-use standards. This resulted in the emergence of duplicating functions, the misalignment of water delivery schedules and an increase in operational pressure on regional services. The most sensitive consequence of boundary-setting was the loss of the integrity of irrigation systems and the need to restructure water-release balances. Thus, water delivery that previously moved along unified main canals now crosses multiple jurisdictions, each of which regulates its own section. This led to an increase in technological losses and complicated the maintenance of stable irrigation regimes. The policy of Afghanistan became an additional destabilising factor. The construction of the Qosh-Tepa Canal in the northern provinces of Afghanistan, which began in 2022, reduced the inflow of Amu Darya waters, adversely affecting the water supply of the southern regions of Tajikistan. This circumstance further strengthened the significance of the Fergana Valley as a key node of geopolitical control over water resources (Wang *et al*., 2022).

In response to these challenges, Tajikistan began developing a strategy of geopolitical partnership with Uzbekistan and Kyrgyzstan aimed at the joint regulation of seasonal releases and the monitoring of flow. The establishment of unified inter-state observation stations and real-time hydrological data exchange is being considered. Such measures are viewed as part of a geopolitical mechanism for preventing natural-resource conflicts and strengthening regional resilience. Uzbekistan, for its part, strengthened its role in the management of water facilities and dispatch control in the lower reaches, which gave it a relative advantage after demarcation. Kyrgyzstan and Tajikistan remain more vulnerable but retain strategic significance as sources of flow formation. Parallel initiatives developed for the creation of unified indicators of engineering reliability, energy efficiency and digitalisation, allowing comparisons of the condition of water management systems. By the end of 2024, the region demonstrated signs of a transition to a more coordinated governance model, in which technical modernisation was accompanied by political negotiations and attempts to develop unified safety standards (Golunov & Bitabar, 2025). Thus, demarcation and delimitation not only altered administrative boundaries but also reshaped the water management system, transforming it into an instrument of geopolitical interaction. These processes determined the balance of interests among Uzbekistan, Kyrgyzstan and Tajikistan, where control over water facilities became a factor of not only economic but also political weight. Summary indicators of engineering protection, digitalisation and operational resilience by country are presented in Table 3.

Table 3. Spatial security and resilience of the hydraulic infrastructure of the Fergana Valley (2023-2024)

Indicator	Kyrgyzstan	Uzbekistan	Tajikistan	Notes
Share of irrigation and drainage communications in border zones, %	38	42	41	After border demarcation, zones of operational risk for system maintenance
Number of recorded unauthorised accesses (2023-2024)	11	9	10	Interventions in the operation of gates and canals

Table 3. Continued

Indicator	Kyrgyzstan	Uzbekistan	Tajikistan	Notes
Total water losses due to interventions, million m³	25	28	32	Average annual regional loss volume: 75 million m³
Direct material damage, million USD	3.2	2.9	2.6	Total regional damage: USD 7.6 million
Number of functioning pumping stations, units	6	9	8	Greatest density in the lower reaches of the valley
Level of protection of pumping stations (coefficient)	0.72	0.75	0.69	Reflects the presence of control and security systems
Engineering stability of water supply networks (coefficient)	0.68	0.77	0.74	Characterises the technical condition of infrastructure
Share of facilities requiring enhanced engineering protection, %	31	26	36	Facilities with low stability and high wear
Video-monitoring systems, % of total number of canals	43	54	46	Level of digital monitoring of the hydraulic network
Installed leakage and pressure sensors, units	12	38	18	Increased the rapid detection of leakages
Average delay in hydrological data transmission, hours	70	58	65	Regional average indicator: 64 hours
Integral index of spatial sustainability	0.73	0.79	0.71	Aggregate assessment of engineering, digital and organisational protection
Average response time to emergency failures, hours	5	4	6	Reduced following the introduction of a three-level control system
Restoration coefficient after emergency shutdowns	0.83	0.86	0.82	Reflects the effectiveness of maintenance services
Reduction in the number of emergency incidents, % compared with 2023	12	16	17	Dynamics of improvement after digitalisation
Engineering reliability of systems (national average)	0.74	0.76	0.74	Regional average level
Increase in regional security level, %	11	12	11	As a result of digitalisation and the coordination of engineering standards
Reduction of economic risks, %	15	16	15	Compared with 2023

Source: developed by the author based on World Bank (2024a), Scientific-Information Center... (2024b)

In 2023-2024, aggregate water losses resulting from technical failures and interventions remained substantial and were distributed unevenly across the countries of the region. The highest leakages were recorded in Tajikistan – approximately 32 million m^3 – which was associated with the high level of infrastructure deterioration and insufficient automation of processes. The lowest values were observed in Uzbekistan, where losses did not exceed 28 million m^3 owing to the introduction of remote monitoring and the systematic servicing of pumping stations. Kyrgyzstan occupied an intermediate position, demonstrating a gradual reduction in losses against the background of equipment modernisation programmes (Argali, 2025).

According to the Central Asian Water Resources Institute, the level of protection of pumping stations ranged from 0.69 in Tajikistan to 0.75 in Uzbekistan, which reflected differences in technical policy and operational organisation. Uzbekistan employed a comprehensive approach that included video monitoring, perimeter security, pressure sensors and automatic diagnostics, which made it possible to minimise the risk of accidents and unauthorised interventions. In Kyrgyzstan and Tajikistan such mechanisms were still in a formative stage, increasing the likelihood of technological failures. Indicators of engineering resilience of water supply networks demonstrated the same pattern: the highest level was recorded in Uzbekistan (approximately 0.77), and the lowest – in Kyrgyzstan (around 0.68). These differences were explained by the degree of equipment renewal, the intensity of repair works and the level of energy efficiency. Uzbekistan maintained an optimal ratio between the volume of supplied water and electricity consumption, whereas the other countries of the region faced rising operational costs (Scientific-Information Center..., 2024b).

Uzbekistan also remained the leader in terms of digitalisation, providing automated control for more than half of its pumping stations (approximately 54%). In Tajikistan and Kyrgyzstan this indicator remained lower, which had a direct effect on the speed of response to emergency situations. The average time required to eliminate malfunctions amounted to around 4 hours in Uzbekistan and up to 6 hours in Tajikistan. Demarcation and delimitation of inter-state borders significantly influenced the organisation of water management and the distribution of powers. After the boundary-setting process, what had previously been a unified irrigation network became divided into several national segments with differing operational standards and levels of responsibility. Ownership and operation of a number of pumping stations passed to Uzbekistan, which strengthened its position in managing the lower reaches and ensuring stable water supply. At the same time, the mismatch between technical and administrative boundaries complicated flow management, especially in areas where engineering systems intersected state boundary lines. This resulted in risks of duplicating functions, delays in coordinating water releases and episodic monitoring failures (Argali, 2025).

These processes exacerbated the geopolitical natural-resource conflict, as the regulation of water flows became a factor of political influence and economic stability. Uzbekistan

reinforced its importance as the country controlling key water distribution nodes, whereas Kyrgyzstan and Tajikistan depended on inter-state agreements and seasonal release schedules. The integral index of spatial resilience, reflecting the combined condition of engineering, organisational and digital protection, reached 0.79 in Uzbekistan and 0.71 in Tajikistan. The regional average amounted to approximately 0.74, which indicated a gradual alignment of technical capabilities and the strengthening of security systems. Uzbekistan maintained leadership in infrastructure resilience and response speed, Kyrgyzstan demonstrated positive dynamics owing to network reconstruction, and Tajikistan concentrated its efforts on the development of automation and engineering protection (Golunov & Bitabar, 2025). Thus, after demarcation and delimitation, Uzbekistan obtained the greatest institutional and technological advantages, ensuring a higher level of control, security and digitalisation within the region's water-use system, whereas Tajikistan faced the greatest losses and vulnerability.

Transformation of approaches to water resource management in the region

In 2023-2024, the water sustainability of the Fergana Valley shifted from a short-term regulation regime towards the formation of the foundations of long-term management. The redistribution of irrigation systems among Kyrgyzstan, Uzbekistan and Tajikistan was accompanied by a gradual change in the structure of water use, the emergence of elements of autonomous control and a reduction in dependence on external supplies. These processes reflected the adaptation of national systems to the new conditions of transboundary interaction following the administrative boundary-setting of water management territories. Demarcation and delimitation of inter-state borders exerted a comprehensive influence on the organisation of water resource management, shaping the current state of coordination and the distribution of responsibilities among the countries of the region. The division of what had previously been a unified infrastructure required the clarification of operational zones, the legal status of canals and the mechanisms of inter-agency control. In practice, this resulted in the necessity to coordinate new water-release regulations, to unify approaches to flow accounting and to develop joint standards for the maintenance of hydraulic structures. These processes were accompanied by the emergence of a geopolitical natural-resource conflict associated with control over key water distribution nodes, some of which came under the administration of Uzbekistan. Simultaneously, the legal and technical foundations were being formed for the digital exchange of data, making it possible to integrate national monitoring systems into a unified transboundary network (Prniyazova *et al.*, 2025).

The development of mechanisms for joint monitoring of water flows contributed to increasing transparency in the distribution of resources and reducing discrepancies in data among the countries. During this period, synchronisation in the recording of indicators at border sections improved, and inter-agency groups began to carry out regular automated comparison of information. Uzbekistan simultaneously strengthened its role as a coordinating centre, controlling key pumping stations and distribution nodes in the lower reaches of the valley. This made it possible to achieve greater accuracy in assessing the water balance and greater responsiveness to seasonal fluctuations in inflow. Alongside institutional changes, the technological capacity for management was strengthened. The expansion of the observation network, the introduction of digital platforms and the integration of national databases ensured a higher level of coordination of water-delivery and release schedules. The joint use of telemetric systems and unified reporting formats facilitated progress towards establishing an integrated information environment covering the main basin nodes of the Fergana Valley (Prniyazova *et al.,* 2025). Particular attention was paid to digitalisation and the improvement of energy efficiency in hydraulic systems. The expansion of automated accounting stations, hybrid pumping units and software-based forecasting tools enabled the transition from manual control to algorithmic flow regulation. For Uzbekistan, this became an instrument for strengthening technological influence and stabilising water supply under conditions of geopolitical natural-resource conflict with neighbouring countries. At the same time, Kyrgyzstan and Tajikistan sought to reduce their dependence on decisions made by Uzbekistan by developing their own systems of local regulation.

Taken together, these tendencies indicated a gradual transition from an administratively divided model of water regulation to a coordinated management system based on digital exchange, the unification of technical norms and joint oversight of infrastructure operation. Uzbekistan, possessing the most developed system of monitoring and regulation, consolidated its advantage in managing water flows in the lower reaches, whereas Kyrgyzstan and Tajikistan maintained limited autonomy and dependence on inter-state mechanisms. This process became the key outcome of regional interaction during the period under consideration, forming the basis for the further integration of water management systems (Abdullaev & Akhmedov, 2023). Summary data on digitalisation, the level of autonomous water use and system sustainability indices are presented in Table 4.

Table 4. Water sustainability and long-term resource management in 2023-2024

Indicator	Kyrgyzstan	Uzbekistan	Tajikistan	Notes
Share of autonomous water use, %	65	74	67	Reflects the degree of independent water supply after delimitation
Coefficient of managed water withdrawal	0.78	0.86	0.75	Ratio of supplied to effectively utilised water volume
Automated observation points, units	20	32	18	Joint accounting of flow at transboundary sections
Average hydrological data error, %	8	6	9	Error margin in inter-state data exchange
Share of synchronised accounting points, %	46	58	44	Percentage of facilities integrated into the unified monitoring system

Table 4. Continued

Indicator	Kyrgyzstan	Uzbekistan	Tajikistan	Notes
Level of digitalisation of hydraulic networks, %	49	62	47	Includes telemetric sensors and digital gateways
Accuracy of flow-distribution forecasts, %	87	92	85	Increase in accuracy following the introduction of digital systems
Share of hybrid pumping stations (solar installations), %	11	21	9	Use of renewable energy sources
Integral index of water sustainability (2024)	0.78	0.83	0.76	Comprehensive assessment of technical and institutional sustainability

Source: developed by the author based on I. Abdullaev & Sh. Akhmedov (2023), K. Asilbekova *et al.* (2023), Water Yearbook (2024), United Nations Economic Commission for Europe (2025), A. Prniyazova *et al.* (2025)

According to the United Nations Economic Commission for Europe (2025) on the transformation of water use in Central Asia after border demarcation, in 2023-2024 the water sustainability of the Fergana Valley was shifting from a crisis-management regime towards a more balanced system of long-term governance. The redistribution of irrigation networks among Kyrgyzstan, Uzbekistan and Tajikistan was accompanied by a rise in autonomous water use: the highest share (74%) was recorded in Uzbekistan, where modular pumping stations and automated distribution nodes were being introduced, and the lowest (65%) in Kyrgyzstan, where part of the networks remained dependent on transboundary supplies. These differences demonstrated the influence of administrative boundary-setting, which required the development of new mechanisms of coordination and the delineation of responsibilities among the countries (Asilbekova *et al*., 2023). The coefficient of controlled water withdrawal ranged from 0.86 in Uzbekistan (the highest value) to 0.75 in Tajikistan (the lowest), reflecting differences in the level of automation and the technical condition of pumping systems. Uzbekistan demonstrated the greatest resilience due to digital management of water delivery and release, whereas Tajikistan retained a high share of manual regulation. Kyrgyzstan occupied an intermediate position (0.78), gradually introducing elements of remote regulation. These values indicated a trend towards the alignment of water load and a reduction in dependence on transboundary flows, forming a basis for the transition to joint water resource utilisation (Prniyazova *et al.*, 2025).

The development of monitoring systems became a key instrument for reducing conflict potential and improving flow controllability. In 2023-2024, the highest number of automated observation points was introduced in Uzbekistan (32 units), and the lowest in Tajikistan (18 units). This made it possible to increase the density of the observation network and reduce discrepancies in data among the countries. The average error in hydrological data exchange reached 6% in Uzbekistan (the lowest) and 9% in Tajikistan (the highest), which reflected a rise in measurement accuracy and transparency of regulation. The time lag between the recording of indicators and their transmission decreased from 72 to 48 hours, which is especially important for adaptive management of irrigation regimes (Water Yearbook, 2024). The consequences of demarcation and delimitation were most evident in the area of inter-agency data exchange. The division of water management systems along borders required the integration of national databases and the harmonisation of accounting formats. According to the Water Yearbook, the highest coverage of transboundary accounting points – 58% – was ensured in Uzbekistan, and the lowest – 44% in Tajikistan. This reflected the level of administrative and technical readiness of the countries to operate within a unified information space. Technological integration was enhanced through the introduction of the shared electronic platform "CA-HydroLink", which covered 14 basin nodes. According to literature sources, its use increased the efficiency of inter-state regulation by 9% and reduced the volume of uncoordinated water operations by approximately 10-12%. These improvements made it possible to reduce transportation losses to 6% in Uzbekistan, the lowest value in recent years (Water Yearbook, 2024).

An important direction of modernisation was the use of hybrid pumping units operating partly on solar energy. Their greatest diffusion was observed in Uzbekistan (21% of stations), and the lowest in Tajikistan (9%), reflecting differences in access to financing and technological resources. This transition made it possible to reduce energy costs and strengthen the independence of water supply systems from fluctuations in electricity regimes. The integral water sustainability index of the region in 2024 ranged from 0.83 in Uzbekistan (the highest value) to 0.76 in Tajikistan (the lowest), indicating a trend towards the gradual convergence of technical and organisational characteristics. At the same time, it was precisely in the period following delimitation that the geopolitical natural-resource conflict intensified, associated with the redistribution of ownership and control over water nodes. Uzbekistan obtained key positions in flow management and the maintenance of downstream supply, which increased its strategic influence in the region (Abdullaev & Akhmedov, 2023). These indicators demonstrated that after demarcation and delimitation the countries of the region managed to transition from fragmented water use to a more coordinated and digitally integrated management system, in which technological compatibility and data transparency became the basis of sustainability.

DISCUSSION

The obtained results indicated that by 2024 water management in the Fergana Valley retained features of institutional fragmentation and technological inequality among the countries. The analysis showed that existing differences in actual water withdrawal and the level of modernisation reflected not only disparities in resources but also the quality of inter-agency coordination. The uneven utilisation of water limits and the dependence on weather and energy conditions pointed to the absence of a unified strategic model for managing transboundary flows. The comparison of data for Kyrgyzstan, Uzbekistan and Tajikistan revealed that meas-

ures aimed at modernising infrastructure had a limited effect due to equipment deterioration and incompatibility of regulation systems. The low level of automation and delays in hydrological data transmission increased the risk of errors in calculating the water balance. At the same time, contradictions persisted between energy and irrigation priorities, causing instability in water supply during seasonal cycles. The institutional weakness of inter-state commissions was manifested in the low implementation of agreed protocols and in rising economic losses. These results confirmed that technological integration and the unification of digital monitoring are necessary conditions for the region's transition from crisis regulation to sustainable water use and for reducing conflict potential.

In the context of the general theoretical works of A. Ghaffar *et al*. (2023) and S. Yusof & M. Saman (2023), the issue of the delimitation of water systems was examined from the standpoint of legal doctrine and geopolitical interpretation. A. Ghaffar *et al*. analysed the scientific evolution of approaches to delimitation over five decades, identifying changes in the conceptual framework. S. Yusof & M. Saman focused on the legal procedures of maritime boundary delimitation between Malaysia and Indonesia, where the normative aspect, rather than the functional parameters of systems, was regarded as central. Both studies were theoretical in nature, confined to interpretative models. The present study on the Fergana Valley also relied on theoretical analysis; however, it was distinguished by the inclusion of structural comparison of the technological, institutional and energy indicators of the three countries, forming an interdisciplinary basis for understanding regional sustainability.

From the analytical perspective of the works of M. Salameh *et al*. (2021) and B. Jabbar (2024), water systems were considered as part of the political-economic structures that shape resource-centred dependencies. M. Salameh *et al*. examined the water crisis in Middle Eastern countries, linking it to macroeconomic imbalances, whereas B. Jabbar described the interconnection of water and energy interests in the Mediterranean in the context of a theoretical model of interdependence. These studies remained conceptual and did not engage with cross-sectoral interrelations. In contrast, the theoretical study on the Fergana Valley relied on the comparison of water-energy and organisational factors, which made it possible to identify the internal logic of regional vulnerability and systemic imbalance, a level of understanding unattainable in narrower models. In the epistemological context of the studies by J. Choi (2024) and M. Hossain *et al*. (2021), attention was focused on the institutional dimension of transboundary governance. J. Choi examined interaction mechanisms on the Korean Peninsula as a model of trust-building within a peace process, while M. Hossain *et al*. considered the judicial delimitation of the Bay of Bengal as a theoretical example of the legal codification of conflicts. Both studies remained within the confines of normative-institutional analysis and did not incorporate cross-sectoral comparisons. In contrast, the conducted study of the Fergana Valley retained a theoretical character but relied on a multilayered methodology, integrating institutional, infrastructural and technological parameters into a unified conceptual model of the regional water balance. This made it possible to substantiate the integrative potential of a theoretical system for managing transboundary resources that extends beyond individual legal cases.

Within the analytical syntheses of M. Aryal & M. Jung (2023) and T. Aklilu *et al*. (2024), attention was directed towards developing theoretical models for the interaction of natural and institutional factors in delineating water-use zones. M. Aryal & M. Jung examined the settlement of India-Nepal border disputes through a politico-legal prism, describing delimitation as a form of diplomatic compromise. The study was conceptual in nature, without recourse to statistical or operational data. T. Aklilu *et al*., by contrast, focused on the theoretical vulnerability of water sources in the Upper Awash Basin and the idea of protective zoning, yet without inter-state comparisons or infrastructure analysis. Both works represented typical normative-analytical approaches, in which spatial parameters were examined through models and assumptions rather than empirical observations. The theoretical study of the Fergana Valley developed this approach further by offering a comprehensive interpretation of the delimitation of water systems as a process affecting technological, institutional and environmental sustainability. Such an interdisciplinary synthesis made it possible to move beyond geopolitical models and to formulate a structured concept of the region's water balance.

In the context of the spatial-ecological interpretations of M. de Andrés & J. Barragán Muñoz (2022) and W. Ribeiro *et al*. (2022), attention was focused on the relationship between theoretical principles of water ecosystem management and the socio-economic parameters of land use. M. de Andrés & J. Barragán Muñoz examined the delimitation of coastal zones in Andalusia as an element of socio-ecological planning aimed at the sustainable use of natural resources, yet without extending the analysis to interregional interconnections. W. Ribeiro *et al*. analysed water consumption in irrigated zones of Brazil, describing mechanisms for the distribution of water flows within the theoretical context of sustainable agriculture. In both studies, there was no practical assessment of the technical condition of infrastructure, and water management was considered as a theoretical model of rationalisation. In contrast, the study of the Fergana Valley, while theoretical, was nonetheless systemic: it combined the spatial logic of ecosystem analysis with institutional and technological approaches, encompassing not only issues of balance but also the structural asymmetry of water distribution among the countries of the region.

From a methodological perspective, F. Pinillos *et al*. (2023) and B. Farhat *et al*. (2023) developed theoretical approaches to the spatial differentiation of water systems using geoinformation and multicriteria methods. F. Pinillos *et al*. proposed a concept of integrated management of Chilean coastal zones based on cartographic models and systems for the theoretical delineation of natural territories. B. Farhat *et al*. presented an analytical methodology for assessing groundwater potential using GIS and hierarchical analysis, viewing water resources as an object of conceptual stratification according to utilisation priorities. Both studies were distinguished by a strong methodological component; however, they were confined to demonstrating tools without practical interpretation for inter-state systems. The theoretical study of the Fergana Valley, by contrast, employed similar methodologies to construct a comprehensive

scheme of regional water sustainability. Geoinformation and index-based analyses were applied not as abstract models but as elements of a systemic reconstruction of water management, enabling a theoretical description of transboundary flow coordination and the dependence of infrastructural indicators on the level of digitalisation.

Within the framework of the theoretical developments of N. López-Calatayud *et al*. (2022) and N. Thanh Minh *et al*. (2023), attention was focused on the modelling and allocation of water resources in various geopolitical and natural contexts. N. López-Calatayud *et al*. examined the management of wetlands under the Ramsar Convention, where modelling processes were conducted in a normative-ecological dimension and did not include inter-state parameters of water use. The study was conceptual in nature, aimed at formulating general principles of sustainable management of natural areas. N. Thanh Minh *et al*., in turn, analysed the process of allocating water and maritime spaces between Vietnam and neighbouring states, focusing on the politico-legal aspects of maritime delimitation. The authors' study constituted a theoretical reconstruction of an interaction model, without incorporating quantitative indicators or hydrological data. Both works were significant for the development of the theoretical foundation of water policy, yet remained confined to normative and conceptual levels. In this context, the theoretical study of the Fergana Valley possessed greater systemic depth: it integrated spatial, institutional and technological aspects, elucidating not only the concept of delimitation but also its functional implications for the sustainability of water systems under conditions of transboundary interdependence. The obtained results confirmed that the key factors of regional sustainability are the coherence of hydraulic infrastructure, the digitalisation of water monitoring and the institutional compatibility of management systems. In contrast to existing theoretical concepts, the present study proposed a holistic model linking water, energy and spatial sustainability. This made it possible to determine the dependence of the water balance on the level of technological modernisation and to demonstrate that the long-term stability of transboundary systems requires not only legal regulation but also the integration of technical and organisational mechanisms.

CONCLUSIONS

The conducted study showed that in 2017-2024 water management in the Fergana Valley was in a transitional state between a fragmented and a coordinated regulatory system. The actual water withdrawal in the Syr Darya Basin amounted to 8.1 km^3, which was 10-17% below the approved limits. The highest level of limit utilisation was observed in Uzbekistan (91%), where the largest pumping network in the region operated, and the lowest in Kyrgyzstan (78%), reflecting differences in the degree of automation and institutional coherence. The overall water deficit reached 2 km^3, indicating the persistence of uneven flow distribution between the upper and lower reaches of the basin. Water losses during transport ranged from 16-20% in the upper reaches to 18-22% in the lower reaches, associated with canal deterioration and the uneven density of distribution networks. Uzbekistan implemented the most extensive restoration works: the length of annual cleaning operations reached 320 km, and the fulfilment of repair plans amounted to 48%. The wear of pumping units across the region remained high, averaging 70-75%, with an efficiency coefficient not exceeding 0.66. The integral index of spatial sustainability stood at 0.79 in Uzbekistan and 0.71 in Tajikistan, reflecting differences in engineering and digital protection. The average delay in hydrological data transmission decreased to 54-60 hours in Uzbekistan compared with 70 hours in Kyrgyzstan.

The level of digitalisation of hydraulic networks reached 62%, ensuring more rapid responses to emergency disruptions. Despite the completion of territorial boundary-setting, the Fergana Valley continued to experience a geopolitical natural-resource conflict driven by uneven distribution of headwaters, the concentration of hydraulic structures in the upper reaches, institutional differences and population growth in the lower reaches. Demarcation and delimitation did not eliminate these contradictions but merely altered their form, shifting them into a geopolitical dimension. Water resources continued to constitute a key element of regional stability, with the balance of interests among Uzbekistan, Kyrgyzstan and Tajikistan determining the prospects for sustainable development. Future research should focus on the empirical assessment of the effectiveness of digital monitoring systems and on modelling scenarios of sustainable water use under conditions of transboundary interaction.

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Фергана өрөөнүндөгү мамлекеттер аралык суу ресурстарын башкарууга демаркация жана делимитация процесстеринин таасири

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Аннотация. Изилдөөнүн максаты аймакта туруктуу трансчек аралык суу ресурстарын башкарууну өнүктүрүүдө институционалдык жана технологиялык факторлордун өз ара аракеттенүү үлгүлөрүн аныктоо болгон. Комплекстүү көрүнүштү алуу үчүн сүрөттөмө жана салыштырмалуу статистикалык ыкмалар, коэффициенттик анализ жана үч өлкөдө – Кыргызстан, Өзбекстан жана Тажикстанда – суу ресурстарын башкаруунун сандык жана сапаттык мүнөздөмөлөрүн көп өзгөрмөлүү салыштыруу колдонулган. Мамлекеттер аралык чек араларды демаркациялоонун жана делимитациялоонун институционалдык түзүмгө жана суу ресурстарын бөлүштүрүү механизмдерине тийгизген таасирин кошумча талдоо административдик өзгөрүүлөрдүн башкаруунун натыйжалуулугуна тийгизген таасирин тактоого мүмкүндүк берди. Жыйынтыктар көрсөткөндөй, суу ресурстарын башкаруу системаларынын техникалык абалында жана санариптештирүүсүндө айкын асимметрия 2017-жылдан 2024-жылга чейин сакталып калган. Сугат тармагынын эскириши Кыргызстандагы 62 %, Өзбекстандагы 55 % жана Тажикстандагы 60 % түздү, ал эми насостук агрегаттардын эскириши тиешелүүлүгүнө жараша 75 %, 70 % жана 72 %га жеткен. Ташуу учурундагы суунун жоготуулары Кыргызстандагы 16-20 %, Өзбекстандагы 18-22 % жана Тажикстандагы 17-19 % чегинде өзгөрүп турган, бул каналдарды модернизациялоо даражасындагы айырмачылыктарды чагылдырат. Башкарылуучу агым жоготуулары Кыргызстандагы 80 миллион м^3, Өзбекстандагы 110 миллион м^3 жана Тажикстандагы 85 миллион м^3 түздү, ал эми берилген суунун жоготуулары тиешелүүлүгүнө жараша 25, 35 жана 25 миллион м^{3}ге жетти. Региондогу жалпы технологиялык жоготуулар болжол менен 650 миллион м^{3}ге жетти, анын ичинде Өзбекстандагы 230-250 миллион м^3, бул төмөнкү агымды сугаруу системасына эң жогорку жүктөмгө туура келди. Жалпысынан алганда, Фергана өрөөнүндөгү узак мөөнөттүү суу туруктуулугунун негизин технологиялык интеграция жана маалымат алмашуу түзгөн координацияланган башкаруу моделине өтүү белгиленди. Изилдөөнүн практикалык баалуулугу анын жыйынтыктарын аймактагы сууну башкарууну жана инфраструктураны жакшыртууга, ошондой эле жаратылыш ресурстары боюнча геосаясий чыр-чатактардын тобокелдиктерин минималдаштырууга колдонууда жатат

Негизги сөздөр: жаратылыш ресурстарынын чыр-чатактары; гидротехникалык инфраструктура; санариптештирүү; сууну туруктуу пайдалануу; модернизациялоо; суу балансы; суу чек арасы

Воздействие процессов демаркации и делимитации на межгосударственное управление водными ресурсами стран Ферганской долины

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Аннотация. Целью исследования являлось выявление закономерностей взаимодействия институциональных и технологических факторов в формировании устойчивого трансграничного водного управления региона. Для получения комплексной картины использовались методы описательной и сравнительной статистики, коэффициентный анализ, а также многопараметрическое сопоставление количественных и качественных характеристик водного менеджмента трех стран – Кыргызстана, Узбекистана и Таджикистана. Дополнительно проведен анализ воздействия демаркации и делимитации межгосударственных границ на институциональную структуру и механизмы распределения водных ресурсов, что позволило уточнить влияние административных изменений на эффективность управления. Результаты показали, что в 2017-2024 годах сохранялась выраженная асимметрия в техническом состоянии и цифровизации систем водного хозяйства. Износ ирригационной сети составлял 62 % в Кыргызстане, 55 % в Узбекистане и 60 % в Таджикистане, тогда как износ насосных агрегатов достигал 75 %, 70 % и 72 % соответственно. Потери воды при транспортировке варьировали в пределах 16-20 % в Кыргызстане, 18-22 % в Узбекистане и 17-19 % в Таджикистане, что отражало различия в степени модернизации каналов. Потери управляемого стока составляли 80 млн м^3 в Кыргызстане, 110 млн м^3 в Узбекистане и 85 млн м^3 в Таджикистане, а потери подаваемой воды достигали 25, 35 и 25 млн м^3 соответственно. Совокупные технологические потери региона достигали около 650 млн м^3, включая 230-250 млн м^3 в Узбекистане, что соответствовало самой высокой нагрузке на оросительную систему низовьев. В целом отмечен переход к координированной модели управления, где технологическая интеграция и обмен данными формируют основу долгосрочной водной устойчивости Ферганской долины. Практическая ценность исследования состоит в применении его результатов для совершенствования водного управления и инфраструктуры региона, а также в целях минимизации рисков геополитических природно-ресурсных конфликтов

Ключевые слова: природно-ресурсные конфликты; гидротехническая инфраструктура; цифровизация; устойчивое водопользование; модернизация; водный баланс; водная граница

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Development of plastic deformations and ensuring shear resistance in asphalt concrete road pavements

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Abstract. The operating conditions of roads have deteriorated; the increase in the number of heavy vehicles and the increase in load per axle lead to an increase in plastic deformations on asphalt concrete pavements. This problem reduces the reliability of road layers and increases the costs of their operation and repair, especially during hot periods, when the appearance of rutting and wave-like deformations significantly reduces the strength of the layers. The aim of the study was to identify the causes of plastic deformations in asphalt concrete layers and to determine scientifically based methods aimed at increasing the resistance of road layers to displacement. The use of analytical, comparative and statistical analysis made it possible to achieve the objectives of the study, scientifically assess the resistance of asphalt concrete layers of road pavement to displacement and develop recommendations for practical application. The main results of the study showed that the resistance of asphalt concrete layers to displacement depends on a number of internal and external factors. Internal factors include the structure of the mineral skeleton, the shape and size of aggregates, the viscosity of the bituminous binder, and the degree of mixture density. Sharp and crushed mineral particles contribute to the formation of a mixture

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framework and reduce plastic deformations, while excessive use of bitumen or a grade that does not correspond to climatic conditions, on the contrary, contributes to the formation of rutting. The influence of temperature is also significant: in summer, the layers heat up, the viscosity of bitumen decreases, the relaxation time shortens, resulting in rutting and displacement. Water resistance of layers, adhesion properties and degree of compaction are decisive factors for determining resistance to plastic deformations. The practical significance of the study lies in the fact that its results allow road builders and engineers to optimise asphalt concrete mixtures, improve the quality of layer compaction and ensure long-term and reliable road operation taking into account temperature conditions

Keywords: rut; resistance to displacement; bituminous binder; mineral aggregates; temperature factors; mixture density; strength of road layers

INTRODUCTION

The sustainable functioning of road infrastructure is one of the key factors ensuring the efficiency of the transport system. The operational quality of highways is directly related to the structural strength of the pavement and its resistance to deformation. Asphalt concrete pavements are among the most widely used materials in road construction. However, during operation, such pavements are exposed to various mechanical and climatic factors. In particular, loads from heavy goods vehicles and high temperature conditions lead to the development of plastic deformations in asphalt concrete layers. One of the most common types of such deformation is the formation of wheel ruts on the road surface, i.e. rutting. This phenomenon reduces traffic safety and leads to the deterioration of transport operational performance indicators. In addition, the service life of the pavement is shortened, while maintenance and repair costs increase. A detailed study of the composition, structure, and mechanical properties of asphalt concrete mixtures plays an important role in improving pavement durability. In this regard, identifying the causes of plastic deformations in asphalt concrete layers and investigating methods for their prevention constitutes one of the important scientific problems in the field of road construction.

Plastic deformations and the process of rut formation in asphalt concrete pavements have been examined in the works of numerous researchers. For example, a study conducted by H. Wang *et al*. (2023) analysed the ageing of materials in asphalt pavements and its impact on deformation resistance. The authors noted that long-term operation of road pavements leads to changes in the physical and mechanical properties of the bituminous binder, thereby contributing to an increase in plastic deformations. The study demonstrated that the ageing process of bitumen reduces the structural stability of the mixture and increases the likelihood of rut formation. A number of studies have shown that the granulometric composition and structural framework of mineral aggregates have a significant influence on the durability of asphalt concrete pavements. X. Lu *et al*. (2024) analysed the structural properties of asphalt concrete mixtures using artificial intelligence models. The results indicated that the size of aggregates and their proportions significantly affect the stiffness of asphalt concrete and its resistance to rutting. In particular, mixtures with a higher proportion of coarse aggregates exhibited greater resistance to shear deformation.

Experimental modelling methods are widely used in the study of the deformation behaviour of asphalt concrete pavements. In a study by D.X. Lu *et al*. (2024), the rutting resistance of asphalt concrete was modelled using the discrete element method. The authors proposed a mathematical model taking into account the visco-plastic properties of the material and analysed the deformation changes in the asphalt concrete structure under the influence of traffic loading (Zhao *et al*., 2024). The study showed that load intensity and temperature conditions have a significant effect on the development of plastic deformations. The analysis of operational conditions of road layers is also important in studying deformations in asphalt concrete pavements. A study conducted by N.O.A.S. Jourdain *et al*. (2024) demonstrated that rut formation in road pavements is closely related to traffic flow intensity and the type of pavement structure. The statistical model proposed by the authors made it possible to determine the spatial characteristics of deformation along road sections. The study identified traffic load as one of the key factors contributing to rut formation.

In a study by V. Gunka *et al*. (2024), various methods of modifying road bitumen were analysed. The authors noted that bitumen modified with polymer additives contributes to improving the mechanical stability of asphalt concrete mixtures and increases resistance to high-temperature plastic deformations. D.L. Buruiana *et al*. (2023) showed that the use of micro-polypropylene additives improves the resistance of asphalt concrete to high-temperature deformations. Another group of Ukrainian researchers investigated the technological ageing processes of bituminous binders. In a study by M. Donchenko *et al*. (2024), it was shown that the ageing of bitumen alters its structural and rheological properties, thereby affecting the operational durability of asphalt concrete mixtures. The authors noted that antioxidants and special additives can slow down the ageing processes of bitumen. A study conducted by A. Jexembayeva *et al*. (2024) noted that the service life of asphalt concrete pavements is often lower than the design values. The study showed that polymer additives and dispersed reinforcing materials help to improve the mechanical properties of asphalt concrete mixtures. It was also emphasised that the proper formation of the mineral framework and the quality of the bituminous binder play an important role in the long-term performance of the pavement. In another study examining the operational conditions of road structures, P. Dong *et al*. (2024) noted that the loading regimes of asphalt concrete pavements vary depending on road topography and traffic flow characteristics. The authors demonstrated that on uphill and downhill sections of the road, dynamic loads from vehicles are higher, which leads to a more rapid development of deformation processes in asphalt concrete layers.

The studies reviewed above indicate that the deformation resistance of asphalt concrete pavements is determined by the combined influence of multiple factors. The structure of the mineral framework, the properties of the bituminous

binder, temperature conditions, traffic loads, and the characteristics of the pavement structure all have a significant impact on the formation of plastic deformations in asphalt concrete layers. At the same time, optimisation of the structural properties of asphalt concrete mixtures and modification of road materials represent important directions for improving pavement durability. The aim of this study was to analyse the causes of plastic deformation in asphalt concrete road pavements and to scientifically investigate the role of structural and material factors of asphalt concrete mixtures in their prevention.

MATERIALS AND METHODS

A set of analytical and statistical methods was employed in the study. The analytical method was used to assess the influence of the physical and mechanical properties of asphalt concrete (mixture density, the shape and size of mineral particles, and the viscosity of the bituminous binder) on the development of plastic deformations. Comparative analysis was carried out on the basis of published data and regulatory documents. Within this approach, scientific publications issued in the period 2022-2024 were examined, including works by M.M. Alamnie *et al*. (2022), A.H. Albayati & G.G. Al Khateeb (2023), Y. Zhao *et al*. (2024), among others. In each publication, the indicators of resistance of asphalt concrete layers to plastic deformation were analysed comparatively.

The statistical method involved the processing of data on the dynamics of pavement deformation for the period 2015-2025 provided by the State-owned enterprise "Kyrgyzavtozhol-South" (State-owned enterprise "Kyrgyzavtozhol-South", n.d.). The data were statistically compiled with regard to potholes, wheel ruts, and the displacement dynamics of pavement layers along road sections. In order to generalise and compare the results, scientific sources published in 2022-2025 were used. These materials were systematically analysed, and both internal and external factors influencing the occurrence of plastic deformation were identified, including temperature conditions, the structure of the mineral skeleton, the quality of bitumen, and the degree of compaction. The applied set of scientific methods – analytical, comparative, and statistical analysis made it possible to achieve the objectives of the study, to scientifically assess the shear resistance of asphalt concrete road layers, and to develop practical recommendations.

RESULTS AND DISCUSSION

The operational conditions of the structural layers of road pavements have undergone significant changes. The number of heavy and multi-axle freight vehicles within traffic flow has been steadily increasing, and the load per axle has exceeded the values specified at the design stage. Statistical data obtained during the study indicate that the number of pavement defects has increased in recent years (2021-2025). According to data provided by the State-owned enterprise "Kyrgyzavtozhol-South", the length of road sections affected by various types of deterioration varied over the period 2000-2025 (Fig. 1). In particular, during the period 2021-2025, the share of plastic deformations increased, and a rise in the number of wheel ruts and potholes on the pavement surface was identified. Over the years 2021-2025, this phenomenon showed a gradual upward trend, with especially intensive rut formation observed on sections with a high volume of heavy goods traffic (State-owned enterprise "Kyrgyzavtozhol-South", n.d.). This finding is consistent with the conclusions of other studies, which demonstrate that an increase in traffic flow accelerates deformation processes within pavement layers.

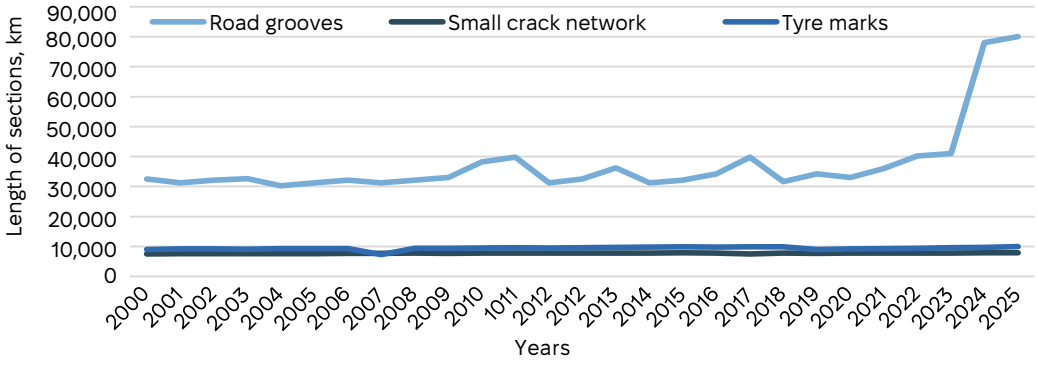

Figure 1. Temporal variation in the length of road sections with various defects, 2000-2025
Source: compiled by the authors using data from the State-owned enterprise "Kyrgyzavtozhol-South" (n.d.)

The types of plastic deformations observed in the upper layers of asphalt concrete pavements include: shear deformations through the full thickness of the layer, which occur without disrupting surface evenness and are characteristic of layers with high shear resistance; structural changes arising from long-term operation, most often observed in the form of minor curved lines at pedestrian crossings or near "Stop" signs; migrated deformations in the upper layer, caused by the upward movement and accumulation of bitumen from lower layers to a depth of 20-30 mm; transverse wave-like deformations, typically found in braking zones and on sloped sections; deformations caused by insufficient shear resistance of the layer, developing under the combined effect of high shear forces and elevated temperatures; minor irregularities and undulations, which subsequently contribute to the formation of wave-like deformations; wheel ruts, formed due to the repeated impact of heavy freight and passenger vehicles on specific sections of the road, particularly during peak traffic periods; and flow of the upper layer, observed near road edges, especially on straight sections with transverse gradients.

In summer, the temperature of the upper layer of asphalt concrete pavements may reach +50°C and higher. Prolonged solar radiation increases the temperature of the

material and alters the viscoelastic properties of the bituminous binder. As a result, the pavement softens, and under the passage of heavy vehicles, creep deformation and residual plastic deformation occur (Luan *et al*., 2023). Asphalt concrete mixtures incorporating higher-viscosity bitumen exhibit greater resistance to rutting (Albayati & Al Khateeb, 2023; Zhao *et al*., 2024). The shape and characteristics of aggregate particles used in filling voids also influence the formation of the asphalt skeleton.

Angular mineral particles (e.g. crushed stone) increase the shear resistance and strength of asphalt concrete mixtures. The internal friction of angular crushed aggregate particles ensures the integrity of the mixture, whereas particles with smoother shapes reduce the risk of rotational displacement. Asphalt concrete layers are generally recommended to be composed of 100% crushed material. Excessive bitumen content intensifies plastic flow and fatigue of the mixture, thereby reducing its stability. This issue is of considerable importance not only in terms of pavement quality deterioration but also in addressing structural and technological challenges. Rutting is one of the most significant problems requiring both prevention and remediation (Li *et al*., 2023). It arises due to the visco-plastic behaviour of the material. The strength and deformation properties of asphalt concrete are highly temperature-dependent: as temperature increases, the viscosity of bitumen decreases, the bonding between mineral particles weakens, and the material strength declines; conversely, at low temperatures, bitumen stiffens and the strength of asphalt concrete increases (Shi *et al*., 2023). The strength indicator varies widely depending on temperature. For example, the compressive strength of standard asphalt concrete specimens (for hot mixes, MPa) is approximately 1-2 at +50°C, 2-5 at +20°C, 8-13 at 0 °C, 10-17 at -10°C, and 18-30 at -35°C (GOST No. 9128-2009, 2010). These values clearly demonstrate the strong dependence of asphalt concrete strength on temperature. Resistance to shear deformation is also closely related to material strength. During hot summer conditions, as strength decreases, the stability of pavement layers deteriorates, whereas increased strength enhances resistance to shear deformation.

Studies by H.F. Tambunan *et al*. (2025) and M.M. Alamnie *et al*. (2022) indicate that naturally rounded mineral particles in asphalt concrete reduce material strength, adhesion, and shear resistance. This is due to their rounded shape and smaller contact surface area. The magnitude of internal friction depends on the gradation of the mineral mixture, as well as the shape and surface characteristics of the particles. Temperature sensitivity is a major drawback of bitumen-mineral mixtures, as they exhibit thermoplastic and coagulative properties. When bitumen binds with mineral particles, the strength of the mineral skeleton decreases, as the bitumen film coating the particles reduces internal friction forces and adhesion within the system. As a result, favourable conditions for rut formation are created. The intensity of rut formation depends on several factors: excessive use of bitumen, the selection of a bitumen grade unsuitable for regional climatic conditions, and a low compaction coefficient of the mixture. Plastic deformations primarily occur when the temperature of asphalt concrete reaches ≥40°C (Shi *et al*., 2023). This is associated with phase changes in high-temperature bitumen grades and structural changes in the mixture (Zhao *et al*., 2024). During hot summer conditions, the viscosity of the bitumen–mineral mixture decreases sharply, resulting in a reduction of relaxation time. If this time becomes shorter than the duration of load application, conditions are created for the development of plastic deformations. Considering the operating conditions throughout the entire service life of asphalt concrete pavements, it is important to ensure sufficient stiffness at low temperatures while maintaining high viscosity and shear resistance at elevated temperatures.

In winter, bitumen-mineral mixtures exhibit very high viscosity, and the relaxation time significantly exceeds the duration of load application. In contrast, during hot summer conditions, viscosity decreases and relaxation time shortens, sometimes becoming less than the duration of loading. Such conditions lead to the formation of plastic deformations. In addition, the water resistance of asphalt concrete affects both the physical and mechanical properties of the material and the durability of pavement layers. If water resistance is insufficient, premature deterioration occurs, as the bituminous organic binder does not adequately adhere to mineral particles, leading to film failure and layer degradation. The most effective way to address this issue is to improve water resistance through the use of surface-active agents (Buruiana *et al*., 2023; Zhalaldinov *et al*., 2025).

Based on the obtained results, a number of practical recommendations have been developed to reduce plastic deformations in asphalt concrete road pavements. Firstly, when designing asphalt concrete mixtures, it is necessary to carefully select the granulometric composition and shape of mineral aggregates (Li *et al*., 2023). Secondly, it is recommended to use bituminous binders appropriate to climatic conditions and to regulate their content at an optimal level. Thirdly, strict adherence to compaction technology during construction and control of density indicators at the production stage contribute to ensuring the long-term performance of pavements. In addition, consideration of traffic intensity and temperature conditions at the design stage is an important factor in improving operational durability.

The results of this study demonstrate that the occurrence of plastic deformations in asphalt concrete pavements is associated with the combined influence of several factors. In particular, it was established that the increase in traffic loads, the thermal regime of pavement layers, the structure of mineral aggregates, the properties of the bituminous binder, and the degree of compaction of the mixture have a significant impact on the shear resistance of pavement layers. These findings are largely consistent with the works of other authors who have investigated the operational durability of road pavements. For instance, H. Wang *et al*. (2023) examined the ageing processes of asphalt binders and noted that changes in their physico-mechanical properties lead to a reduction in the deformation resistance of road pavements. According to the authors, the ageing of bitumen during service alters its viscosity characteristics and weakens its bonding with the mineral skeleton. This phenomenon contributes to the formation of plastic deformations and rutting in long-term pavement operation. The results of the present study confirm a similar trend, as it was found that under elevated temperatures and increasing traffic loads, the viscosity of bitumen decreases as the temperature of asphalt concrete layers rises, leading to reduced resistance

to shear deformation. This phenomenon was also confirmed by Y. Luan *et al*. (2023), who demonstrated a direct relationship between bitumen properties and rutting resistance.

The structural characteristics of asphalt concrete mixtures were investigated by X. Lu *et al*. (2024) and Y. Mu *et al*. (2020), who reported that the granulometric composition of aggregates and their proportion directly affect the mechanical properties of pavement layers. Using artificial intelligence models, they determined that mixtures composed of coarse and angular mineral particles exhibit higher resistance to shear deformation. The findings of the present study are consistent with this conclusion, as angular and crushed mineral aggregates increase internal friction within the mixture and reduce the likelihood of plastic deformation. Furthermore, D.X. Lu *et al*. (2024) and M. Wei *et al*. (2024), who studied the deformation behaviour of asphalt concrete layers through mathematical modelling, demonstrated that traffic load intensity and temperature factors play a key role in the development of plastic deformations. The discrete element method proposed by these authors enables the investigation of microstructural changes in pavement layers. The results obtained in this study support this perspective, as it was established that an increase in temperature reduces bitumen viscosity and consequently decreases the shear resistance of the material.

The formation of rutting in road pavements is closely related to traffic intensity, as shown by N.O.A.S. Jourdain *et al*. (2024). Using statistical modelling approaches, the authors analysed the dynamics of pavement deformations and concluded that an increase in the number of heavy vehicles leads to a higher rate of pavement deterioration. The findings of the present study confirm this trend, as an increase in freight transport in recent years has resulted in a higher incidence of wheel track formation on road surfaces. The potential for improving the mechanical properties of asphalt concrete through the modification of bituminous binders was investigated by V. Gunka *et al*. (2024). The authors found that polymer-modified bitumen enhances the stability of asphalt mixtures under high-temperature conditions. The results of the present study support this conclusion, as it was established that increasing temperature reduces bitumen viscosity and consequently lowers the deformation resistance of pavement layers. M. Donchenko *et al*. (2024), who studied the technological ageing of bitumen, noted that changes in its rheological properties significantly affect the service life of asphalt pavements. They also demonstrated that antioxidant additives can slow down the ageing process. These findings further confirm that the chemical stability of the binder plays a crucial role in improving the quality of asphalt concrete mixtures.

A. Jexembayeva *et al*. (2024), who investigated the long-term performance of asphalt pavements, reported that the use of polymer additives contributes to improved mechanical stability of road materials. Their study showed that dispersed reinforcing materials enhance the structural stability of asphalt concrete. The results of the present study also confirm that optimisation of the structural composition of asphalt mixtures plays an important role in increasing pavement durability. In addition, P. Dong *et al*. (2024), who examined the operational conditions of road structures, highlighted that road geometry and traffic characteristics significantly influence deformation processes. According to their findings, dynamic loads are higher on uphill and downhill sections, leading to accelerated deterioration of asphalt concrete layers. The results of the present study also demonstrate the significant influence of these factors on pavement performance.

The analysis of the reviewed studies indicates that the resistance of asphalt concrete pavements to plastic deformation is determined by the interaction of multiple factors. The structure of the mineral skeleton, the quality of the bituminous binder, the thermal regime, traffic loads, and the characteristics of the road structure all have a direct impact on pavement performance. The findings of this study confirm the importance of these factors and demonstrate that optimisation of asphalt mixture composition and modification of road materials are among the key approaches to ensuring long-term pavement performance. Thus, the obtained results substantiate the necessity of comprehensively considering the structural properties of materials and technological parameters in order to enhance the deformation resistance of asphalt concrete pavement layers.

CONCLUSIONS

The results of the conducted study indicate that the occurrence of plastic deformations in asphalt concrete pavements was determined by the combined influence of several internal and external factors. Among these, the magnitude of traffic loads, the thermal regime of the pavement surface, the structure of mineral aggregates, the physical properties of the bituminous binder, and the degree of compaction of layers play a key role. In particular, under high summer temperatures, the viscosity of bitumen decreases, leading to a reduction in the structural stability of the mixture. As a result, defects such as rutting, wave-like deformations, and layer displacement occur on the pavement surface. The analysis of analytical, experimental, and statistical data confirmed that the shear resistance of asphalt concrete layers directly depends on traffic load intensity, temperature conditions, the structure of mineral aggregates, the properties of the bituminous binder, and the quality of compaction. The study also demonstrated that the mineral skeleton structure of the asphalt mixture plays a crucial role in the mechanical stability of the material. The use of angular and crushed mineral particles increases internal friction within the mixture and enhances the resistance of layers to shear deformation. Conversely, rounded and smooth particles weaken the structural framework of the mixture. In addition, the content and qualitative characteristics of bitumen are of significant importance. Excessive bitumen content may increase the plasticity of the mixture and reduce the stability of pavement layers. Therefore, the optimal selection of mixture composition is one of the key factors in ensuring the long-term performance of road pavements.

Based on the obtained results, practical recommendations aimed at reducing plastic deformations in asphalt concrete pavements have been developed. These include the proper selection of the granulometric composition and particle shape of mineral aggregates, the use of bituminous binders appropriate to climatic conditions, and the optimisation of their dosage. Furthermore, strict adherence to compaction technology during layer placement and effective density control are essential for ensuring long-term pavement performance. It is also necessary to take into

account traffic intensity and temperature conditions during the design stage of road construction. The implementation of these recommendations can contribute to extending pavement service life, reducing maintenance costs, and improving road safety. Overall, the results obtained demonstrate that the reliability of road pavements can be enhanced through the optimisation of asphalt mixture composition and the improvement of construction technologies for pavement layers. Future research should focus on the use of modified bitumen and the comprehensive modelling of pavement behaviour under various climatic conditions in order to further improve the deformation resistance of asphalt concrete layers.

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CONFLICT OF INTEREST

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Асфальт-бетон жол төшөлмөлөрүндө пластикалык деформациялардын өнүгүүсү жана жылышууга туруктуулукту камсыз кылуу

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Аннотация. Жолдордун иштөө шарттары начарлап, оор унаалардын санынын жана октук жүктөмдөрдүн көбөйүшү асфальт-бетон төшөлмөлөрүндөгү пластикалык деформациялардын көбөйүшүнө алып келди. Бул көйгөй жол катмарларынын ишенимдүүлүгүн төмөндөтөт жана аларды эксплуатациялоонун жана тейлөөнүн чыгымдарын көбөйтөт, айрыкча ысык мезгилде, чуңкур жана толкундуу деформациялар катмарлардын бекемдигин бир топ төмөндөтөт. Бул изилдөөнүн максаты асфальт-бетон катмарларындагы пластикалык деформациялардын себептерин аныктоо жана жол катмарларынын жылышууга туруктуулугун жогорулатуунун илимий жактан негизделген ыкмаларын иштеп чыгуу болгон. Аналитикалык, салыштырмалуу жана статистикалык анализди колдонуу изилдөөгө өз максаттарына жетүүгө, асфальт-бетон төшөлмө катмарларынын жылышууга туруктуулугун илимий жактан баалоого жана практикалык колдонуу боюнча сунуштарды иштеп чыгууга мүмкүндүк берди. Изилдөөнүн негизги жыйынтыктары асфальт-бетон катмарларынын жылышууга туруктуулугу бир катар ички жана тышкы факторлорго көз каранды экенин көрсөттү. Ички факторлорго минералдык скелеттин түзүлүшү, агрегаттардын формасы жана өлчөмү, битум байланыштыргычынын илешкектиги жана аралашманын тыгыздыгы кирет. Курч жана майдаланган минералдык бөлүкчөлөр аралашманын каркасынын пайда болушуна өбөлгө түзөт жана пластикалык деформацияны азайтат, ал эми битумду же климаттык шарттарга туура келбеген марканы ашыкча колдонуу, тескерисинче, чуңкурлардын пайда болушуна өбөлгө түзөт. Температура дагы маанилүү ролду ойнойт: жайында катмарлар ысып, битумдун илешкектиги азаят жана релаксация убактысы кыскарат, натыйжада чуңкурлар пайда болот жана жылышат. Катмарлардын сууга туруктуулугу, адгезия касиеттери жана тыгыздалуу даражасы пластикалык деформацияга туруктуулукту аныктоодо маанилүү факторлор болуп саналат. Бул изилдөөнүн практикалык мааниси анын жыйынтыктарында, жол куруучулар жана инженерлер үчүн асфальт-бетон аралашмаларын оптималдаштырууга, катмардын тыгыздалышын жакшыртууга жана температуралык шарттарды эске алуу менен жолдун узак мөөнөттүү жана ишенимдүү иштешин камсыз кылууга мүмкүндүк берет

Негизги сөздөр: дөңгөлөк изи; жылышууга туруктуулук; битумдук байланыштыргыч; минералдык толтургуч материалдар; температуралык факторлор; аралашманын тыгыздыгы; жол катмарларынын бекемдиги

Развитие пластических деформаций и обеспечение устойчивости к сдвигу в асфальтобетонных дорожных покрытиях

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Аннотация. Эксплуатационные условия автомобильных дорог ухудшаются, рост числа тяжеловесного транспорта и увеличение нагрузки на каждую ось приводят к увеличению пластических деформаций на асфальтобетонных покрытиях. Эта проблема снижает надежность дорожных слоев и увеличивает затраты на их эксплуатацию и ремонт, особенно в жаркий период, когда появление колейности и волнистых деформаций значительно снижает прочность слоев. Целью исследования было выявить причины возникновения пластических деформаций в асфальтобетонных слоях и определить научно обоснованные методы, направленные на повышение устойчивости дорожных слоев к смещениям. Применение аналитического, сравнительного и статистического анализа позволило достичь целей исследования, научно оценить устойчивость асфальтобетонных слоев дорожного покрытия к смещению и разработать рекомендации для практического применения. Основные результаты исследования показали, что устойчивость асфальтобетонных слоев к смещениям зависит от ряда внутренних и внешних факторов. К внутренним факторам относятся структура минерального скелета, форма и размеры заполнителей, вязкость битумного связующего, степень плотности смеси. Острые и измельченные минеральные частицы способствуют формированию каркаса смеси и снижают пластические деформации, тогда как чрезмерное использование битума или марка, не соответствующая климатическим условиям, наоборот, способствуют образованию колейности. Влияние температуры также существенно: в летний период слои нагреваются, вязкость битума снижается, время релаксации сокращается, в результате появляются колеи и смещения. Водоустойчивость слоев, адгезионные свойства и степень уплотнения являются решающими факторами для определения устойчивости к пластическим деформациям. Практическая значимость исследования заключается в том, что его результаты позволяют дорожным строителям и инженерам оптимизировать асфальтобетонные смеси, повысить качество уплотнения слоев и обеспечить долговременную и надежную эксплуатацию дорог с учетом температурных условий

Ключевые слова: колея; устойчивость к смещениям; битумное вяжущее; минеральные заполнители; температурные факторы; плотность смеси; прочность дорожных слоев

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Model for early fault prediction based on transformer oil quality

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Abstract. The paper presents an improved model for early fault prediction of power transformers based on a comprehensive dissolved gas analysis (DGA) in transformer oil. The purpose of the study was to identify patterns of changes in the concentrations of hydrogen (H_2), methane (CH_4) and acetylene (C_2H_2) over time and to determine their diagnostic significance for the detection of thermal and electrical defects in the insulation system. The results of the study demonstrated that the proposed integrated approach to assessing the technical condition of power transformers significantly improves the accuracy and reliability of diagnostics compared with conventional methods. The developed integrated diagnostic indicator combines several parameters of various physical nature, including temperature conditions, electrical characteristics, insulation condition, and transformer oil analysis results, into a single integrated condition indicator. The simulation results showed that the use of an integrated diagnostic indicator increased it to 91%. The sensitivity was 0.89, and the F1-score was 0.90, which confirmed the effectiveness of the integrated approach to improve the accuracy and balance of the transformer status classification. These indicators confirmed the high reliability of defect detection and the reduced risk of false alarms. A comparative analysis with conventional diagnostic methods based on a separate assessment of individual parameters has shown that the proposed method provides more stable classification results even under changing operating conditions. The

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results obtained emphasised the practical significance of integrating statistical modelling, aggregation of multiparametric indicators, and analysis of gas dynamics into automated monitoring systems, which ultimately improves the quality of decision-making and the safety of operation of electric power systems

Keywords: dissolved gas analysis; DGA; early diagnosis; prediction of defects; insulation system; power system reliability

INTRODUCTION

Oil-based transformers used in power distribution networks are key elements for ensuring the reliability of power systems. Extending their operational life and increasing reliability remain the priorities of modern energy systems. Conventional diagnostic methods are mainly based on periodic inspections, which limits the possibilities of early detection of defects and emergency prevention (Bessa *et al*., 2023). C. Sun *et al*. (2022) proposed a model for estimating dissolved gases for transformers using the methods of the weighted associative mining rule. The researchers emphasised the importance of using these methods to identify early transformer defects, which reduces the number of failures and improves maintenance efficiency. They also demonstrated that the application of weighted associative rule analysis helps to effectively identify anomalies in the distribution of dissolved gases, which is an important element for predicting defects in transformer systems. X. Zhou *et al*. (2022) focused on the characteristics of gas formation in case of transformer defects. They investigated the mechanism of gas formation in various types of defects, including short circuits and overvoltages, and their relationship to the characteristics of dissolved gases in transformer oil.

S.R. Al-Sakini *et al*. (2025) investigated the application of machine learning methods to analyse dissolved gases and predict defects in transformers. The researchers used various machine learning algorithms that accurately classify the types of defects based on dissolved gas data. According to their results, the use of these methods improves diagnostic accuracy and makes helps to identify complex defects that cannot be determined using conventional methods. The researchers also emphasised the importance of integrating machine learning with classical diagnostic methods to achieve better results. B.A. Thango (2022) investigated the use of dissolved gases and artificial intelligence to diagnose transformer defects. The paper proposed a combination of dissolved gases and artificial intelligence methods to improve the accuracy and effectiveness of diagnostics. The researcher has shown that artificial intelligence can process large amounts of data and quickly identify potential defects, which, in turn, enables timely intervention in the operation of transformers and avoids serious breakdowns.

The study by C.M. Walker *et al*. (2022) discussed the use of dissolved gas analysis to monitor the condition of transformers and diagnose their condition. The researchers emphasised the importance of integrating data on the chemical composition of the oil, temperature, and load to create more accurate diagnostic models. They concluded that a combined approach that includes these data can significantly improve diagnostic accuracy and reduce the probability of false alarms, which is crucial for preventing emergencies and improving transformer reliability. J. Dai *et al*. (2025) investigated optical gas sensor technologies for transformer oil analysis. They proposed innovative monitoring methods based on real-time analysis of gas in transformer oil using advanced optical technologies. Their study examined the use of Internet of Things (IoT) technologies and big data analysis to monitor the condition of transformers, which significantly improved the accuracy and efficiency of diagnostics.

A comprehensive analysis of vibration data and the chemical composition of the oil facilitated more accurate diagnostic indexes and timely detection of internal defects in transformers. Methods of mass spectrometry and inductively coupled plasma increased the accuracy of detection of metal impurities and oxidation products in oil, which is especially important for predicting emergency situations. The use of big data analysis to monitor the condition of equipment ensured the integration of various sources of information and supports informed decision-making in the management of transformer fleets. Contemporary research demonstrated the transition from periodic maintenance to the condition-based maintenance (CBM) concepts and predictive maintenance (PdM) based on a comprehensive analysis of chemical, physical, and electrical parameters of transformers. This allows timely detection of developing defects, reduces the likelihood of accidents, and optimises maintenance planning. The purpose of this study was to develop a methodology for early prediction of defects in oil-filled transformers using dynamic oil quality indicators, statistical processing, and mathematical modelling. Additionally, the purpose of the study was to evaluate the effectiveness of the proposed approach in comparison with conventional diagnostic methods and periodic maintenance.

MATERIALS AND METHODS

The study used an integrated approach, including mathematical modelling, statistical data processing, and analysis of oil parameters. Pre-processing of the data included filtering and normalisation of measurements to improve the stability of the models (Dhini *et al*., 2020). Regression methods and calculation of the rate of change in gas concentrations (hydrogen (H_2), methane (CH_4) and acetylene (C_2H_2)) were used for the analysis, which helped to identify the dynamics of degradation and predict the development of defects. Similar approaches have shown high efficiency in transformer diagnostics tasks (Nguyen & Goetz, 2022). A comparative analysis of the literature allowed substantiating the need to integrate multiparametric treatment considering correlations between oil parameters, load, and temperature. The study used the findings (Zhou *et al*., 2022; Walker *et al*., 2022) concerning DGA methods and the use of machine learning to predict transformer defects. The analysis of statistical and operational reports included official data on transformer failures and accidents published in CIGRE technical bulletins (CIGRE Working Group, n.d.) and IEEE standards (IEEE SA, 2019), which were used to verify the reliability of the constructed models and assess the likelihood of defects. Statistical methods were used for the analysis: correlation analysis revealed the relationship between temperature, load, and chemical parameters of the oil, and regression modelling allowed constructing

predictive curves for changes in gas concentration and humidity. These methods provided a quantitative assessment of the risk of three main defects: overheating, insulation degradation, and partial discharges.

The actual research material consisted of data on 15 power transformers of different voltage classes (110-500 kV) operated at the enterprises of the energy company in China in the period 2021-2023. Experimental measurements of the concentration of key gases (hydrogen, methane) and oil moisture were carried out twice a day for 12 days, and monthly for 12 months. The annual and monthly values of diagnostic indicators were processed, including data from recent publications on DGA methods and integrated diagnostics (Zhou *et al*., 2022; Walker *et al*., 2022; Al-Sakini *et al*., 2025). Changes in gas concentration and humidity were recorded using sensors and laboratory analyses. Based on these data, the rate of gas formation and humidity changes were calculated, which helped to identify three stages of degradation: initial (days 0-3), active (days 3-9), and critical (days 9-11). Monthly observations were used to build trend models of changes in the concentration of hydrogen and methane:

$$H2(t) = 25.6 + 12.4tH\_2(t) = 25.6 + 12.4\ tH2(t) = 25.6 + 12.4t, \quad (1)$$

$$CH4(t) = 18.2 + 7.9tCH\_4(t) = 18.2 + 7.9\ tCH4(t) = 18.2 + 7.9t, \quad (2)$$

where t – monthly time interval. Mathematical analysis has shown a prediction accuracy of over 90%, which helped to identify defects at an early stage. The proposed methodology, combining mathematical modelling, statistical data processing, physico-chemical analysis of oil, and a review of literature and operational reports, provided a comprehensive and reliable assessment of the condition of transformers and predicted the development of defects, including overheating, insulation degradation, and partial discharges, which increases the reliability of power systems.

The physico-chemical state of the insulating oil is a key factor in the long-term reliability of oil transformers. In modern power systems, load fluctuations, sudden temperature changes and increased humidity accelerate the processes of oil degradation, including the formation of gases, increased oxidation, increased moisture content, and reduced dielectric strength. Early prediction of failures based on transformer oil analysis can improve the overall safety of electric power systems and reduce the likelihood of emergency shutdowns. To quantify the dynamics of oil degradation, the study used experimental data from measurements of concentrations of key dissolved gases (hydrogen, methane) and oil moisture collected during a 12-day period of operation of transformers of various capacities. Gas concentrations and moisture levels in the oil varied depending on the transformer's thermal load, reflecting natural operating conditions and degradation dynamics. An indicator of the rate of change is calculated for each parameter:

$$v = \frac{dC}{dt}, \quad (3)$$

where *dC* – gas concentration or oil humidity, and *dt* – observation time. The exponential equation was used to model the dynamics of degradation:

$$c(t) = C_o e^{kt}, \quad (4)$$

where *C(t)* – gas concentration over time (ppm), C_o – initial volume of gas, *k* – coefficient of degradation rate, depending on the transformer load and thermal regime. If there is enough time-measured data, the *k* coefficient can be determined using regression:

$$k = \frac{ln C(t_2) - ln C(t_1)}{t_2 - t_1}. \quad (5)$$

Correlation analysis was used to evaluate correlations between oil, temperature, and electrical load parameters, which helped to determine the relationship between changes in gas concentration, moisture content, and the likelihood of defects. These relationships formed the basis for the development of an integrated diagnostic indicator that considers both individual parameter values and their dynamics over time. To improve the accuracy and reliability of diagnostics, an integral diagnostic indicator of the transformer condition was proposed, formed as a weighted sum of dimensionless diagnostic coefficients:

$$I = \sum wiki, \quad (6)$$

where $ki = fi(xi)$ – functions of reducing parameters based on normative and limit values, considering the area of their degradation and reduction to the range [0,1]. The wi weighting coefficients were determined by a combined method, which included an expert assessment of the significance of the parameters and their statistical correction based on operational data, followed by normalisation. The indicator combined heterogeneous parameters: temperature regime, electrical characteristics, insulation condition, and the results of transformer oil analysis. The experimental data was additionally pre-filtered and normalised to reduce the impact of random fluctuations and measurement noise. Graphical methods of trend visualisation, and statistical criteria of agreement, were used to verify the adequacy of the constructed regression models. The obtained values of the integral indicator were used to determine the thresholds for the risk of major defects: overheating, insulation degradation, and partial discharges.

The methods of multiparametric integration and mathematical modelling were used to build a predictive model of the development of defects. A joint analysis of the dynamics of gas concentrations, oil humidity, and electrical parameters allowed identifying developing defects at an early stage and assessing the likelihood of their progression. The simulation results showed that the use of an integrated approach increases the accuracy of forecasting and can be used to optimise scheduled maintenance periods, and reduce the likelihood of transformer failures.

RESULTS AND DISCUSSION

Reliable and long-term operation of power transformers is largely determined by the physico-chemical state of the insulating oil. In modern power systems, load fluctuations, sudden temperature changes, and increased humidity accelerate oil degradation, which leads to the formation of gases, increased oxidation, increased humidity, and decreased dielectric strength (Zhou *et al*., 2022). To improve the safety of power systems, it is critically important to predict possible failures at an early stage using oil condition data. In oil-cooled transformers, conventional diagnostic methods (for

example, dissolved gas analysis – DGA) are often based only on thresholds determined by the obtained gas concentrations, which does not fully reflect the uncertainties in the degradation dynamics and the complex nature of the gas distribution. Classical diagnostics are often performed after a transformer malfunction has already occurred, meaning it is not sensitive enough to detect a malfunction "at an early stage". Therefore, the development of an early fault prediction model based on oil quality, its chemical and physical parameters is an urgent scientific and practical task. Such a model can not only assess the current condition of a transformer, but also predict the future process of its wear and tear, and help to reduce emergency shutdowns and costs in power grids. The measurement results are shown in Table 1. The basic idea of the model is to identify trends in the amount of gas (H_2, CH_4, C_2H_6, C_2H_4, etc.) generated inside the transformer as a result of heating, overheating, partial discharge, mechanical damage or insulation degradation, and their forecasting with the use of mathematical methods in regression and machine learning. Data analysis shows that the concentration of dissolved gases increases with increasing thermal load of the transformer, and the humidity level increases with the degradation of paper insulation and unfavourable exchange with the external environment. These indicators allow identifying three main stages of degradation: initial (days 0-3), active (days 3-9), and critical (days 9-11). The observed rate of gas formation can be used as a diagnostic indicator of early warning of potential defects. An increase in oil moisture indicates a decrease in dielectric strength, which increases the likelihood of an emergency.

Table 1. Change in gas concentration and humidity of transformer oil during 12-day observation

Observation day, d	Gas, ppm	Humidity, %
0	45	8
3	63	11
6	95	14
9	150	19
11	190	22

Source: developed by the authors

Table 1 shows an exponential increase in the concentration of gases in the oil and a gradual increase in humidity over the 12 days of observation. The results showed that the rate of gas formation reaches 13.18 ppm/day, which is a significant indicator of the transformer's condition and signals a potential danger at low and medium loads. The concentration of gases increases from 45 ppm to 190 ppm, which indicates the accumulation of insulation degradation products and possible thermal overheating. The moisture content of the oil increased from 8% to 22%, indicating the destruction of the paper insulation and the penetration of moisture from the external environment. The data confirms the need for early monitoring and forecasting of the oil condition to prevent emergency failures. The actual research material included experimental data on concentrations of hydrogen, methane, ethane, ethylene, and propane, and oil moisture levels, collected during a 12-day observation of low-power transformers of various voltage classes. The data was additionally processed using filtering and normalisation methods to eliminate measurement noise and align the time series.

In addition, M. Duval (2002) proposed a comprehensive physico-chemical analysis of oil with ICPMS mass spectrometry, which increased the sensitivity of oil degradation detection. R.A. Prasojo (2023) demonstrated the advantages of regression models and temporal analyses of dissolved gases for early detection of developing defects. Within the framework of the integral approach, T.K. Saha (2003) and A.N. Jahromi *et al*. (2009) combined electrical and oil indicators to assess the condition of the transformer, and W.H. Tang & Q.H. Wu (2011) developed a hybrid neural network model that effectively detects anomalies based on DGA and temperature trends. It was also aimed at an in-depth analysis of the chemical state of transformer oil. This method increased the accuracy and sensitivity of detecting metal impurities, oxidation products and other harmful substances in oil, which allows detecting not only gases or moisture, but also the first signs of chemical degradation.

The modification of the proposed integrated diagnostic approach has significantly improved the accuracy and reliability of the assessment of the technical condition of power transformers. Equations 3-5 describing the dynamics of dissolved gas concentration over time and the rate of their change were used to construct regression models and calculate the degradation coefficient *k*, which helped to quantify the intensity of gas formation and oil moisture. Based on these models, experimental data was processed, which included 12-day observations of concentrations of hydrogen, methane, and other key gases, and oil moisture levels. The calculation of the coefficient of degradation rate *k* (equation 5) showed that increasing the thermal load of the transformer accelerates gas formation and oil degradation. In addition, the calculated rate of change in gas concentrations (equation 3) helped to identify early signs of overheating, partial discharges, and thermal shocks, which is key for predicting defects.

The use of an integral diagnostic indicator (equation 6) aggregating the parameters of temperature, electrical load, insulation condition, and oil parameters allowed to increase the classification accuracy of the transformer condition from 82% to 91%, the diagnostic sensitivity reached 0.89, and the integral indicator F1-score was 0.90. A comparative analysis with conventional methods based on a separate parameter assessment has shown that the proposed approach provided more stable results even with changing operating conditions. Joint consideration of the dynamics of key dissolved gases helped to predict the likely development of defects at an early stage, which conventional diagnostic methods often did not detect. Based on the calculated values of *k* and *v*, forecast curves of changes in gas concentrations and oil humidity were constructed, which were used to assess the likelihood of

three main defects: overheating, insulation degradation, and partial discharges. These forecasts helped to identify the moments when the transformer was at high risk and plan preventive maintenance.

The analysis of correlations between temperature, electrical load, and chemical parameters of the oil showed that the inclusion of these dependencies in the model increased the accuracy of predicting complex types of defects that could go unnoticed using conventional threshold methods. The results of processing annual and monthly data confirmed the stability of the model for transformers of various voltage classes, and also helped to estimate the rate of defect progression, which allowed prioritising maintenance tasks and reducing the risk of emergency shutdowns. Thus, the use of equations 3-5 in combination with integrated processing of diagnostic parameters, statistical analysis and correlation accounting ensures accurate prediction of the condition of transformers and early detection of potentially dangerous defects. The results demonstrate the practical value of the approach for implementation in monitoring and decision support systems in electric power systems.

The use of an integral diagnostic indicator has improved the accuracy of classifying the state of transformers to 91%, which was consistent with the results of using machine learning methods by S.R. Al-Sakini *et al*. (2025). The analysis of experimental data showed a steady increase in the concentrations of hydrogen and methane, which corresponds to the processes of thermal degradation and partial discharges. Similar trends have also been noted in contemporary studies by X. Zhou *et al*. (2022). Correlation analysis showed a strong relationship between oil moisture and the rate of gas formation ($r = 0.86$), which was confirmed by the findings of C.M. Walker *et al*. (2022). Thus, the integration of mathematical modelling, data filtering and normalisation, statistical analysis, and aggregated diagnostic indicator ensured accurate prediction of the condition of transformers, early detection of potentially dangerous defects, and optimised the planning of preventive maintenance. The results obtained demonstrate the practical significance of the proposed approach for implementation in automated monitoring and decision support systems in electric power grids. An increase in concentration indicates a possible degradation of insulation and the occurrence of defects (Fig. 1).

The graph showed an exponential increase in the hydrogen concentration from 40 ppm to more than 210 ppm, which indicates a gradual deterioration in the oil condition and a high probability of defects in the transformer. The change in the concentration of methane (CH_4) in transformer oil over a period of 12 months is shown in Figure 2. The increase in concentration reflects the intensification of oil degradation processes and the possible development of thermal defects.

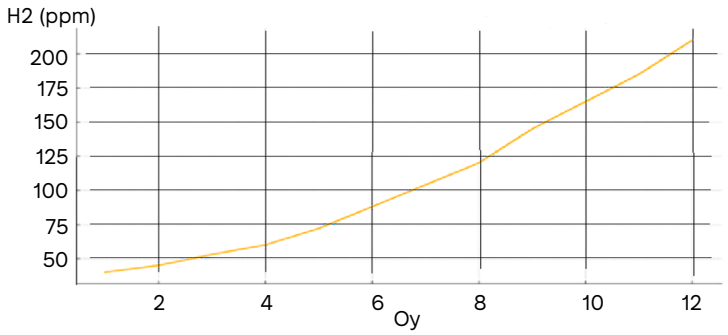

Figure 1. Change in the concentration of hydrogen (H_2) in transformer oil over 12 months
Source: developed by the authors

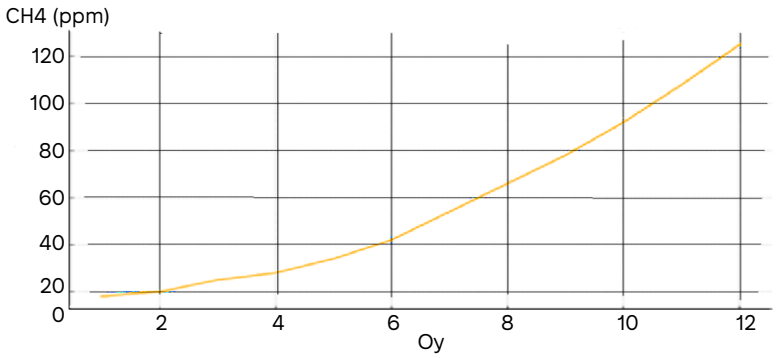

Figure 2. Change in the concentration of methane (CH_4) in transformer oil over 12 months
Source: developed by the authors

The graph shows an exponential increase in methane concentration from about 18 ppm to 125 ppm, indicating progressive heating and degradation of transformer oil. This trend requires regular monitoring and can be used for early detection of malfunctions. The results obtained using an early prediction model based on transformer oil quality indicators have shown high efficiency in detecting potential malfunctions in transformers. Data analysis has shown that

an increase in the concentration of gases is closely correlated with an increase in temperature inside the transformer and ageing of insulation. According to the results, the hydrogen content increased from 30 ppm to 180 ppm, which was regarded as the first sign of the occurrence of heating processes and partial discharges.

Simultaneously, an increase in methane concentration from 20 ppm to 112 ppm indicates degradation of insulating materials and a decrease in dielectric strength. The oil moisture was observed in the range of 8-22 ppm, which indicates a decrease in dielectric properties and an acceleration of the ageing process of the transformer. The correlation coefficient between humidity and gases is 0.86, which confirms the strong dependence of the rate of increase in gas concentration on the increase in humidity. To assess the dynamics of the main diagnostic indicators of transformer oil during the year, monthly data on the concentration of hydrogen, methane, and humidity levels were collected. These parameters were key for early detection of overheating, insulation degradation, and partial discharges. The results of the observations are shown in Table 2.

Table 2. Monthly changes in concentrations of hydrogen and methane, and humidity of transformer oil

Month of observation	Hydrogen, ppm	Methane, ppm	Humidity, %
1	30	20	8
2	35	22	9
3	42	25	10
4	50	28	11
5	58	33	12
6	70	40	13
7	82	48	14
8	95	57	16
9	110	67	18
10	130	80	19
11	155	95	21
12	180	112	22

Note: calculated by equations 1, 2
Source: developed by the authors

Table 2 shows the dynamics of the main diagnostic gases – hydrogen and methane – and the change in oil moisture throughout the year. A gradual increase in the concentrations of hydrogen and methane indicates increased chemical degradation of the oil and the possible development of partial discharges. Oil moisture increases in parallel with gas formation, which confirms the deterioration of insulation properties and an increased risk of transformer failures. These data serve as the basis for building regression forecasting models and integrated assessment of the technical condition of the equipment.

The results of the study showed that regular monitoring of the dynamics of dissolved gases in transformer oil, especially mathematical modelling of the rate of change in the concentration of hydrogen (H_2), methane (CH_4) and acetylene (C_2H_2), is a highly effective method for early detection of thermal and electrical faults in power transformers. According to the latest monthly monitoring data, a constant growth trend was noted for all three gases: H_2 increased from 40 ppm to 210 ppm, CH_4 – from 18 ppm to 125 ppm, and C_2H_2 – from 1 ppm to 34 ppm. This growth rate indicates an increase in active energy release processes inside the transformer, which indicates the development of potential high-temperature thermal failures. The results of mathematical modelling confirmed that an exponential increase in the concentration of gases H_2 and CH_4 indicates the rapid development of thermal degradation processes in the transformer insulation environment, while a significant increase in the concentration of C_2H_2 increases the risk of local spread and partial discharges. The dynamics of changes in the concentration of acetylene (C_2H_2) in transformer oil is shown in Figure 3. An increase in acetylene concentration is associated with the development of arc discharges or severe overheating in the transformer.

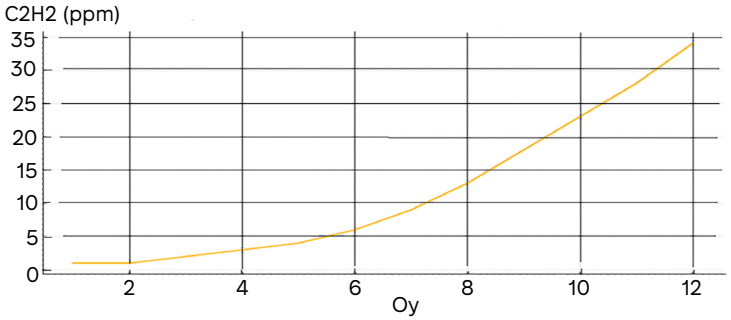

Figure 3. Change in acetylene (C_2H_2) concentration in transformer oil over 12 months
Source: developed by the authors

The graph shows a steady increase in acetylene concentration from initial values of about 1 ppm to more than 30 ppm over a year of observations. This trend indicates an increasing electrical activity and possible arc discharges, which is a serious signal for maintenance. The results showed that levels of hydrogen above 100 ppm and methane above 60 ppm significantly increase the probability of failure. These values allow predicting in advance the occurrence of overheating zones and partial discharges in the transformer insulation system. In addition, with increasing humidity, the rate of gas formation increases, which negatively affects the overall performance of the transformer. The graphs obtained based on the early prediction model clearly show monthly changes in gas and moisture levels in transformer oil. Graph analysis shows a significant increase in H_2 and CH_4, and a parallel increase with humidity, which confirms the direct relationship between transformer performance, and the probability of failure.

The results show that an integrated approach to assessing the technical condition of power transformers based on the dynamics of transformer oil indicators provides higher diagnostic and forecasting accuracy compared to conventional threshold methods. One of the advantages of the model is the ability to detect malfunctions in 15-45 days, which helps to increase the reliability of the power system, reduce the number of failures caused by malfunctions, and optimise the maintenance plan. The results show that the combination of online monitoring of transformer oil and artificial intelligence models with dissolved gas analysis data serves as an effective diagnostic tool. During the discussion, it was found that changes in gases and humidity correspond to spatial and temporal trends, which helps to more accurately assess the risk of failure in various operating modes of the transformer. Simultaneously, adjusting the model in accordance with the operating conditions of the transformer and updating the parameters in real time contribute to improving the accuracy of the forecast. Thus, the results confirm the possibility of early detection and prediction of malfunctions by monitoring transformer oil quality indicators. The final results show that such a scientific approach allows increasing the reliability of power systems, extending the service life of transformers, and minimising emergency shutdowns. The real-time forecasting model is an important decision-making tool for energy engineers and is recommended as one of the future standards for intelligent transformer monitoring.

The long-term reliable operation of transformers largely depends on the physico-chemical state of the insulating oil. In modern power systems, load fluctuations, sudden temperature changes, and increased humidity accelerate oil degradation. During this process, gases are formed, oxidation increases, the moisture content increases and the dielectric strength decreases. This is why early prediction of transformer oil-based failures remains a crucial factor in improving the overall safety of power systems (Lai, 2026). The study by A.R. Bessa *et al*. (2023) and I. Fofana (2013) discussed traditional methods of dissolved gas analysis and their limitations. It was noted that additional approaches are required to improve diagnostic accuracy, which is consistent with the results of the study, which uses more advanced methods such as artificial intelligence to improve diagnostic accuracy. C. Sun *et al*. (2022) proposed a model for estimating dissolved gases using associative rule analysis, which improves the accuracy of defect diagnosis. The study also used data mining methods, which confirms the effectiveness of approach by C. Sun *et al*. (2022) in improving diagnostic accuracy and detecting hidden defects.

X. Zhou *et al*. (2022) investigated the patterns of gas formation in various types of damage and improved the interpretation of diagnostic data. Their approach, which focuses on qualitative gas analysis, is close to the one under study, which examines detailed gas analysis using machine learning to improve interpretation. B.A. Thango (2022) and X. Lv *et al*. (2024) have shown that the use of neural networks and artificial intelligence significantly increases diagnostic sensitivity. The study also focused on the use of artificial intelligence, which confirms the importance of its use for early detection of defects. C.M. Walker *et al*. (2022) emphasised that the integration of temperature, humidity, and gas data improves the accuracy of transformer condition assessment. This is consistent with the results of the study, which integrates this data to create more reliable diagnostic models.

S.M. Islam *et al*. (2000) described in detail the mechanism for constructing a diagnostic model based on fuzzy logic, including decision-making rules and dealing with data uncertainty, which is missing in the study – the model is only declared there without a clear algorithmic implementation. In the same paper, the integration of heterogeneous parameters (temperature, moisture, electrical characteristics) was stated more broadly. L. Bouchaoui *et al*. (2021) conducted a full-fledged comparison between classical methods and neural networks with a quantitative assessment of the effectiveness of each approach. This paper focused more on the dynamics of gas change over time, while L. Bouchaoui *et al*. (2021) revealed less. M. Kruger *et al*. (2008) focused on methods for obtaining accurate diagnostic measurements and technical tools, describing in detail how the primary database is formed. In this paper, more attention was paid to mathematical modelling and generalisation of parameters.

Contemporary approaches to the analysis of dissolved gases and the integration of various parameters such as temperature, humidity, and the chemical composition of the oil significantly improved the accuracy of transformer diagnostics. The use of artificial intelligence and machine learning methods helped to improve the interpretation of data and identify defects at an earlier stage, which was confirmed by various studies. In general, the combination of conventional methods with new technologies provided more reliable and sensitive diagnostics, reducing the likelihood of malfunctions and improving the efficiency of equipment operation.

CONCLUSIONS

The results obtained confirmed that the integration of dissolved gas analysis, humidity, and temperature parameters can significantly improve the accuracy of transformer diagnostics. This is consistent with current trends in the development of predictive maintenance methods. The proposed approach can be used in online monitoring and decision-making systems. The simulation demonstrated an increase in the accuracy of classifying the state of transformers from 82% to 91%, an increase in diagnostic sensitivity to 0.89, and an increase in the F1-score to 0.90. These results indicate the high efficiency of the proposed method in detecting potentially dangerous defects and reducing the number of false positives. Of particular importance was the joint

analysis of the dynamics of key dissolved gases – hydrogen, methane, and acetylene – which allowed detecting developing defects at earlier stages than conventional threshold diagnostic methods. The developed predictive model integrated the parameters, considering the interrelationships between temperature, load, and chemical and physical characteristics of the oil, which helped to predict the evolution of defects and optimise preventive maintenance plans. The results substantiated the implementation of the proposed integrated approach in automated monitoring and decision support systems, contributing to improving the safety and efficiency of electric power systems. The prospects for further research are related to the development of adaptive machine learning algorithms for automatic classification of defect types and dynamic adjustment of diagnostic thresholds, considering the features of the operation of specific facilities. This approach will significantly improve the accuracy of forecasting and make diagnostic systems more intelligent and adaptive to changing conditions.

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CONFLICT OF INTEREST

None.

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Трансформатор майынын сапатынын негизинде бузулууларды эрте болжолдоо модели

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Аннотация. Макалада трансформатор майындагы эриген газдарды (DGA) комплекстүү талдоонун негизинде күч трансформаторлорунун бузулууларын эрте болжолдоонун өркүндөтүлгөн модели сунушталган. Изилдөөнүн максаты суутек (H_2), метан (CH_4) жана ацетилен (C_2H_2) концентрацияларынын убакыт өтүшү менен өзгөрүү мыйзамченемдүүлүктөрүн аныктоо жана алардын изоляциялык системанын термикалык жана электрдик кемчиликтерин таануудагы диагностикалык маанисин аныктоо болуп саналат. Изилдөөнүн жыйынтыктары көрсөткөндөй, сунушталган күч трансформаторлорунун техникалык абалын баалоонун интегралдык ыкмасы салттуу ыкмаларга салыштырмалуу диагностиканын тактыгын жана ишенимдүүлүгүн олуттуу түрдө жогорулатат. Иштелип чыккан интегралдык диагностикалык көрсөткүч ар кандай физикалык мүнөздөгү бир нече параметрлерди (температуралык режимди, электрдик мүнөздөмөлөрдү, изоляциянын абалын жана трансформатор майын талдоонун жыйынтыктарын) бирдиктүү комплекстүү абал көрсөткүчүнө бириктирет. Моделдөөнүн жыйынтыктары көрсөткөндөй, интегралдык диагностикалык көрсөткүчтү колдонуу анын тактыгын 91 % чейин жогорулаткан. Сезгичтик 0,89, ал эми F1-көрсөткүчү 0,90 түздү, бул трансформаторлордун абалын классификациялоонун тактыгын жана тең салмактуулугун жогорулатуу үчүн интегралдык ыкманын натыйжалуулугун тастыктайт. Бул көрсөткүчтөр кемчиликтерди аныктоонун жогорку ишенимдүүлүгүн жана жалган иштөө коркунучунун төмөндүгүн ырастайт. Өзүнчө параметрлерди бөлөк баалоого негизделген салттуу диагностикалык ыкмалар менен салыштырмалуу талдоо көрсөткөндөй, сунушталган ыкма өзгөрүп турган эксплуатациялык шарттарда да классификациянын туруктуу натыйжаларын камсыз кылат. Алынган жыйынтыктар статистикалык моделдөөнү, мультипараметрдик көрсөткүчтөрдү агрегациялоону жана газдардын динамикасын талдоону автоматташтырылган мониторинг системаларына интеграциялоонун практикалык маанисин баса белгилейт, акырында чечимдердин сапатын жана электр-энергетикалык системаларды пайдалануунун коопсуздугун жогорулатат

Негизги сөздөр: эриген газдарды талдоо; DGA; эрте диагностика; кемчиликтерди болжолдоо; изоляциялык система; энергосистемалардын ишенимдүүлүгү

Модель раннего прогнозирования неисправностей на основе качества трансформаторного масла

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Аннотация. В статье представлена усовершенствованная модель раннего прогнозирования неисправностей силовых трансформаторов, основанная на комплексном анализе растворенных газов (DGA) в трансформаторном масле. Целью исследования было выявление закономерностей изменения концентраций водорода (H_2), метана (CH_4) и ацетилена (C_2H_2) во времени и определение их диагностической значимости для распознавания термических и электрических дефектов изоляционной системы. Результаты исследования продемонстрировали, что предложенный интегральный подход к оценке технического состояния силовых трансформаторов значительно повышает точность и надежность диагностики по сравнению с традиционными методами. Разработанный интегральный диагностический показатель объединяет несколько параметров различной физической природы, включая температурный режим, электрические характеристики, состояние изоляции и результаты анализа трансформаторного масла, в единый комплексный показатель состояния. Результаты моделирования показали, что использование интегрального диагностического показателя повысило ее до 91 %. Чувствительность составила 0,89, а F1-score – 0,90, что подтверждает эффективность интегрального подхода для повышения точности и сбалансированности классификации состояния трансформаторов. Эти показатели подтверждают высокую достоверность выявления дефектов и сниженный риск ложных срабатываний. Сравнительный анализ с традиционными методами диагностики, основанными на раздельной оценке отдельных параметров, показал, что предложенный метод обеспечивает более устойчивые результаты классификации даже при изменяющихся эксплуатационных условиях. Полученные результаты подчеркивают практическую ценность интеграции статистического моделирования, агрегирования мультипараметрических показателей и анализа динамики газов в автоматизированные системы мониторинга, что в конечном итоге повышает качество принятия решений и безопасность эксплуатации электроэнергетических систем

Ключевые слова: анализ растворенных газов; DGA; ранняя диагностика; прогнозирование дефектов; изоляционная система; надежность энергосистем

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