Vol. 16, No. 2
2025

Ecological Safety
and Balanced Use of Resources

ISSN (print) 2415-3184, ISSN (online) 2522-9508
Journal homepage: https://esbur.com.ua/en

Received: 30.05.2025. Revised: 01.11.2025. Accepted: 10.12.2025. Published: 07.01.2026.

UDC 551.212.2

DOI: 10.63341/esbur/2.2025.151

Predictive modelling of the movement of pollutants of the Naryn River using the SWAT+ model

Ayana Myrzabekowa*

Master
Kyrgyz-Turkish Manas University
720044, 56 Ch. Aitmatov Ave., Bishkek, Kyrgyz Republic
https://orcid.org/0009-0008-2446-7031

Nurzat Totubaeva

Doctor of Environmental Engineering, Associate Professor
Kyrgyz-Turkish Manas University
720044, 56 Ch. Aitmatov Ave., Bishkek, Kyrgyz Republic
https://orcid.org/0000-0002-5919-9363

Uken Myrzabekova

PhD in Biological Sciences, Associate Professor
Kyrgyz National University named after Jusup Balasagyn
720033, 547 Frunze Str., Bishkek, Kyrgyz Republic
https://orcid.org/0009-0004-9524-9331

Abstract. The relevance of the study is conditioned by the need to assess the ecological state of the Naryn River basin under the influence of anthropogenic pollution and climatic changes caused by mining, agricultural runoff, urbanisation, and accumulation of sediments below hydroelectric power plants. The purpose of the study was to quantify the degradation of water quality and ecosystems in the Naryn River basin under the influence of anthropogenic pollutants and climate change. Methods of monitoring data analysis and mathematical modelling were used to achieve the goal. The results showed a significant decrease in biodiversity by 10-20% and water quality caused by an increase in concentrations of heavy metals – lead (up to 0.053 mg/l) and phosphorus (up to 0.48 mg/l) by 2050 under a high-emission climate scenario. It was found that erosion increased to 460 t/km2/year, and the productivity of the transboundary Syrdarya River decreased by 11%, which highlights the vulnerability of mountain and aquatic ecosystems. In addition, a decrease in the dissolved oxygen content to 4.7 mg/l was recorded, which increases the negative impact on aquatic biocoenoses. There was also an 18% decrease in the reproduction of fish populations, which indicates serious risks for their survival in conditions of habitat fragmentation below hydroelectric power plants. The practical significance of the study was to provide a framework for developing measures for monitoring and managing water resources in the region, which can be used by government authorities in Kyrgyzstan and neighbouring Central Asian countries, such as Kazakhstan and Uzbekistan, to coordinate transboundary water use, and environmental organisations and local communities for the conservation of biodiversity and sustainable development of the Naryn River basin

Keywords: anthropogenic impact; ecosystem degradation; transboundary river systems; climate change; water resources; biodiversity

Suggested Citation: Myrzabekowa, A., Totubaeva, N., & Myrzabekova, U. (2025). Predictive modelling of the movement of pollutants of the Naryn River using the SWAT+ model. *Ecological Safety and Balanced Use of Resources*, 16(2), 151-162. doi: 10.63341/esbur/2.2025.151.

*Corresponding author

Introduction

Pollution of transboundary rivers in Central Asia, such as the Naryn, poses a threat to the region's water supply, irrigation, and ecosystems, which underscores the relevance of this study. Anthropogenic factors, including mining and agricultural runoff, combined with climate change, worsen the water quality of the Naryn River, affecting the sustainability of ecosystems and water users in Kyrgyzstan and neighbouring countries (Janybek kyzy, 2024). The problem lies in the lack of understanding of the long-term effects of Naryn pollution and the lack of predictive models that consider climate scenarios for this region.

M. Pamirbek kyzy *et al.* (2022) found that seasonal peaks in nitrogen and phosphorus concentrations in the middle reaches of the Naryn River reach 2.5 mg/l in summer due to agricultural runoff. Their analysis showed that melting snow and glaciers increases runoff by 10-12%, which contributes to the transport of pollutants downstream. However, their study did not consider long-term climate scenarios, but was limited to current observations. N. Degembaeva *et al.* (2024) found that lead concentrations in the upper Naryn River exceeded the maximum permissible limits by 1.5 times in June due to mining activities. They noted seasonal changes in water quality associated with increased erosion in mountainous areas. Their study highlighted the local contribution of anthropogenic sources, but did not include predictive models. F. Betz *et al.* (2023) showed that erosion in the Naryn Basin leads to a decrease in the vegetation cover of the basin by 15% due to hydromorphological changes. They used satellite data to analyse the interaction of vegetation and runoff, revealing the vulnerability of ecosystems to seasonal runoff peaks. L. Ma *et al.* (2020) investigated the hydrochemical composition of the transboundary Chu-Talas Basin in Kyrgyzstan. They found that arsenic concentrations in surface waters reached 10-15 mcg/l, exceeding the maximum permissible concentrations (MPC) by 1.5-2 times, due to natural weathering and anthropogenic emissions. These results indicate the risks of bioaccumulation in aquatic ecosystems and highlight the need for monitoring to prevent biota degradation.

In their research, N.A. Kaldybaev *et al.* (2024) conducted a geochemical assessment of the rivers of southern Kyrgyzstan, including the Kara Darya, a tributary of the Naryn Basin. Their analysis showed that the concentrations of lead and zinc in the sediments were up to 50 mg/kg and 120 mg/kg, respectively, which are lower than the MPC, but create cumulative risks for benthic organisms when resuspended during flood periods. These data highlight the importance of remediation to minimise trophic transfer of pollutants. M. Severinenko *et al.* (2024) investigated the impact of mining facilities in Kyrgyzstan on pollution of the Shu River. They found that the concentrations of uranium in irrigation channels reached 30 mcg/l, exceeding the MPC by 3 times, and molybdenum up to 20 mcg/l, which threatens agricultural ecosystems and increases soil erosion. Their findings highlighted the need for barriers to groundwater and strict control of tailings ponds.

A.D. Egemberdieva (2025) investigated anthropogenic and microbiological pollution in the Mailuu-Suu River Basin. The researcher found that the concentrations of mercury and cadmium in the water were up to 0.5 mcg/l and 1.2 mcg/l, respectively, exceeding the MPC by 2-3 times, which causes degradation of floodplain vegetation and microbial communities, increasing eutrophication. These results highlighted the need for advanced cleaning technologies to restore ecosystems. P. Kuznietsov & O. Biedunkova (2025) applied multidimensional statistical methods, including cluster analysis and principal component analysis, to assess heavy metal pollution in freshwater systems. They showed that the concentrations of copper and nickel in the sediments ranged from 40 to 100 mg/kg, which is associated with anthropogenic foci and leads to a decrease in species diversity by 15-20%. Their approaches confirmed the importance of statistical modelling for the development of adaptive protection measures.

Despite significant progress in the study of water pollution, gaps remain in understanding the dynamics of the spread of pollutants under climate change and anthropogenic pressure, especially in transboundary basins such as Naryn, where mining activities, such as the Kumtor mine, have led to the accumulation of more than 100 million tons of toxic waste since the 1990s. The lack of integrated models combining hydrochemical and climatic factors limits the accuracy of forecasts of environmental impacts. The purpose of the study was to numerically simulate the impact of anthropogenic pollutants and climate change on the deterioration of water resources and ecosystems in the Naryn River basin, including species diversity, hydrochemical characteristics, and sustainability of the transboundary water systems of the Syr Darya. The hypothesis was that anthropogenic pollutants, including heavy metals, significantly degrade water quality, increasing environmental risks such as loss of biodiversity and degradation of irrigation systems.

Materials and Methods

General characteristics of the method and research data

The study was conducted using the SWAT+ model, which integrates the hydrological cycle, sedimentation and transport of pollutants, to assess the impact of anthropogenic pollutants (heavy metals Pb, Cd, biogens N, P) and climatic changes on the ecosystems of the Naryn River basin. The model allowed quantifying the degradation of water quality and ecosystem functions (biodiversity, water regulation, biotreatment), considering mining runoff, agricultural activity (22% of the area) and climate scenarios RCP 4.5/8.5. Pollutants were modelled in the SWAT+ (n.d.) transportation module, considering both the dissolved and the fractions associated with the solid phase (suspended sediments). For heavy metals Pb and Cd, the distribution coefficients (K_d) 0.5-1.4 l/kg and 0.3-0.7 l/kg, respectively, were used, determining the proportion of metals adsorbed on suspended sediment particles according to the equation (1):

$$C_s = K_d \times C_d, \tag{1}$$

where C_s – concentration in the solid phase; C_d – dissolved phase; K_d – distribution coefficient. The model assumed a proportion of the bound form of 60-75% for Pb and 45-60% for Cd, depending on the granulometric composition of sediments. The deposition rate of pollutants was 0.01-0.04 m/day, and the resuspension rate was 0.005-0.015 m/day, which corresponds to the parameters of the sediment routing module in SWAT+. Concentrations of biogenic elements N (0.8-2.4 mg/l) and P (0.12-0.48 mg/l) were set in dissolved form, modelled through the mechanisms of surface and groundwater runoff. Thus, the model considered the combined transfer of metals in two phases – dissolved and solid (in suspended sediments), which provided a correct assessment of their migration and accumulation in bottom sediments. Calibration was performed according to Kyrgyzhydromet (n.d.). data (2020-2025) with the Nash-Sutcliffe index (NSE > 0.68 for runoff and > 0.65 for suspended sediment (SSC/SY)) and the balance deviation (PBIAS < 6.5%) for the flow variables (Q) and suspended sediment concentration (SSC). For the dissolved components (DO, Pb, Cd, N, P), the accuracy was estimated by the criteria $R^2 > 0.70$ and the mean absolute deviation ($MAD < 10\%$), which ensured consistency between the observed and modelled values in the space-time context.

In SWAT+, reservoirs (including the Kambarat hydroelectric power station) are defined as reservoirs with a seasonal operating curve (target volume/level by month) and throughput rules (average flow rate of 10-15 m³/s). Sediment trapping is implemented through the RES_{SED} parameter (deposition coefficient 0.02-0.05 m/day) and PSE (delay efficiency 65-80%), which explains the sediment accumulation below the hydropower plant (HPP) (up to 5-10% decrease in efficiency). The input data included hydrometeorological parameters (runoff, suspended sediments, temperature, humidity) from Kyrgyzhydromet, and measurements of Pb, Cd, N, and P at the Uch-Terek (upper reaches), Naryn (middle reaches), and Bolshoy Naryn (lower reaches) posts. Complementary sources: Digital Elevation Model (DEM) SRTM (30 m) (Earth Resources Observation and Science Center, 2018), soil (Food and Agriculture Organization (n.d.) (FAO), land management Landsat 8/9 (U.S. Department of the Interior, 2025), which provided spatial and temporal representativeness for ecosystem impact analysis.

Sampling approach and modelling process

The methodology included a spatial sampling of a basin (59,100 km²) divided into subbasins in ArcGIS Pro for accurate mapping of hydrological units (HRU) and assessment of the impact of pollutants on ecosystems (tugai forests, river biocoenoses, mountain meadows). The basin was divided into 128 sub-basins and 2,450 HRUs with thresholds: 5% land use, 10% soil, 15% slope. The time sample covered the years 2020-2025 with a forecast up to 2050. The modelling process in SWAT+ began with data entry (DEM SRTM, FAO soils, Landsat 8/9), calibration (NSE > 0.68 for runoff, > 0.65 for suspended sediment; PBIAS < 6.5%) and validation according to Kyrgyzhydromet data (2021-2025). Sensitivity analysis of the parameters (CN2 -0.20, $ALPHA_{BF}$ 0.18, SOL_{AWC} 0.22) in SWAT+ Toolbox optimised the assessment of the impact of pollutants on biodiversity (-20%), fish reproduction (-18%), and productivity of the Syr Darya (-11%). The RCP 4.5/8.5 scenarios (warming +1.7-2.4 °C, precipitation +8-11%) modelled changes in runoff (+12%), erosion (+11%, up to 510 t/km²/year), and biogenic load (+18-22%), allowing long-term impacts on ecosystems and transboundary water resources to be estimated. Based on the results, recommendations have been developed to reduce anthropogenic impact and adapt to climate change. To assess the stability of the SWAT+ model and identify key parameters affecting the hydroecological parameters of the basin, a One-At-a-Time (OAT) sensitivity analysis was performed. Each parameter varied in the range of ±20% of the calibrated value, after which the normalised sensitivity was calculated (2):

$$S = (\Delta Y/Y0)/(\Delta p/p0), \tag{2}$$

where Y – response value (for example, Q, SY, DO, Pb, Cd); p – model parameter. Positive values of S reflect the direct effect of the parameter on the indicator, while negative values reflect the opposite.

Equipment and tools used

The equipment and tools used included SWAT+ 2024 software for performing calculations, ArcGIS Pro for spatial analysis, and SWAT+ Toolbox for evaluating parameter sensitivity, providing a high degree of automation and accuracy (SWAT+, n.d.). All the data involved in the study were publicly available, which contributed to the transparency and reproducibility of the results.

Results

Geoecological characteristics of the Naryn River basin and trends in ecosystem degradation

The Naryn River basin, 807 km long from the upper reaches of the Chon-Naryn to its confluence with the Karadarya River, covers an area of about 59,100 km² and is characterised by a complex mountainous terrain with heights from 1,500 to 5,135 m (SRTM 30 m DEM). The basin (59,100 km²) is divided in SWAT+ into 128 sub-basins and 2,450 HRUs with thresholds: 5% land use, 10% soil, 15% slope. The main tributaries are At-Bashi and On-Archa. The climate of the region is continental, with an average annual precipitation of about 320 mm and a temperature range from -14 to +26°C, which forms pronounced seasonal fluctuations in runoff and water temperature. The average annual runoff in the upper reaches is 13.8 m³/s with peaks in June and July up to 24.7 m³/s, while 70% of the runoff is provided by glacial nutrition and 20% by precipitation, which causes intensive transfer of pollutants to the lower parts of the basin, affecting water users in Central Asia.

Anthropogenic load is manifested in high levels of erosion in mountain subbasins, reaching 460 t/km²/year, the mass fraction of Pb+Cd in the total mass of pollutants in bottom sediments is approximately 26% (Food and Agriculture Organization, n.d.). The initial degradation of biotopes is observed in the lower reaches: a decrease in dissolved oxygen by 17% and a decrease in biodiversity by 10-20%, including fish species (osman, marinka) and bird populations (ducks, herons). The forecast scenarios of climate change (RCP 8.5) provide for an increase in runoff by 12% by 2050 (up to 15.5 m^3/s) due to increased glacier melting by 15% and precipitation growth by 8%, which increases the transport of pollutants.

From 2010 to 2015, metal concentrations in water and bottom sediments increased by an average of 30%, and erosion processes in mountain sub-basins contributed to the deepening degradation of coastal ecosystems. The ecosystems of the basin are represented by tugai forests (18%) and mountain meadows (42%), while protected areas (hotspot, 5% of the area) turned out to be particularly vulnerable to anthropogenic and climatic influences. SWAT+ modelling predicts a further loss of species diversity by 10-20%, with an index of 15% reduction in the number of species due to erosion and pollution.

Thus, the geo-ecological situation in the Naryn River basin demonstrates high seasonal and spatial variability of water resources, significant anthropogenic impact, and the threat of degradation of coastal and aquatic ecosystems. The combined effect of glacier melting, erosion processes, and metal pollution requires integrated water resources management and environmental monitoring, and the introduction of preventive measures to preserve biodiversity and stabilise the basin's water balance (De Serio & Mossa, 2016). An analysis of pollution in the Naryn River basin using the SWAT+ model revealed a variety of sources of anthropogenic and natural impacts that shape the current environmental situation presented in Table 1.

Table 1. Sources of pollution and their consequences in the Naryn River basin

Source of pollution	Effects
Mining activities (Kumtor mine)	Increased concentrations of lead (Pb) to 0.048 mg/l and cadmium (Cd) to 0.018 mg/l, exceeding the MPC by 1.5 times, degradation of aquatic ecosystems
Agricultural land (22% of the territory)	Increase of nitrogen (N) to 2.4 mg/l and phosphorus (P) to 0.48 mg/l, eutrophication and decrease of oxygen content by 12-16%
Urbanised areas (12% of the territory)	An increase in organic pollutants by 7.5%, an increase in biochemical oxygen demand (BOD), and a deterioration in water quality in the lower reaches
Erosion and snowmelt in mountainous areas	Increased transport of lead by 28% in June, removal of sediments (460 t/km^2) containing 26% by weight of pollutants to the downstream
Climate change (RCP 4.5/8.5)	Increase in runoff by 12% and concentrations of N, P by 18%, decrease in WQI by 11% by 2050, loss of 10% of vegetation cover of floodplain meadows

Source: calculated by the authors in the SWAT+ (n.d.) based on Food and Agriculture Organization (n.d.), Earth Resources Observation and Science Center (2018), U.S. Department of the Interior (2025)

The reasons for these indicators are related to intensive anthropogenic activity and changes in natural conditions. Mining activities, including the Kumtor mine, contribute to the accumulation of heavy metals due to waste leaching into watercourses. Agricultural runoff is enhanced by the use of fertilisers during the growing season, which leads to eutrophication. Urbanisation adds organic pollutants through wastewater, and erosion and snowmelt in mountainous areas, accelerated by climate change, increase the transport of pollutants downstream.

Scenario modelling: Climate and management scenarios

To assess the potential impact of climate change and management measures on the hydroecological indicators of the Naryn River basin, scenarios RCP4.5 and RCP8.5 for 2050, and three management measures (M1-M3) and their combined version (M4) were modelled. Stable hydrological observations by Kyrgyzhydromet (Janybek kyzy, 2024) with minimal climatic anomalies were used as the base period (2010-2015), which helped to calibrate the SWAT+ model and determine reference values of key indicators (average annual flow rate, erosion, dissolved oxygen, background concentrations of Pb and Cd in water and bottom sediments).

Climate change scenarios consider ensembles of CMIP6 models (ACCESS-ESM1-5, MIROC6, IPSL-CM6A-LR, GFDL-ESM4, NorESM2-MM) with a median and a range of 25-75 percentiles, adjusted using delta-change, and quantile matching techniques for forecasting for 2030 and 2050. Management measures have been implemented in SWAT+ through the reduction of erosion coefficients (USLE-C and USLE-P), the creation of coastal buffer strips 15-30 m wide and the modernisation of wastewater treatment plants. The combined M4 scenario allowed assessing how much a set of measures compensates for the increase in risks under the influence of climate change. The main modelling results for each scenario are presented in Table 2, including annual changes in key indicators, ensemble medians, and ranges of possible deviations.

Table 2. Changes in key indicators of the Naryn River basin by scenarios (2050, median of the ensemble±range)

Scenario	ΔQ (%)	Q (m^3/s)	ΔSY (%)	SY ($t/km^2/year$)	ΔDO (%)	DO (mg/l)	ΔPb (%)	Pb (mg/l)	ΔCd (%)	Cd (mg/l)
RCP4.5	+7 [4-10]	14.8	+9 [5-12]	500	-11 [-15-8]	5.0	+4	0.050	+6	0.019
RCP8.5	+12 [8-17]	15.5	+11 [8-15]	510	-16 [-20-12]	4.7	+10	0.053	+11	0.020

Table 2. Continued

Scenario	ΔQ (%)	Q (m³/s)	ΔSY (%)	SY (t/km²/year)	ΔDO (%)	DO (mg/l)	ΔPb (%)	Pb (mg/l)	ΔCd (%)	Cd (mg/l)
M1	-2 [-1 to -3]	15.2	-28 [-25 to -32]	395	+0.4 [0.2-0.6]	5.3	-16	0.044	-14	0.017
M2	-1 [0 to -2]	15.3	-22 [-18 to -26]	405	+0.3 [0.1-0.5]	5.2	-12	0.047	-10	0.018
M3	0 [-1 to 1]	15.5	-5 [-3 to -7]	485	+0.6 [0.4-0.8]	5.6	-18	0.043	-17	0.017
M4 (comb.)	-3 [-2 to -4]	15.0	-35 [-30 to -40]	330	+0.9 [0.7-1.1]	5.6	-22	0.037	-21	0.015

Source: compiled by the authors

As shown in Table 2, the RCP4.5 and RCP8.5 climate scenarios are characterised by an increase in mean annual discharge (up to 14.8-15.5 m³/s), intensification of erosion processes, a decrease in dissolved oxygen concentration, and an increase in the content of heavy metals in water. Under the RCP8.5 scenario by 2050, discharge increases by 12% and erosion by 11%, while dissolved oxygen concentration decreases by 16%, indicating a substantial rise in hydroecological stress on the basin ecosystems. At the same time, Pb and Cd concentrations increase to 0.053 and 0.020 mg/l, respectively, approaching ecotoxicological threshold values and increasing risks to aquatic biocenoses.

The implementation of management measures (M1-M3) does not lead to abnormal changes in river discharge: ΔQ deviations remain within -2 to 0% relative to the baseline period, confirming the internal consistency of the SWAT+ hydrological module. The main effect of the management scenarios is associated with reductions in erosion and pollutant concentrations. Anti-erosion measures (M1, M2) reduce sediment yield by 22-28%, while modernisation of wastewater treatment facilities (M3) primarily improves the oxygen regime of the watercourse (+0.6 mg/l) and reduces Pb and Cd concentrations by 17-18%. The combined M4 scenario demonstrates the highest efficiency: erosion losses decrease by 35-40%, Pb and Cd concentrations by 21-22%, and dissolved oxygen stabilises at approximately 5.6 mg/l, creating favourable conditions for the functioning of aquatic organisms even under climate warming conditions. However, the annual average values do not fully reflect the seasonal dynamics of processes, on which the state of aquatic ecosystems significantly depends. To assess seasonal variability, an additional quarterly analysis was performed, considering changes in temperature, precipitation, runoff, dissolved oxygen concentration, and erosion losses. The main results are shown in Table 3.

Table 3. Seasonal changes in climatic and hydroecological indicators according to the RCP8.5 scenario by 2050 (median of the ensemble)

Indicator/Season	Winter	Spring	Summer	Autumn
ΔT (°C)	+1.9	+2.2	+2.4	+2.1
ΔP (%)	+7	+9	+11	+8
ΔQ (%)	+8	+11	+14	+9
ΔSY (%)	+7	+10	+13	+8
ΔDO (%)	-9	-13	-16	-11
ΔPb (%)	+6	+9	+12	+8
ΔCd (%)	+7	+10	+11	+9

Source: compiled by the authors based on SWAT+ (n.d.)

Seasonal analysis shows that the most pronounced changes are observed in the spring and summer period, when an increase in temperature and precipitation leads to an increase in runoff and increased erosion processes. During this period, the concentration of dissolved oxygen decreases to the minimum values (4.5-4.6 mg/l), which coincides with an increased intake of suspensions and metals. In winter and autumn, there is a moderate increase in water consumption with lower DO losses, but the effect of seasonal water quality degradation persists. These results emphasise the importance of a seasonal approach in assessing ecosystem risks, since it is the spring-summer extremes that have a key impact on the state of biota and the indicators of biodiversity (IBI). Combined management measures (M4) are particularly effective during the peak runoff season, reducing erosion by approximately 30-35% and increasing dissolved oxygen concentrations by about 0.9 mg/l during peak runoff periods. The OAT sensitivity analysis was performed. The most sensitive parameters were those related to surface runoff, moisture retention, and sedimentation (Table 4).

Table 4. Sensitivity of hydroecological parameters to the main parameters of the SWAT+ model (OAT method, range ±20%)

Parameter/Indicator	Q (Flow rate, m^3/s)	SY (Erosion, $t/km^2/year$)	DO (mg/l)	Pb (water, mg/l)	Cd (water, mg/l)
CN2 (Curve Number)	+0.48	+0.36	-0.22	+0.27	+0.29
$ALPHA_{BF}$ (Baseflow recession)	-0.21	-	+0.18	-	-
SOL_{AWC} (Soil moisture storage)	+0.19	+0.11	+0.25	+0.16	+0.18
$USLE_C$ (Cover ratio)	-	+0.52	-0.31	+0.41	+0.44
$USLE_P$ (Anti-erosion practices)	-	+0.47	-	+0.38	+0.35
LAT_{TTIME} (Lateral drain time)	+0.14	-	+0.12	-	-

Note: sensitivity range ±20% of the calibrated values
Source: calculated by the authors in the SWAT+ (n.d.)

The results of the sensitivity analysis allowed identifying the key parameters that were used in the development of management scenarios (M1-M4). In particular, the $USLE_C$ and $USLE_P$ parameters, which showed the greatest impact on erosion and transport of heavy metals, were directly considered when modelling environmental protection measures. The next stage of the analysis was aimed at quantifying the effectiveness of each management scenario in reducing erosion losses, Pb and Cd concentrations, and improving the oxygen regime of the watercourse without inducing significant changes in river discharge.

Four management scenarios were modelled to reduce the negative effects of climate change:

- M1 – implementation of anti-erosion practices (reduction of $USLE_P$ by 30%);
- M2 – improvement of vegetation cover ($USLE_C$↓ by 25%);
- M3 – modernisation of sewage treatment plants (BOD and metal removal efficiency +20%);
- M4 – combined scenario (M1+M2+M3).

The effectiveness was assessed by the relative changes in key indicators compared to the base period (2010-2015) and relative to the RCP8.5 climate background by 2050 (Table 5).

The combined M4 scenario compensates for approximately 35-40% of the climate-related increase in hydroecological risks, with the strongest effect observed for erosion control and heavy metal reduction. The main contribution to reducing erosion and metal pollution is provided by measures aimed at reducing $USLE_C$ and $USLE_P$. Improved wastewater treatment (M3) increases dissolved oxygen levels, while agrotechnical measures (M1-M2) stabilise runoff and reduce suspension.

A comparison of climate and management scenarios shows that even with the implementation of the set of measures (M4), part of the residual risk remains, mainly due to rising temperatures and reduced summer costs affecting oxygen saturation and metal mobility. To assess the environmental consequences of the residual risk and possible changes in the structure of aquatic communities, the obtained DO, Pb, and Cd values were compared with biotic thresholds and biodiversity indices. This analysis allows quantifying the sustainability of the basin ecosystem under various scenarios by 2050.

Table 5. Effects of management scenarios relative to RCP8.5 by 2050 (median of the ensemble)

Indicator/Scenario	M1	M2	M3	M4 (comb.)
ΔQ (%)	-2	-1	0	-3
ΔSY (%)	-28	-22	-5	-35
ΔDO (mg/l)	+0.4	+0.3	+0.6	+0.9
ΔPb (water, %)	-16	-12	-18	-22
ΔCd (water, %)	-14	-10	-17	-21
Residual risk (% of RCP8.5)	72	78	69	58

Source: calculated by the authors in the SWAT+ (n.d.)

Even with the implementation of a set of environmental protection measures, part of the climate-related risk to aquatic ecosystems remains (Shumka *et al.*, 2020; Hussain *et al.*, 2022). This is conditioned by an increase in summer extremes, an increase in temperature and a change in the flow regime, which affects the oxygen balance and migration of metals. The relative changes in key indicators (Q, SY, DO, Pb, Cd) compared to the baseline period (2010-2015) were used for the integral assessment of residual risk. The residual risk index characterises the proportion of unrealised negative changes after the application of management measures (Table 6).

Table 6. Changes in key indicators under different scenarios relative to the baseline

Indicator/Scenario	ΔRCP4.5 (%)	ΔRCP8.5 (%)	DM4 (comb.)	Residual risk (%)
Q (Consumption)	+7	+12	-3	+5
SY (Erosion)	+9	+11	-35	+1

Table 6. Continued

Indicator/Scenario	ΔRCP4.5 (%)	ΔRCP8.5 (%)	DM4 (comb.)	Residual risk (%)
DO (mg/l)	-11	-16	+0.9	-4
Pb (water)	+10	+14	-22	+3
Cd (water)	+9	+13	-21	+2

Source: calculated by the authors in the SWAT+ (n.d.), CMIP6 ensemble calculations

Combined measures (M4) significantly compensate for the climatic increase in risks: the erosion load decreases by about 35%, Pb and Cd concentrations by about 21-22%, and the dissolved oxygen content increases by approximately 0.9 mg/l (to about 5.6 mg/l). However, the residual risk (2-5%) remains due to incomplete levelling of extreme seasonal fluctuations and rising water temperatures. A comparison with biotic thresholds (DO < 5 mg/l, Pb > 0.05 mg/l, Cd > 0.02 mg/l) indicates a likely decrease in the biodiversity index (IBI) by 8-10% under the RCP8.5 scenario and only by 2-3% under the implementation of the package of measures (M4). Comparison with other landlocked countries (Ethiopia, Uganda, Algeria) showed similar trends in increased erosion and biogenic pollution under the RCP8.5 scenario. However, the Naryn Basin is characterised by a unique water supply structure (up to 70% of glacial runoff) and a pronounced transboundary nature, which increases the vulnerability of ecosystems (Table 7).

Table 7. Decline of ecosystem functions under RCP8.5 scenario by 2050, %

Component	Biodiversity	Water regulation	Bio-purification
Floodplain forests	17	11	19
River biocoenoses	20	14	17
Mountain meadows	10	9	11

Source: calculated by the authors in the SWAT+ (n.d.)

The decrease in ecosystem functions is associated with the combined influence of climatic and anthropogenic factors. Increasing concentrations of Pb and Cd, and erosion processes, accelerate the degradation of riverine biocoenoses and pasture ecosystems. Below the Kambarat hydroelectric power station, habitat fragmentation and a decrease in hydropower efficiency by 5-10% are observed due to sediment accumulation. Transboundary wetlands in the lower reaches of the Syr Darya are losing about 10% of their area due to eutrophication, which reduces the productivity and biodiversity of aquatic and coastal ecosystems (Table 8).

Table 8. Projected changes in ecosystem conditions under the RCP8.5 scenario (2020-2050)

Ecosystem	Indicator	2020-2025	2050 (RCP8.5)	Environmental impact
Tugai forests	DO (mg/l)	5.6	4.7 (-16%)	Increased eutrophication, degradation of flora and birds
	Pb (mg/l)	0.048	0.053 (+10%)	Toxic effects, reduction of species composition
Mountain meadows	Erosion (t/km^2/year)	460	510 (+11%)	Reduced pasture productivity and sustainability
River biocoenoses	Biodiversity (%)	100	80 (-20%)	Reduction of fish numbers (osman, marinka)
	Fish reproduction (%)	100	82 (-18%)	Disruption of migration and reproduction below the HPP

Source: calculated by the authors in the SWAT+ (n.d.)

The combined impact of climate change and anthropogenic stress leads to the loss of 10-20% of the ecosystem functions of the Naryn Basin by 2050. Riverine biocoenoses and floating ecosystems are the most vulnerable, where the combination of temperature rise, erosion, and heavy metal pollution increases the degradation of biodiversity (Bilyalov *et al*., 2025). These processes have a transboundary effect, reducing the environmental sustainability of the lower reaches of the Syrdarya River and requiring the expansion of adaptation measures on a regional scale.

The results of scenario modelling confirmed the hypothesis that the introduction of management measures can significantly compensate for the climate-related risks of degradation of aquatic ecosystems in the Naryn Basin. Despite the expected increase in temperature and erosion activity under the RCP8.5 scenario by 2050, the integrated approach (M4) reduces erosion losses by 35%, reduces Pb and Cd concentrations by approximately 21-22% and increases dissolved oxygen by nearly 0.9 mg/l, confirming the effectiveness of integrated management measures under adverse climatic conditions. Thus, it is confirmed that the implementation of a set of environmental and engineering measures can slow down the degradation of ecosystem functions and stabilise hydroecological parameters even under adverse climatic conditions. The results highlight the need for adaptive water resources management and the integration of climate risks into regional sustainable development strategies.

Discussion

The study revealed a deterioration in water quality and biodiversity caused by anthropogenic pollution and climate change, which will lead to a decrease in the biodiversity and productivity of the Syr Darya by 2050. The results confirmed the hypothesis that a combination of anthropogenic and natural factors leads to degradation of the basin's ecosystems, emphasising the need for further monitoring and adaptation measures. The relevance of the study was to provide empirical data to assess the transboundary impact on Central Asia, especially for irrigation and energy, which was critical for regional environmental security.

A comparison with studies by other researchers has shown both similarities and differences. L. Yuan *et al.* (2020) in a review of watershed models, including SWAT, noted the effectiveness of modelling non-point sources of pollution, which corresponded to data on the prediction of concentrations of N (0.8-2.4 mg/l) and P (0.12-0.48 mg/l) in agricultural areas of Naryn. However, their analysis covered a wider range of watershed areas in the United States with a lower impact of erosion (200-300 t/km^2) compared to 460 t/km^2 in Naryn, which indicated more intense natural processes in the highlands, and also did not include RCP climate scenarios. Z. Hong *et al.* (2020) investigated heavy metal pollution along the Yellow River and found concentrations of Pb up to 0.05 mg/l, which coincided with the data for Naryn. Their impact on biodiversity (5-10%) turned out to be lower than 18-22% due to lower anthropogenic pressure and erosion in the study area, which could also be related to differences in water protection measures.

X. Zhang *et al.* (2025) revealed chemical characteristics of anthropogenic waters in the Jinji River Basin with Cd concentrations (0.01-0.03 mg/l) exceeding 0.005-0.02 mg/l in Naryn. This indicated a similar level of industrial pollution, but erosion in Naryn was more significant, increasing ecosystem degradation, and there was a lack of data on transboundary effects. S. Arora & A.K. Keshari (2021) applied cluster analysis in the Yamuna River study and identified seasonal pollution peaks similar to a 30% increase in Pb in Naryn in June. However, their water quality index (WQI) decreased by 8%, while Naryn was projected to decrease by 12% by 2050, reflecting a stronger impact of climatic factors and erosion in mountainous areas. S.H. Ewaid *et al.* (2020) developed a water quality index for Iraqi rivers, where an increase in salinity (up to 600 mg/l) corresponded to data on 500 mg/l in the lower reaches of the Naryn. Their analysis did not include climate scenarios, limiting comparison with RCP 8.5 forecasts, and also did not consider the effects of erosion and transboundary runoff, which distinguished the approach from this study.

W. Yang *et al.* (2020) applied the analysis of the main components in the Xinanjiang River Basin and revealed the effect of biogens on eutrophication, similar to the data on an 18% decrease in DO in Naryn. However, their DO decrease was only 10% at a concentration of P (0.3 mg/l), which was lower than 0.53 mg/l in Naryn, indicating more intense pollution, and there were no data on transboundary impacts. K. Kandel *et al.* (2024) found high concentrations of ions in the Himalayan rivers of Nepal, but their effect on biodiversity (5-7%) was less than 20% in the river biocoenoses of Naryn. This highlighted the high sensitivity of Naryn ecosystems to erosion and pollution, and the lack of analysis of the effect of heavy metals on fish reproduction in their study. D. Dimri *et al.* (2021) assessed the water quality of the Ganges River in the western Himalayas and showed the effect of erosion on biocoenoses similar to an 8% decrease in the coverage of mountain meadows in Naryn. Their decrease in productivity (5-8%) turned out to be lower than 10-15%, which could be conditioned by a lower anthropogenic load, and the cross-border aspects characteristic of Naryn were not considered.

X. Dong *et al.* (2022) in the Weihe Basin revealed spatial differences in hydrochemistry similar to seasonal pollution peaks in Naryn. However, their impact on transboundary ecosystems was less pronounced than the 12% loss of productivity in the Syr Darya, which highlighted the regional specifics of Naryn, and there was a lack of data on climate forecasts. K. Khatri *et al.* (2023) investigated the chemistry of snow and rain rivers in western Nepal and found a concentration of P (0.2 mg/l), which contrasted with 0.53 mg/l in Naryn. Their erosion data (400 t/km^2) was close to 460 t/km^2, but the transboundary effect remained less pronounced, and the analysis did not include impacts on fish biodiversity. G. Matta *et al.* (2022) assessed changes in water quality in the upper Ganges Basin and identified the effect of heavy metals on biodiversity (10-15%), which corresponded to part of the Naryn data. Their decrease in water regulation (5%) was less than 10-15%, which indicated differences in the intensity of climatic effects, and there were no data on transboundary water resources.

A. Bamal *et al.* (2025) in a global review showed that hydroclimatic factors increase pollution, which corresponded to the forecasts of a 10-15% increase in runoff under RCP 4.5 in this study. However, their analysis did not focus on transboundary ecosystems, unlike the data on the Syr Darya, nor did it include an assessment of the impact of erosion on biodiversity. M.T. Ejigu (2021) summarised water quality modelling and confirmed the effectiveness of SWAT+ for forecasts, which coincided with the approach to Naryn. The lack of a cross-border aspect and heavy metal analysis in their work limited direct comparison with Pb and Cd data. T.K. Karimov *et al.* (2024) identified problems with the safety of water supply in Kyrgyzstan, where mineralisation corresponded to Naryn data. Their focus on drinking water excluded ecosystem analysis, and also failed to consider climate scenarios, which distinguished the approach from this study.

A.F. Hill *et al.* (2017) investigated the socio-hydrological aspects of Naryn and identified vulnerability to flow changes, which corresponded to data on peaks of 25 m^3/s. Their analysis did not include heavy metals and erosion, limiting comparison with data on the degradation of biocoenoses, and there were no forecasts for 2050. A joint study by M.J. Nasir *et al.* (2023) in Pakistan evaluated the pollution index and identified the effect of Pb on precipitation, similar to the data from Naryn. Their concentrations (0.08 mg/l) exceeded 0.053 mg/l, indicating more intense local pollution, and cross-border aspects and climate forecasts were not considered. A. Nazir *et al.* (2022) revealed metal variations in the Ganges similar to seasonal changes in Naryn. Their decrease in biodiversity (8%) was less than 20%, which could be attributed to less erosion, and there was also a lack of data on transboundary water resources. I. Karaouzas *et al.* (2020) in Greece showed a higher level of heavy metal pollution than in Naryn, but the effect on biocoenoses was similar. Their analysis did not include climate scenarios and erosion, which limited comparison with data on mountain ecosystems.

D. Gupta *et al.* (2024) in Narmada identified health risks from Pb, which corresponded to a 20% decrease in fish reproduction in Naryn. Their research focused on human health rather than ecosystems, and did not include a cross-border context, which distinguished the approach in this study. M. Asim & K.N. Rao (2021) in Yamuna showed spatial differences similar to those in Naryn, but their WQI dropped by 10%, which was lower than the projected 12%. This indicated a less pronounced effect of climate change, and there was also no data on cross-border effects. F. Ustaoğlu *et al.* (2020) found a similar effect of mineralisation in Turkey, but the impact on biodiversity was less than in Naryn. Their analysis did not include erosion and forecasts for 2050, limiting comparison with data on ecosystem degradation. N. Sheripov *et al.* (2024) emphasised the need for legal reforms in Kyrgyzstan, which supported recommendations based on data on ecosystem degradation. Their study focused on legal aspects, not including direct environmental data, which made the comparison indirect. Thus, the results of the study corresponded to global trends in the deterioration of water quality and biodiversity due to anthropogenic impact and climate change, but were distinguished by a higher level of degradation due to the mountainous terrain and the transboundary context. These findings highlighted the importance of a regional approach to water resources management and moved on to the conclusions section for further recommendations.

Conclusions

The results of the study, obtained using the SWAT+ model based on empirical monitoring data, demonstrated a pronounced degradation of water quality and ecosystems in the Naryn River basin under the influence of anthropogenic pollution and climate change. It was found that concentrations of heavy metals such as lead (up to 0.053 mg/l by 2050) and phosphorus (up to 0.48 mg/l), and erosion (up to 510 $t/km^2/year$) led to a decrease in biodiversity by 10-20%, and dissolved oxygen content by 16% (up to 4.7 mg/l) and reproduction of fish populations by 18%, which confirms the hypothesis of the cumulative impact of anthropogenic factors, including mining and agricultural runoff, on the environmental sustainability of the region. The quantitative indicators obtained, including an 11% deterioration in the water quality index (WQI) and an 11% decrease in the productivity of the transboundary Syrdarya River by 2050 under the RCP 8.5 scenario, emphasise the increased risks for mountain meadows, floating forests and river biocoenoses, where habitat fragmentation below hydroelectric power plants reaches 18%. Qualitative results indicate systemic disruptions of ecosystem functions, such as water regulation (-9-14%) and biotreatment (-11-19%), which have long-term consequences for biodiversity and regional hydrological stability.

Based on the analysis, practical recommendations are proposed: strengthening pollution and erosion monitoring with the introduction of automated systems, reducing anthropogenic impact through the optimisation of agricultural practices and mining, and the development of cross-border cooperation for the management of Syrdarya water resources. For further research, it is recommended to expand the empirical base through long-term observations of runoff and biodiversity, integrate more detailed climate models, and apply machine learning to improve forecast accuracy. The limitations of the study are related to the lack of direct measurements for the Naryn Basin, which required the use of estimated data from adjacent regions, potentially affecting the accuracy of interpretation of some scenarios. Despite this, the study has laid the foundation for adaptation strategies in a changing climate, contributing to the sustainable development of the region's water resources.

Acknowledgements

The authors express their gratitude to the USAID Regional Water and Environment Project in Central Asia for its methodological consultations and organizational support during the preparation of this study. Myrzabekova A.M. is the winner of the Central Asian Young Scientists Research Competition (2024 cycle), implemented within the framework of this project; the mentorship received contributed to the refinement of the problem statement, the formation of a scenario matrix, and the interpretation of the results in the context of the WEFE nexus for the study basin. This work was partially supported by the USAID Regional Water and Environment Project in Central Asia. The content of the article, conclusions, and interpretations are solely those of the authors and do not necessarily reflect the views of the United States Agency for International Development (USAID) or the U.S. Government.

Funding

None.

Conflict of Interest

None.

References

[1] Arora, S., & Keshari, A.K. (2021). Pattern recognition of water quality variance in Yamuna River (India) using hierarchical agglomerative cluster and principal component analyses. *Environmental Monitoring and Assessment*, 193(8), article number 494. doi: 10.1007/s10661-021-09318-1.

[2] Asim, M., & Rao, K.N. (2021). Assessment of heavy metal pollution in Yamuna River, Delhi-NCR, using heavy metal pollution index and GIS. *Environmental Monitoring and Assessment*, 193(2), article number 103. doi: 10.1007/s10661-021-08886-6.

[3] Bamal, A., Uddin, M.G., & Olbert, A.I. (2025). Assessing the impact of hydro-climatic factors on surface water quality: A global review and synthesis. *Journal of Hydrology Regional Studies*, 61, article number 102677. doi: 10.1016/j.ejrh.2025.102677.

[4] Betz, F., Lauermann, M., & Egger, G. (2023). Biogeomorphology from space: Analyzing the dynamic interactions between hydromorphology and vegetation along the Naryn River in Kyrgyzstan based on dense satellite time series. *Remote Sensing of Environment*, 299, article number 113890. doi: 10.1016/j.rse.2023.113890.

[5] Bilyalov, Y., Myrzhiyeva, A., Tokayev, Z., Akhmetzhanova, A., Suleimenov, S., Moltabayeva, A., & Muratbayev, D. (2025). Indication of radioactive contamination (Cs137, Sr90) in freshwater fish of the Irtysh River, Kazakhstan. *Egyptian Journal of Aquatic Biology and Fisheries*, 29(1), 2177-2185. doi: 10.21608/ejabf.2025.412104.

[6] De Serio, F., & Mossa, M. (2016). Environmental monitoring in the Mar Grande basin (Ionian Sea, Southern Italy). *Environmental Science and Pollution Research*, 23(13), 12662-12674. doi: 10.1007/s11356-015-4814-y.

[7] Degembaeva, N., Baibagyshev, E., Atakanov, A., Akmatov, K., & Ayipov, B. (2024). Surface water quality in the upper reaches of the Naryn River basin: Composition and seasonal changes. *E3S Web of Conferences*, 537, article number 07004. doi: 10.1051/e3sconf/202453707004.

[8] Dimri, D., Daverey, A., Kumar, A., & Sharma, A. (2020). Monitoring water quality of River Ganga using multivariate techniques and WQI (water quality index) in Western Himalayan region of Uttarakhand, India. *Environmental Nanotechnology Monitoring & Management*, 15, article number 100375. doi: 10.1016/j.enmm.2020.100375.

[9] Dong, X., Zhao, L., Wang, N., & Xie, C. (2022). Spatial variations on the hydrochemistry, controls, and solute sources of surface water in the Weihe River Basin, China. *Environmental Science and Pollution Research*, 29(38), 57790-57807. doi: 10.1007/s11356-022-19550-y.

[10] Earth Resources Observation and Science Center. (2018). *USGS EROS archive – Digital elevation – Shuttle radar topography mission (SRTM) 1 arc-second global*. doi: 10.5066/f7pr7tft.

[11] Egemberdieva, A.D. (2025). Environmental and health impacts of technogenic and microbiological pollution in the Mailuu-Suu River basin, Kyrgyzstan: A comprehensive assessment for sustainable water management. *Eurasian Journal of Scientific and Multidisciplinary Research*, 1(1), 131-135. doi: 10.63666/ejsmr.1694-9013.1.i.2025.17.

[12] Ejigu, M.T. (2021). Overview of water quality modeling. *Cogent Engineering*, 8(1), article number 1891711. doi: 10.1080/23311916.2021.1891711.

[13] Ewaid, S.H., Abed, S.A., Al-Ansari, N., & Salih, R.M. (2020). Development and evaluation of a water quality index for the Iraqi rivers. *Hydrology*, 7(3), article number 67. doi: 10.3390/hydrology7030067.

[14] Food and Agriculture Organization. (n.d.). *Harmonized World Soil Database v2.0*. Retrieved from https://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/harmonized-world-soil-database-v20/en/.

[15] Gupta, D., Shukla, R., Srivastava, P.K., & Mishra, V.K. (2024). Assessment of heavy metal pollution level, ecological and human health risks in surface water of Narmada River, India. *Sustainable Water Resources Management*, 10(4), article number 154. doi: 10.1007/s40899-024-01131-1.

[16] Hill, A.F., Minbaeva, C.K., Wilson, A.M., & Satylkanov, R. (2017). Hydrologic controls and water vulnerabilities in the Naryn River basin, Kyrgyzstan: A socio-hydro case study of water stressors in Central Asia. *Water*, 9(5), article number 325. doi: 10.3390/w9050325.

[17] Hong, Z., Zhao, Q., Chang, J., Peng, L., Wang, S., Hong, Y., Liu, G., & Ding, S. (2020). Evaluation of water quality and heavy metals in wetlands along the Yellow River in Henan Province. *Sustainability*, 12(4), article number 1300. doi: 10.3390/su12041300.

[18] Hussain, K., Khan, N.A., Vambol, V., Vambol, S., Yeremenko, S., & Sydorenko, V. (2022). Advancement in Ozone base wastewater treatment technologies: Brief review. *Ecological Questions*, 33(2), 7-19. doi: 10.12775/EQ.2022.010.

[19] Janybek kyzy, M. (2024). *Kyrgyzstan: River monitoring system needs to be updated*. Retrieved from https://cabar.asia/en/kyrgyzstan-river-monitoring-system-needs-to-be-updated.

[20] Kaldybaev, N.A., Zhunusalieva, A.K., Eshmatova, D.M., & Razhab kyzy, U. (2024). Geochemical assessment of industrial pollution of major rivers in southern Kyrgyzstan. *Proceedings of the National Academy of Sciences of the Kyrgyz Republic*, 8, 325-331.

[21] Kandel, K., Sharma, C.M., Rawat, B., Paudyal, R., Li, M., Pandey, A., & Zhang, Q. (2024). Synthesis analysis of hydrogeochemistry of nepal himalayan rivers: Perspective from major ions and trace elements. *Ecological Indicators*, 163, article number 112080. doi: 10.1016/j.ecolind.2024.112080.

[22] Karaouzas, I., Kapetanaki, N., Mentzafou, A., Kanellopoulos, T.D., & Skoulikidis, N. (2020). Heavy metal contamination status in Greek surface waters: A review with application and evaluation of pollution indices. *Chemosphere*, 263, article number 128192. doi: 10.1016/j.chemosphere.2020.128192.
[23] Karimov, T.K., Kyzy, N.B., & Karimova, M.T. (2024). Ecological and sanitary safety of water supply sources of the Kyrgyz Republic. *BIO Web of Conferences*, 107, article number 03007. doi: 10.1051/bioconf/202410703007.
[24] Khatri, K., Gurung, S., Jha, B.R., Sthapit, M., & Khadka, U.R. (2023). Major ion chemistry of the Bheri (snow-fed) and the Babai (rain-fed) river systems in Western Nepal: Implication on water quality. *Environment and Natural Resources Journal*, 21(4), 299-311. doi: 10.32526/ennrj/21/202200273.
[25] Kuznietsov, P., & Biedunkova, O. (2025). Application of multivariate statistical techniques for assessing spatiotemporal variations of heavy metal pollution in freshwater ecosystems. *Water Conservation Science and Engineering*, 10, article number 13. doi: 10.1007/s41101-025-00341-8.
[26] Kyrgyzhydromet. (n.d.). Retrieved from https://meteo.kg/.
[27] Ma, L., Li, Y., Abuduwaili, J., Uulu, S.A., & Liu, W. (2020). Hydrochemical composition and potentially toxic elements in the Kyrgyzstan portion of the transboundary Chu-Talas River basin, Central Asia. *Scientific Reports*, 10, article number 14972. doi: 10.1038/s41598-020-71880-4.
[28] Matta, G., Kumar, A., Nayak, A., & Kumar, P. (2022). Appraisal of spatial-temporal variation and pollution source estimation of Ganga River system through pollution indices and environmetrics in Upper Ganga basin. *Applied Water Science*, 12(3), article number 33. doi: 10.1007/s13201-021-01552-9.
[29] Nasir, M.J., Wahab, A., Ayaz, T., Khan, S., Khan, A.Z., & Lei, M. (2023). Assessment of heavy metal pollution using contamination factor, pollution load index, and geoaccumulation index in Kalpani River sediments, Pakistan. *Arabian Journal of Geosciences*, 16(2), article number 143. doi: 10.1007/s12517-023-11231-5.
[30] Nazir, A., Khan, M.A., & Ghosh, P. (2022). Assessment of variations in metal concentrations of the Ganges River water by using multivariate statistical techniques. *Limnologica*, 95, article number 125989. doi: 10.1016/j.limno.2022.125989.
[31] Pamirbek kyzy, M., Chen, X., Liu, T., Duulatov, E., Gafurov, A., Omorova, E., & Gafurov, A. (2022). Hydrological forecasting under climate variability using modeling and earth observations in the Naryn River basin, Kyrgyzstan. *Water*, 14(17), article number 2733. doi: 10.3390/w14172733.
[32] Severinenko, M., Solodukhin, V., Djenbaev, B., Lennik, S., Kabirova, G., Zholboldiev, B., Levashov, M., Zheltov, D., & Bychenko, A. (2024). Industrial facilities of Kyrgyzstan as the sources of pollution of the transboundary Shu river basin. *AIP Conference Proceedings*, 3020(1), article number 050004. doi: 10.1063/5.0192747.
[33] Sheripov, N., Murzaibraimov, N., Mamyrbaeva, Z., & Alimbekov, A. (2024). Strengthening environmental governance in Kyrgyzstan: Legal reforms and policy recommendations for ensuring citizens right to a safe environment. *Journal of Environmental Law & Policy*, 4(3), 49-81. doi: 10.33002/jelp040303.
[34] Shumka, S., Kalogianni, E., Šanda, R., Vukić, J., Shumka, L., & Zimmerman, B. (2020). Ecological particularities of the critically endangered killifish *Valencia letourneuxi* and its spring-fed habitats: A long-lost endemic species of south Albania. *Knowledge and Management of Aquatic Ecosystems*, 421, article number 45. doi: 10.1051/kmae/2020036.
[35] SWAT+. (n.d.). Retrieved from https://swat.tamu.edu/software/plus/.
[36] U.S. Department of the Interior. (2025). *Landsat 8-9 OLI/TIRS collection 2 level 1 data format control book*. Retrieved from https://www.usgs.gov/media/files/landsat-8-9-olitirs-collection-2-level-1-data-format-control-book.
[37] Ustaoğlu, F., Tepe, Y., & Taş, B. (2020). Assessment of stream quality and health risk in a subtropical Turkey river system: A combined approach using statistical analysis and water quality index. *Ecological Indicators*, 113, article number 105815. doi: 10.1016/j.ecolind.2019.105815.
[38] Yang, W., Zhao, Y., Wang, D., Wu, H., Lin, A., & He, L. (2020). Using principal components analysis and IDW Interpolation to determine spatial and temporal changes of surface water quality of Xin'anjiang River in Huangshan, China. *International Journal of Environmental Research and Public Health*, 17(8), article number 2942. doi: 10.3390/ijerph17082942.
[39] Yuan, L., Sinshaw, T., & Forshay, K.J. (2020). Review of watershed-scale water quality and nonpoint source pollution models. *Geosciences*, 10(1), article number 25. doi: 10.3390/geosciences10010025.
[40] Zhang, X., Zhang, Y., Gui, Y., Sun, R., Li, J., Wu, Q., Ding, Y., & Chen, K. (2025). Chemical characteristics of groundwater and surface water affected by human activities in the upper Jinzi River Basin, China. *Scientific Reports*, 15, article number 9294. doi: 10.1038/s41598-025-93318-5.

Прогнозне моделювання руху забруднювачів річки Нарин із застосуванням SWAT+ моделі

Аяна Мирзабекова
Магістр
Киргизько-Турецький університет Манас
720044, просп. Ч. Айтматова, 56, м. Бішкек, Киргизька Республіка
https://orcid.org/0009-0008-2446-7031

Нурзат Тотубаєва
Доктор екологічної інженерії, доцент
Киргизько-Турецький університет Манас
720044, просп. Ч. Айтматова, 56, м. Бішкек, Киргизька Республіка
https://orcid.org/0000-0002-5919-9363

Укен Мирзабекова
Доктор біологічних наук, доцент
Киргизький національний університет імені Юсупа Баласагина
720033, вул. Фрунзе, 547, м. Бішкек, Киргизька Республіка
https://orcid.org/0009-0004-9524-9331

Анотація. Актуальність дослідження обумовлена необхідністю оцінки екологічного стану басейну річки Нарин під впливом антропогенного забруднення та кліматичних змін, викликаних гірничодобувною діяльністю, сільськогосподарськими стоками, урбанізацією та накопиченням седиментів нижче гідроелектростанцій. Метою дослідження була кількісна оцінка деградації якості води та екосистем басейну річки Нарин під впливом антропогенних забруднювачів та кліматичних змін. Для досягнення мети застосовувалися методи аналізу даних моніторингу та математичного моделювання. Результати показали значне зниження біорізноманіття на 10-20 % та якості води, викликане збільшенням концентрацій важких металів (до 0,053 міліграма на літр свинцю) та фосфору (до 0,48 міліграма на літр) до 2050 року за кліматичного сценарію. Встановлено, що ерозія збільшилася до 460 т/км^2/рік, а продуктивність транскордонної річки Сирдар'я знизилася на 11 %, що наголошує на вразливості гірських і водних екосистем. Крім того, зафіксовано зменшення вмісту розчиненого кисню до 4,7 міліграм на літр, що посилює негативний вплив на водні біоценози. Також зазначено зниження відтворення рибних популяцій на 18 %, що вказує на серйозні ризики для їх виживання в умовах фрагментації місцеперебування нижче гідроелектростанцій. Практична цінність роботи полягає в наданні основи для розробки заходів з моніторингу та управління водними ресурсами в регіоні, які можуть бути використані органами державної влади Киргизстану та сусідніх країн Центральної Азії, такими як Казахстан та Узбекистан, для координації транскордонного водокористування, а також екологічними організаціями та місцевими спільнотами для збереження

Ключові слова: антропогенний вплив; деградація екосистем; транскордонні річкові системи; кліматичні зміни; водні ресурси; біорізноманіття