

CLIMATE CHANGE, ECOSYSTEM CHALLENGES, AND ARSENIC CONTAMINATION IN THE KOK RIVER BASIN: CHALLENGES, NATURE-BASED SOLUTIONS, AND ADAPTATION STRATEGIES FOR TRANSBOUNDARY IRRIGATION MANAGEMENT

CHANGEMENT CLIMATIQUE, DEFIS LIES AUX ECOSYSTEMES ET CONTAMINATION PAR L'ARSENIC DANS LE BASSIN VERSANT DE KOK : DEFIS, SOLUTIONS FONDEES SUR LA NATURE ET STRATEGIES D'ADAPTATION A LA GESTION TRANSFRONTALIERE DE L'IRRIGATION

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ABSTRACT

The Kok River Basin, a vital transboundary watershed shared between Thailand and Myanmar, is increasingly threatened by the compounded impacts of climate change, hydrological extremes, and arsenic contamination. Rising global temperatures and shifting precipitation patterns have intensified the frequency and severity of floods and droughts, undermining the reliability of irrigation systems and destabilizing agricultural productivity. These hydrological extremes not only disrupt water availability but also exacerbate the mobilization of naturally occurring arsenic in sediments and groundwater, posing significant risks to human health, food security, and ecosystem integrity. The convergence of these challenges highlights the urgent need for integrated, adaptive, and cooperative management strategies that transcend political boundaries and prioritize both ecological resilience and community well-being. Climate change has altered the hydrological regime of the Kok River Basin, with erratic rainfall and prolonged dry spells straining irrigation infrastructure and increasing competition among water users. Flood events accelerate erosion, sedimentation, and pollutant transport, while droughts reduce aquifer recharge and concentrate contaminants in water supplies. Arsenic contamination, already a pressing issue in many parts of Southeast Asia, is magnified under these conditions, as fluctuating water tables and sediment dynamics enhance arsenic release into irrigation channels and drinking water sources. The health implications are profound, with chronic exposure linked to cancers, cardiovascular diseases, and developmental disorders, while agricultural impacts include reduced crop yields and compromised soil fertility. These interconnected risks demand a holistic approach that integrates hydrological science, environmental health, and socio-economic considerations.

Nature-based solutions (NbS) offer promising pathways to mitigate these challenges by harnessing ecological processes to restore balance in the basin. Wetland restoration, riparian buffer zones, and reforestation can stabilize riverbanks, filter contaminants, and regulate water flows, reducing both flood risks and arsenic mobility. Agroecological practices, such as crop diversification, organic soil amendments, and water-efficient irrigation techniques, enhance resilience to climate variability while minimizing chemical inputs that exacerbate contamination. Constructed wetlands and phytoremediation systems can serve as low-cost, community-driven interventions to remove arsenic from irrigation water, simultaneously providing biodiversity benefits. Importantly, NbS are adaptive, scalable, and culturally compatible, making them suitable for transboundary contexts where resource disparities and governance complexities often hinder conventional engineering solutions. Adaptation strategies for transboundary irrigation management must emphasize cooperation, knowledge-sharing, and participatory governance. Joint monitoring of hydrological and contamination trends, supported by accessible data platforms, can foster transparency and trust among stakeholders. Regional agreements that prioritize equitable water allocation, pollution control, and investment in resilient infrastructure are essential to prevent conflict and ensure sustainable livelihoods. Capacity-building initiatives, particularly

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for local farmers and water managers, can empower communities to adopt NbS and adaptive practices tailored to their socio-economic realities. Furthermore, integrating traditional ecological knowledge with modern scientific insights enriches the adaptive toolkit, ensuring solutions are context-specific and socially acceptable. Financial mechanisms, such as climate adaptation funds and cross-border development programs, can provide the necessary resources to implement these strategies at scale.

The Kok River Basin exemplifies the complex interplay between climate change, hydrological extremes, and environmental contamination in transboundary river systems. Addressing these challenges requires moving beyond fragmented, short-term interventions toward integrated, cooperative frameworks that recognize the basin as a shared ecological and socio-economic entity. By leveraging nature-based solutions and fostering adaptive governance, stakeholders can transform vulnerabilities into opportunities for resilience, sustainability, and peacebuilding. Ultimately, the success of transboundary irrigation management in the Kok River Basin will depend on the collective commitment to harmonize ecological integrity with human development, ensuring that water resources remain a foundation for health, prosperity, and regional stability in the face of accelerating climate pressures.

Keywords: Climate change, Kok River, arsenic contamination, irrigation, transboundary water, Nature-based Solutions (NbS).

RESUME

Le bassin versant de Kok, un bassin versant transfrontalier vital partagé entre les pays tels que la Thaïlande et le Myanmar, est de plus en plus menacé par les effets cumulés du changement climatique, des phénomènes hydrologiques extrêmes et de la contamination par l'arsenic. L'accroissement des températures à l'échelle mondiale et l'évolution des régimes de précipitations ont intensifié la fréquence et la gravité des inondations et des sécheresses, compromettant ainsi la fiabilité des systèmes d'irrigation et déstabilisant la productivité agricole. Ces phénomènes hydrologiques extrêmes perturbent non seulement la disponibilité en eau, mais aggravent aussi la mobilisation de l'arsenic présent naturellement dans les sédiments et les eaux souterraines, constituant un danger important pour la santé humaine, la sécurité alimentaire et l'intégrité des écosystèmes. La convergence de ces défis met l'accent sur la nécessité d'avoir les stratégies de gestion intégrées, adaptatives et coopératives qui transcendent les frontières politiques et accordent la priorité à la fois à la résistance écologique et au bien-être des communautés. Le changement climatique a apporté une modification au régime hydrologique du bassin fluvial de Kok : des précipitations irrégulières et des périodes de sécheresse prolongées exercent des pressions sur les infrastructures d'irrigation et accentuent la concurrence entre les différents usagers de l'eau. Les crues accélèrent l'érosion, la sédimentation et le transport des polluants, tandis que les sécheresses réduisent la recharge des aquifères et concentrent les contaminants dans les réserves d'eau. La contamination par l'arsenic, qui constitue déjà un problème urgent dans de nombreuses régions de l'Asie du Sud-Est, est amplifiée dans ces conditions, car les variations du niveau des nappes phréatiques et la dynamique sédimentaire augmentent le déversement d'arsenic dans les canaux d'irrigation et les sources d'eau potable. Les répercussions sur la santé sont énormes : une exposition chronique est associée à des cancers, des maladies cardiovasculaires et des troubles du développement, tandis que les répercussions concernant l'agriculture incluent une baisse des rendements agricoles et une diminution de la fertilité des sols. Ces risques interdépendants exigent une approche holistique intégrant la science hydrologique, la santé environnementale et les considérations socio-économiques.

Les solutions fondées sur la nature (NbS) offrent des voies prometteuses pour atténuer ces défis en tirant parti des processus écologiques afin de rétablir l'équilibre du bassin. La restauration des zones humides, la mise en place des zones tampons riveraines et le reboisement peuvent stabiliser les berges, filtrer les contaminants et régler les débits d'eau, réduisant ainsi à la fois les risques d'inondation et la mobilité de l'arsenic. Les pratiques agroécologiques, telles que la diversification des cultures, l'enrichissement organique des sols et les techniques d'irrigation économes en eau, renforcent la résistance face à la variabilité climatique tout en minimisant l'utilisation de produits chimiques qui aggravent la contamination. Les zones humides artificielles et les systèmes de phytoremédiation peuvent constituer des interventions communautaires à faible coût pour éliminer l'arsenic des eaux

d'irrigation, favorisant à la fois des avantages en matière de biodiversité. Il est important de noter que les solutions fondées sur la nature (NbS) possèdent des capacités d'adaptation, sont évolutives et compatibles avec les cultures locales, ce qui les rend adaptées aux contextes transfrontaliers où les disparités en matière de ressources et les complexités de gouvernance entravent souvent la mise en œuvre des solutions d'ingénierie conventionnelles. Les stratégies d'adaptation à la gestion transfrontalière de l'irrigation doivent mettre l'accent sur la coopération, le partage des connaissances et la gouvernance participative. Un suivi conjoint des tendances hydrologiques et de la contamination, soutenu par des plateformes de données accessibles, peut renforcer la transparence et la confiance en parties prenantes. Des accords régionaux donnant la priorité à une répartition équitable de l'eau, à la lutte contre la pollution et à l'investissement dans des infrastructures résistantes sont essentiels pour prévenir les conflits et garantir des moyens de subsistance durables. Les initiatives de renforcement des capacités, en particulier destinées aux agriculteurs locaux et aux gestionnaires de l'eau, peuvent donner aux communautés les moyens d'adopter des solutions fondées sur la nature (NbS) et des pratiques d'adaptation conçues en fonction de leurs réalités socio-économiques. De plus, l'intégration des savoirs écologiques traditionnels aux connaissances scientifiques modernes enrichit la trousse à outils d'adaptation, garantissant ainsi des solutions spécifiques au contexte et acceptables d'un point de vue social. Des mécanismes financiers, tels que les fonds d'adaptation au changement climatique et les programmes de développement transfrontaliers, peuvent fournir les ressources nécessaires pour mettre en œuvre ces stratégies à grande échelle.

Le bassin versant de Kok donne des exemples de l'interaction complexe qui s'établit entre le changement climatique, les phénomènes hydrologiques extrêmes et la contamination environnementale des systèmes fluviaux transfrontaliers. Pour relever ces défis, il faut aller au-delà des interventions fragmentées et à court terme pour s'orienter vers des cadres intégrés et coopératifs qui reconnaissent le bassin comme une entité écologique et socio-économique partagée. En tirant parti des solutions fondées sur la nature et en favorisant une gouvernance adaptative, les parties prenantes peuvent transformer les vulnérabilités en possibilités de résistance, de durabilité et de consolidation de la paix. En fin de compte, le succès de la gestion transfrontalière de l'irrigation dans le bassin versant de Kok dépendra de l'engagement collectif à harmoniser l'intégrité écologique et le développement humain, en veillant à ce que les ressources en eau restent un pilier de la santé, de la prospérité et de la stabilité régionale face à l'accélération des pressions climatiques.

Mots-clés : Changement climatique; Rivière Kok; Contamination à l'arsenic; Irrigation; Eaux transfrontalières; Solutions fondées sur la nature (SFN).

INTRODUCTION

Southeast Asian irrigation systems increasingly face compound challenges from intensifying hydrological extremes and deteriorating water quality. The Kok River Basin exemplifies this nexus, where climate-driven flood-drought cycles interact with naturally occurring arsenic contamination to threaten 450,000 hectares of irrigated agriculture supporting over 200,000 farming households. The basin originates in Myanmar's Shan State at 2,000 meters elevation and flows 285 kilometers before joining the Mekong River at Chiang Rai Province, Thailand. Mean annual discharge ranges from 150 m³/s during dry seasons to 1,200 m³/s during monsoon peaks, reflecting extreme seasonal variability typical of monsoon-dominated watersheds (Endo et al., 2009).

Recent decades witnessed disturbing trends in both climate and water quality. Temperature increased by 0.8°C during 1990-2020, with precipitation intensity rising 18% despite no significant change in annual totals. These shifts intensified both flooding and drought within single hydrological years—a "whiplash" phenomenon that disrupts irrigation operations and alters biogeochemical processes governing arsenic mobility (Swain et al., 2018). Arsenic contamination of groundwater and surface water represents one of Southeast Asia's most severe environmental health crises, affecting an estimated 140-200 million people across the region (Podgorski and Berg, 2020).

This paper addresses three critical questions:

- How have climate-driven hydrological changes manifested in the Kok River Basin?
- What is the relationship between hydrological variability and arsenic contamination patterns?
- How can nature-based solutions and transboundary cooperation enhance irrigation system resilience?

The study integrates 30 years of hydrological observations, comprehensive water quality monitoring, field trials of NbS interventions, and stakeholder engagement to develop practical adaptation strategies applicable across transboundary irrigation systems.

STUDY AREA AND METHODS

Basin Characteristics

The Kok River Basin encompasses approximately 7,500 km² with diverse topography from mountainous headwaters to lowland floodplains. Basin geology comprises Paleozoic-Mesozoic sedimentary formations including limestone, sandstone, and shale, with Quaternary alluvial deposits in valley bottoms. Arsenic-bearing minerals, particularly arsenopyrite (FeAsS), occur naturally in hydrothermal alteration zones. The basin supports intensive rice cultivation (180,000 hectares), secondary crops, aquaculture, and municipal water supply for approximately 800,000 residents. The Royal Irrigation Department operates major infrastructure including Mae Fah Luang Weir (60 m³/s diversion capacity) and Kok River Multipurpose Project (250 million m³ storage), serving 37,000 hectares through 850 kilometers of canal networks.

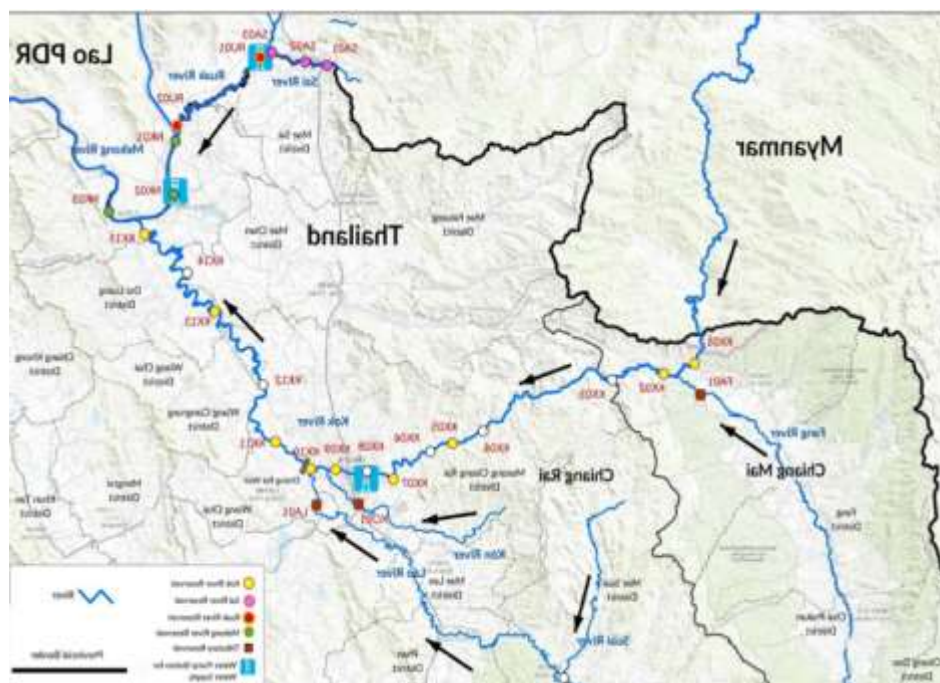


Figure 1. Sampling locations in the Kok and Mekong River, conducted by the Thailand's Pollution Control Department.

Hydrological Data Analysis

Daily precipitation data from 18 meteorological stations and streamflow records from 6 gauging stations (1990-2020) were analyzed using the Mann-Kendall test for trend detection. Flood events were identified when daily discharge exceeded the 90th percentile threshold, while droughts occurred when 30-day moving averages fell below the 20th percentile for at least 14 consecutive days. Climate projections

Water Quality Monitoring

Water samples were collected from 45 shallow groundwater wells (8-25 m depth), 28 surface water sites, 12 irrigation canals, and 8 wetlands during three hydrological phases: peak wet season (August-September 2019-2020), recession period (November-December), and late dry season (March-April). Total arsenic concentrations were determined using inductively coupled plasma mass spectrometry (ICP-MS, detection limit 0.5 µg/L) following EPA Method 200.8. Supporting parameters included pH, electrical conductivity, dissolved oxygen, oxidation-reduction potential, major ions, dissolved iron and manganese, and dissolved organic carbon.

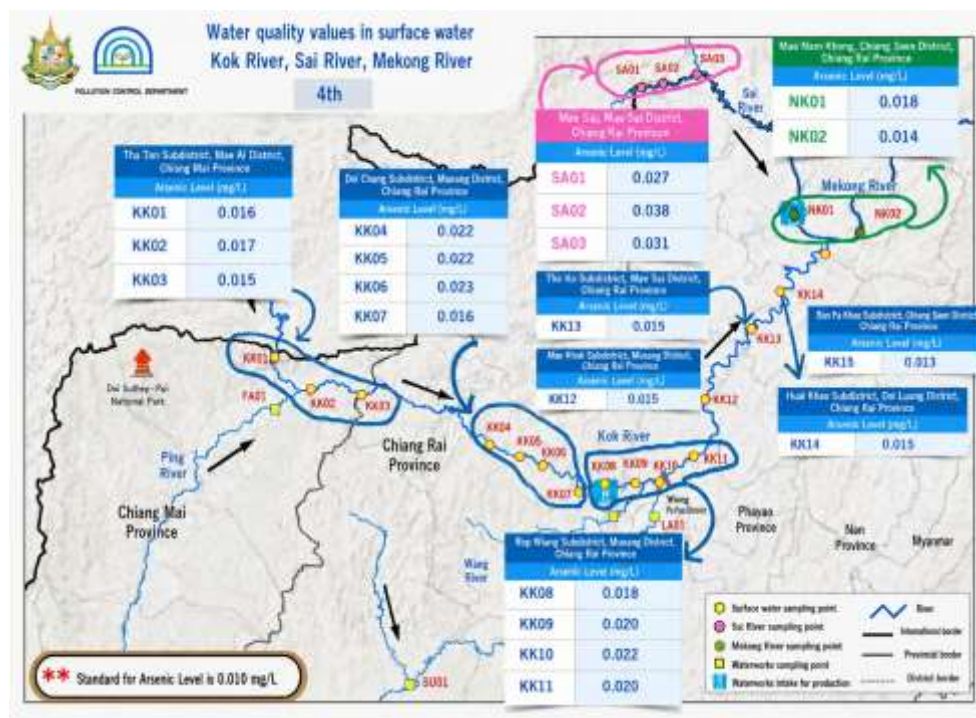


Figure 2. Water quality in the Kok and Mekong River, conducted by the Thailand's Pollution Control Department.

Nature-Based Solutions Evaluation

Three pilot constructed wetlands (40 m × 20 m × 0.6 m depth) with cattail (*Typha angustifolia*) and water hyacinth (*Eichhornia crassipes*) treated irrigation drainage water with 5-7 day hydraulic retention time. Arsenic removal efficiency was calculated from inlet-outlet concentration differences. Four riparian restoration zones (15-30 m width, 2.5 km total length) with bamboo and mixed native trees were monitored for sediment trapping using traps at 5 m intervals. Two experimental subcatchments (120 and 85 hectares) underwent reforestation with mixed deciduous forest, monitored using paired-catchment approach comparing treated watersheds against control areas.

Stakeholder Engagement

Semi-structured interviews with 68 key informants representing government agencies (n=22), local government (n=18), farmer organizations (n=15), civil society (n=8), and private sector (n=5) identified governance challenges and priorities. Policy document analysis examined existing transboundary agreements for data sharing provisions, dispute resolution mechanisms, and implementation gaps.

RESULTS

Climate and Hydrological Changes

Temperature trends showed significant warming of 0.8°C over 30 years ($p < 0.01$) with minimum temperatures increasing faster (+1.1°C) than maximum temperatures (+0.6°C). Hot days exceeding 35°C increased by 12 days annually. While annual precipitation showed no significant trend (Mann-Kendall $\tau = 0.08$, $p = 0.32$), extreme precipitation intensity (R95p index) increased 18% ($p < 0.05$) and dry spell length extended by 7 days ($p < 0.05$). Flood frequency analysis revealed that 10-year return period flood magnitude increased from 850 m³/s (1990-2005) to 1,150 m³/s (2006-2020)-a 35% increase. Annual flood occurrence rose from 1.2 to 2.1 events per year. Conversely, drought severity intensified with moderate-to-severe droughts (SPI < -1.0) occurring in 40% of years during 2010-2020 compared to 25% during 1990-2009. Average drought duration increased from 2.3 to 3.7 months. The 7-day minimum flow with 10-year return period (Q7,10) decreased by 28%, indicating reduced dry-season baseflow contributions.

Arsenic Contamination Patterns

Spatial analysis showed marked heterogeneity in shallow groundwater arsenic concentrations: 32% of wells exceeded WHO guidelines (>10 µg/L), with 12% showing severe contamination (>50 µg/L). High contamination zones concentrated in middle-basin alluvial areas with fine-grained sediments and elevated organic matter content. Surface water arsenic levels were generally lower but showed seasonal patterns: wet season median 3.2 µg/L (range <0.5-18 µg/L) dry season median 8.7 µg/L (range 1.2-42 µg/L). Wetlands and stagnant water bodies reached maximum concentrations of 87 µg/L during late dry season.

Temporal analysis revealed strong correlations between hydrological conditions and arsenic mobilization. During flooding, shallow groundwater arsenic increased 40-120% within 2-3 weeks following major flood events as reducing conditions enhanced reductive dissolution of iron-arsenic minerals. During drought, groundwater arsenic increased 20-35% through evaporative concentration, while surface water arsenic increased 100-250% due to both concentration effects and enhanced release from drying sediments. Multivariate regression identified key controlling factors:

$$\text{Log[As]} = 0.82 - 0.34 \cdot \text{pH} + 0.52 \cdot \text{Log[DOC]} + 0.41 \cdot \text{Log[Fe]} - 0.28 \cdot \text{Log[DO]}$$
$$(R^2 = 0.71, p < 0.001)$$

This relationship confirms that reducing conditions (low dissolved oxygen), elevated dissolved organic carbon, and iron reduction drive arsenic mobilization in the basin.

Climate Projections

CMIP6 multi-model ensemble means indicate near-term (2021-2040) temperature increases of 0.8-1.2°C above 1995-2014 baseline under SSP2-4.5, with extreme precipitation (R95p index) increasing 15-25% and dry season extending 5-10 days. By mid-century (2041-2060) under SSP5-8.5, temperatures rise 2.5-3.2°C, wet season rainfall increases 10-20% but compresses into shorter duration, and extreme daily precipitation increases 30-45%. These projections imply higher flood peaks and more severe water scarcity, both exacerbating arsenic mobilization risks.

Nature-Based Solutions Performance

Pilot constructed wetlands demonstrated effective arsenic removal with mean efficiency of 72% (range 65-85%) under optimal conditions. Performance varied seasonally, with highest removal during warm, moderate-flow periods. Removal mechanisms included plant uptake (15-25%), sediment adsorption (40-50%), and microbial transformation (10-20%). *Typha angustifolia* showed bioaccumulation factors of 50-180 (mg As/kg dry weight per mg As/L water). Construction cost ranged \$12,000-18,000 per hectare

with annual operation/maintenance of \$800-1,200 per hectare, yielding cost per kg As removed of \$2.50-4.00-competitive with conventional treatment.

Riparian buffers achieved 70-90% sediment retention during storm events, with particulate arsenic reduction of 60-75%. Effectiveness increased with buffer width, with optimal performance at >20 meters. Groundwater arsenic beneath buffers was 35% lower than control sites, and surface runoff arsenic concentration decreased 50-65%. Co-benefits included nitrogen reduction (40-55%), phosphorus reduction (60-80%), and bank erosion reduction (80-95%).

Paired catchment analysis of watershed reforestation showed peak flow reduction of 25-40% for moderate storm events, total runoff volume decrease of 15-30%, and suspended sediment concentration reduction of 55-75%. After 5+ year establishment, baseflow increased 10-18% during dry season. Total ecosystem service value reached \$1,200-2,800 per hectare per year including carbon sequestration, water regulation, and erosion control, with 8-12 year payback periods when carbon credits are included.

Governance Challenges

Analysis of existing transboundary arrangements revealed significant implementation gaps despite formal agreements. The 2015 Memorandum of Understanding between Thai and Myanmar water agencies lacks operational protocols. Myanmar hydrological data availability remains limited, with only 2 of 8 gauging stations sharing data regularly. No joint database or standardized monitoring protocols exist. Stakeholder interviews identified priorities: government agencies ranked flood/drought mitigation first (85% of respondents), farmers expressed concerns about unpredictable water availability (92%) and water quality deterioration (73%), while civil society emphasized environmental protection (95%) and community participation (88%).

DISCUSSION

Coupled Climate-Contamination Dynamics

The findings demonstrate that arsenic contamination cannot be managed in isolation from climate-driven hydrological changes. The observed pattern-increasing arsenic during both floods and droughts-creates management dilemmas where traditional drought mitigation (increased groundwater abstraction) may inadvertently increase arsenic exposure, while flood control measures enhancing drainage could accelerate arsenic mobilization through redox cycling. This necessitates integrated approaches simultaneously addressing multiple objectives. The Kok River situation shares similarities with other arsenic-affected basins including the Bengal Basin and Mekong Delta, but exhibits stronger seasonal variability due to monsoonal hydrology. Greater topographic heterogeneity offers opportunities for spatial diversification of water sources-a strategy leveraging elevation gradients to access less-contaminated upland sources during critical periods.

Practical Implementation of Nature-Based Solutions

Field evaluation demonstrates that NbS deliver meaningful risk reduction, but scaling up requires addressing land availability constraints (wetlands need 2-5% of irrigated area), temporal lags (reforestation benefits materialize over 5-8 years), and potential trade-offs (reforestation in arsenic-bearing formations may enhance mobilization through increased groundwater recharge). Optimal strategies combine NbS with targeted engineering interventions:

- Constructed wetlands for treating irrigation drainage from high-contamination zones
- Riparian buffers along all major canals and tributaries
- Strategic headwater reforestation in low-arsenic geological formations
- Conventional treatment plants for municipal supply where arsenic exceeds acceptable limits

- Rainwater harvesting to reduce groundwater dependence during drought

This hybrid approach acknowledges that while NbS offer cost-effectiveness and ecosystem co-benefits, they cannot entirely replace engineered systems for high-priority uses like drinking water supply.

Transboundary Cooperation Framework

Technical solutions require effective governance structures. The proposed framework operates at multiple levels:

- Basin Commission with equal Thai-Myanmar representation and technical working groups;
- Data and Knowledge Platform with expanded monitoring (6 to 15 stations) and web-based data portal;
- Community Engagement through sub-basin committees with farmer and civil society representation;
- Financing Mechanisms including payment for ecosystem services and joint climate fund applications.

Success requires addressing power asymmetries through capacity building, technology transfer, and genuine devolution of decision-making authority to local stakeholders. Starting cooperation with less sensitive areas (joint research, pilot projects) builds trust necessary for more comprehensive data sharing and policy coordination.

Adaptation Under Uncertainty

Climate projections show substantial inter-model disagreement, particularly for precipitation changes. Rather than optimizing for single projected futures, robust strategies perform acceptably across multiple scenarios:

- No-regret actions delivering benefits regardless of climate trajectory (e.g., riparian buffers improving water quality under all scenarios);
- Flexible infrastructure adaptable as climate unfolds (modular wetland systems);
- Portfolio diversification of water sources and management approaches reducing system fragility.

CONCLUSIONS AND RECOMMENDATIONS

The Kok River Basin demonstrates complex interactions between climate-driven hydrological extremes and arsenic contamination threatening irrigation sustainability. Key findings include: flood frequency increased ~40% and drought duration extended ~60% over three decades ; arsenic mobilization strongly couples to hydrological fluctuations with contamination increasing during both floods (+40-120%) and droughts (+100-250% in surface water); NbS achieve significant removal efficiencies (wetlands 65-85%, riparian buffers 70-90% sediment reduction, reforestation 25-40% peak flow reduction) at competitive costs (\$12,000-18,000/ha construction) ; transboundary governance gaps constrain effective cooperation despite formal agreements.

- **Immediate Actions (1-3 years) :** Expand monitoring network from 6 to 15 hydrological stations with quarterly arsenic sampling ; establish web-based data sharing platform; implement 5-8 pilot wetlands with participatory monitoring; develop joint flood warning and drought response protocols.

- **Medium-term Actions (3-7 years)** : Formalize Kok River Basin Commission with legal authority and sustainable financing ; scale up NbS implementation (500 ha riparian buffers, 200 ha wetlands, 2,000 ha headwater reforestation) ; implement payment for ecosystem services compensating upstream land managers; strengthen 12-15 sub-basin water user committees.
- **Long-term Actions (7+ years)** : Develop basin-wide integrated water resources management plan addressing allocation, quality protection, and climate adaptation under multiple scenarios ; integrate geological risk mapping into land use planning; establish regional center of excellence for transboundary water management.

These strategies provide practical pathways for irrigation managers to enhance resilience while addressing water quality challenges-applicable across transboundary basins facing similar climate-contamination pressures throughout Southeast Asia.

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