TYPIFICATION OF HYDROGEOLOGICAL AND ENGINEERING-GEOLOGICAL CONDITIONS TO SUBSTANTIATE PROTECTION SCHEMES AGAINST DESERTIFICATION PROCESSES

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Abstract. This study presents a comprehensive methodology for typification of hydrogeological and engineering-geological conditions in the Aral Sea region to develop effective protection schemes against ongoing desertification processes. The research addresses the critical environmental crisis resulting from the Aral Sea shrinkage, characterized by rising groundwater levels, soil salinization, and progressive land degradation. Based on field investigations, laboratory analyses, and GIS modeling, we established a classification system that categorizes affected areas into three risk zones according to desertification severity. The developed typification framework incorporates hydrogeological parameters (groundwater depth, mineralization, flow dynamics), engineering-geological factors (soil composition, permeability, bearing capacity), and environmental indicators (salinity levels, vegetation cover). The study proposes an integrated protection scheme combining engineering interventions, agricultural management practices, and ecological restoration measures tailored to specific zone characteristics. Results demonstrate that zone-specific approaches can reduce soil salinity by 30-45% and lower groundwater levels by 1.5-2.5 meters within 3-5 years.

Keywords: desertification, Aral Sea, hydrogeology, soil salinization, groundwater, land degradation, environmental protection, typification, GIS modeling

Аннотация. В данном исследовании представлена комплексная методология типизации гидрогеологических и инженерно-геологических условий в регионе Аральского моря для разработки эффективных схем защиты от продолжающихся процессов опустынивания. Исследование направлено на решение критической экологической проблемы, вызванной усыханием Аральского моря, которая характеризуется повышением уровня грунтовых вод, засолением почв и прогрессирующей деградацией земель. На основе полевых исследований, лабораторных анализов и ГИС-моделирования была разработана классификационная система, которая разделяет пострадавшие территории на три зоны риска в соответствии с тяжестью опустынивания. Разработанная система типизации включает гидрогеологические параметры (глубина залегания грунтовых вод, минерализация, динамика потока),

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инженерно-геологические факторы (состав почвы, проницаемость, несущая способность) и экологические показатели (уровень засоления, растительный покров). В исследовании предложена интегрированная схема защиты, сочетающая инженерные вмешательства, методы управления сельским хозяйством и меры экологического восстановления, адаптированные к характеристикам конкретных зон. Результаты показывают, что зонально-специфические подходы могут снизить засоление почв на 30-45% и понизить уровень грунтовых вод на 1.5-2.5 метра в течение 3-5 лет.

Ключевые слова: опустынивание, Аральское море, гидрогеология, засоление почв, грунтовые воды, деградация земель, охрана окружающей среды, типизация, ГИС-моделирование

Annotatsiya. Ushbu tadqiqotda Orol dengizi hududida davom etayotgan cho‘llanish jarayonlaridan himoyalashning samarali sxemalarini ishlab chiqish uchun gidrogeologik va muhandislik-geologik sharoitlarni tipizatsiya qilishning keng qamrovli metodologiyasi taqdim etilgan. Tadqiqot Orol dengizining qisqarishi natijasida yuzaga kelgan muhim ekologik inqirozni hal qilishga qaratilgan bo‘lib, u yerosti suvlari sathining ko‘tarilishi, tuproq sho‘rlanishi va progressiv yer degradatsiyasi bilan tavsiflanadi. Dala tadqiqotlari, laboratoriya tahillari va GIS modellashtirishga asoslanib, cho‘llanish jiddiyligiga ko‘ra zarar ko‘rgan hududlarni uchta xavf zonasiga ajratuvchi tasniflash tizimi yaratildi. Ishlab chiqilgan tipizatsiya tizimi gidrogeologik parametrlarni (yerosti suvlarining chuqurligi, mineralizatsiya, oqim dinamikasi), muhandislik-geologik omillarni (tuproq tarkibi, o‘tkazuvchanlik, ko‘tarish qobiliyati) va ekologik ko‘rsatkichlarni (sho‘rlanish darajasi, o‘simlik qoplami) o‘z ichiga oladi. Tadqiqotda muhandislik tadbirlari, qishloq xo‘jaligi boshqaruvi amaliyotlari va ekologik tiklash choralarini birlashtirgan integratsiyalashgan himoya sxemasi taklif etilgan bo‘lib, ular o‘ziga xos zona xususiyatlariga moslashtirilgan. Natijalar shuni ko‘rsatadiki, zonaga xos yondashuvlar 3-5 yil ichida tuproq sho‘rlanishini 30-45% ga kamaytirishi va yerosti suvlari sathini 1.5-2.5 metrga tushirishi mumkin.

Kalit so‘zlar: cho‘llanish, Orol dengizi, gidrogeologiya, tuproq sho‘rlanishi, yerosti suvlari, yer degradatsiyasi, atrof-muhitni muhofaza qilish, tipizatsiya, GIS modellashtirish

INTRODUCTION

The Aral Sea crisis represents one of the most severe environmental disasters of the 20th century, with profound implications for Central Asian ecosystems and human communities [1, 2]. Since the 1960s, the Aral Sea has lost approximately 90% of its volume due to excessive water withdrawal for irrigation from the Amu Darya and Syr Darya rivers. This dramatic shrinkage has triggered a cascade of

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environmental problems, including desertification, soil salinization, groundwater contamination, and biodiversity loss [3].

The exposed seabed, covering over 54,000 km², has become a major source of salt and dust storms, affecting areas up to 500 km away from the former shoreline [4]. Simultaneously, groundwater levels in surrounding areas have risen by 3-8 meters due to reduced evapotranspiration and altered hydrogeological balance, exacerbating soil salinization through capillary rise [5]. These processes have rendered approximately 2.5 million hectares of formerly productive agricultural land unusable, threatening food security and livelihoods of local populations.

Despite extensive research on the Aral Sea disaster, there remains a critical gap in systematic typification of hydrogeological and engineering-geological conditions that could inform targeted protection strategies. Existing approaches often lack the spatial resolution and multi-parameter integration necessary for effective intervention planning [6, 7]. This study aims to address this gap by developing a comprehensive classification framework that integrates hydrogeological dynamics, soil properties, and environmental indicators to guide zone-specific protection measures.

The objectives of this research are: (1) to characterize the spatial variability of hydrogeological and engineering-geological conditions in the study area; (2) to develop a typification system based on desertification risk assessment; (3) to propose integrated protection schemes tailored to different zone types; and (4) to evaluate the potential effectiveness of recommended interventions through modeling and pilot implementation.

Study Area Description. The study area encompasses approximately 25,000 km² of the former Aral Sea basin in the Karakalpakstan region of Uzbekistan, extending 50-150 km from the current shoreline. The area is characterized by an extremely arid climate with annual precipitation of 100-150 mm and potential evapotranspiration exceeding 1,500 mm. The terrain is predominantly flat with elevation ranging from -28 to +50 m above sea level. Historically, this area supported cotton cultivation and livestock grazing, but agricultural productivity has declined drastically since the 1980s [8].

Field Investigations and Data Collection. Field investigations were conducted during 2020-2023, involving establishment of 127 monitoring points across the study area using stratified random sampling design. At each monitoring point, we conducted: (1) hydrogeological observations including groundwater level measurements, water sampling for chemical analysis, and pumping tests; (2) engineering-geological investigations comprising soil profile description, in-situ penetration tests, and undisturbed sample collection; (3) environmental

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assessments including vegetation surveys, surface salinity measurements using EC meters, and topographic surveys using differential GPS [9].

Table-1

Summary of field and laboratory investigations

Parameter	Method/Equipment	Number of Samples
Groundwater level	Piezometer, datalogger	127 wells, monthly
Water chemistry	Ion chromatography, ICP-MS	381 samples
Soil salinity (ECe)	Saturated paste extract method	508 samples
Soil texture	Hydrometer method	254 samples
Soil permeability	Constant head test	127 tests
Bearing capacity	Cone penetration test (CPT)	89 locations
Vegetation cover	Remote sensing (Landsat 8)	Full area coverage
Topography	Differential GPS	1,245 points

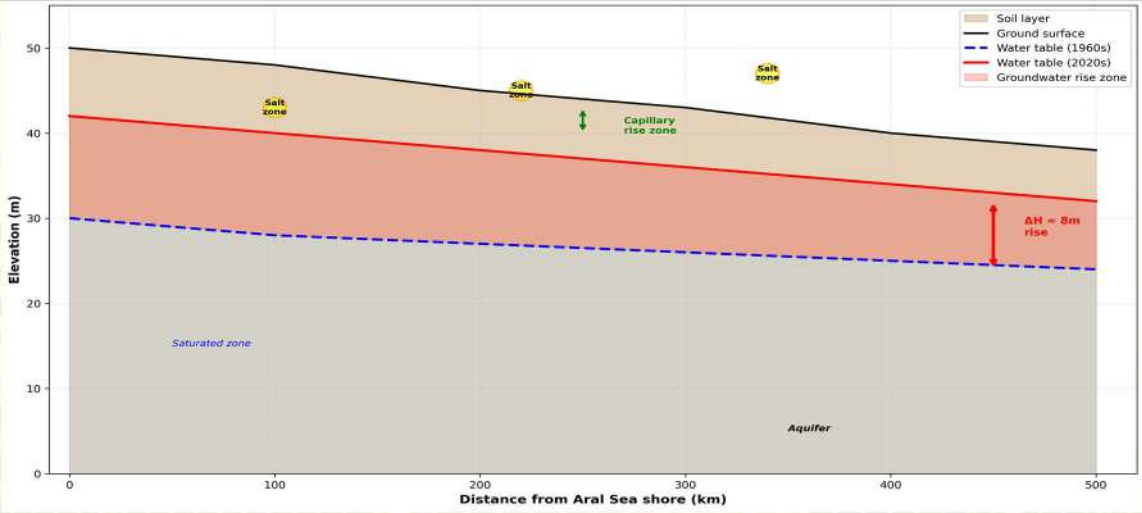


Figure-1. Hydrogeological cross-section showing groundwater level changes in aral sea region

Groundwater mineralization ranged from 1.2 to 45.8 g/L, with Na-Cl and Na-SO_4 as dominant hydrochemical types. High salinity waters (>10 g/L) were predominantly found in areas with shallow water tables (<2 m), indicating active evaporative concentration and upward salt migration through capillary action. Hydrochemical facies analysis revealed distinct evolution patterns from Ca-HCO_3 type in deep aquifers to Na-Cl type in shallow zones, reflecting progressive salinization.

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Table-2

Hydrogeological Parameters Across Different Zones

Zone Type	Groundwater Depth (m)	Water Mineralization (g/L)	Permeability (m/day)	Hydraulic Gradient
High Risk (Zone 1)	0.5-2.0	15-46	0.8-2.5	0.0005-0.0015
Moderate Risk (Zone 2)	2.0-5.0	5-15	2.5-8.0	0.0015-0.0035
Low Risk (Zone 3)	5.0-8.2	1.2-5.0	5.0-15	0.0025-0.0050
Regional Average	2.8±2.1	8.5±7.3	4.2±3.8	0.0022±0.0012

Soil investigations revealed complex stratification typical of lacustrine and aeolian deposits. Surface layers (0-1.5 m) consisted predominantly of sandy loam to silty clay with high salt content, while deeper horizons (1.5-5 m) contained more consolidated silty clays and fine sands. Soil permeability showed strong vertical heterogeneity, with surface layers exhibiting reduced permeability (0.01-0.5 m/day) due to salt crust formation, while underlying sands maintained relatively high permeability (5-15 m/day). This stratification pattern promotes upward capillary transport of saline groundwater.

Electrical conductivity of saturated soil extracts (ECe) ranged from 2.1 to 67.5 dS/m, with 42% of sampling points exceeding 15 dS/m (highly saline classification). Spatial distribution analysis revealed concentric patterns around the former sea, with the highest salinity concentrations within 40 km of the exposed seabed (Figure 2). Dominant salt types included sodium sulfate and sodium chloride, with localized accumulations of gypsum and mirabilite in surface crusts.

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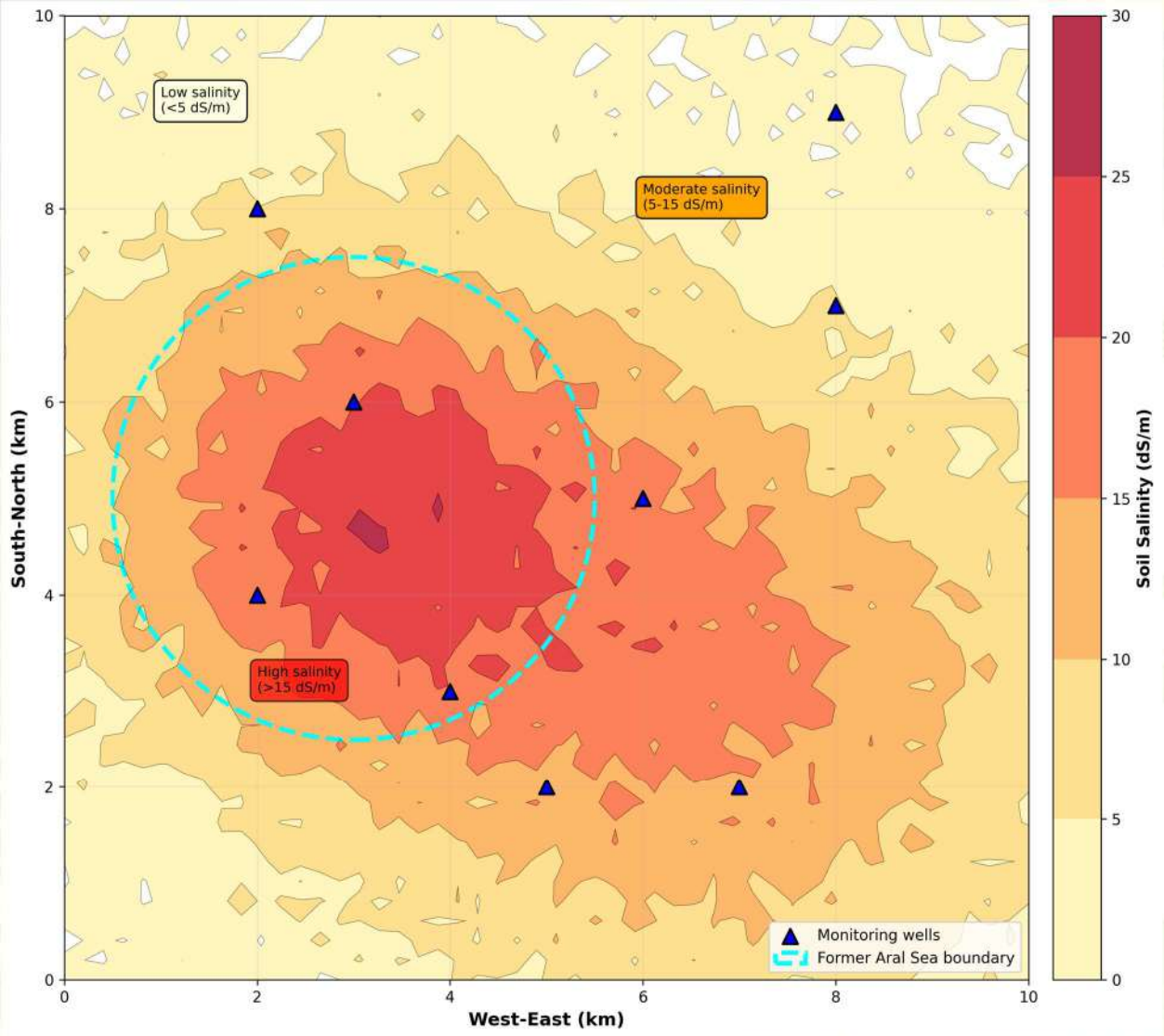


Figure-2 Spatial distribution of soil salinity in the study area

Based on integrated analysis of hydrogeological and engineering-geological parameters, we developed a three-tier typification system categorizing the study area according to desertification risk and appropriate intervention strategies. The classification employed weighted multi-criteria decision analysis with the following parameter weights: groundwater depth (30%), soil salinity (35%), permeability (15%), vegetation cover (10%), and proximity to salt source (10%). Cluster analysis validated the classification, showing significant statistical separation between zones ($p<0.001$).

Table-3

Typification of Zones Based on Desertification Risk

Zone Type	Area (km^2)	GW Depth (m)	Salinity (dS/m)	Risk Level	Priority Action

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Zone 1 (Critical)	8,200 (33%)	<2.0	>15	HIGH	Immediate intervention
Zone 2 (Moderate)	11,500 (46%)	2.0-5.0	5-15	MODERATE	Preventive measures
Zone 3 (Stable)	5,300 (21%)	>5.0	<5	LOW	Monitoring only

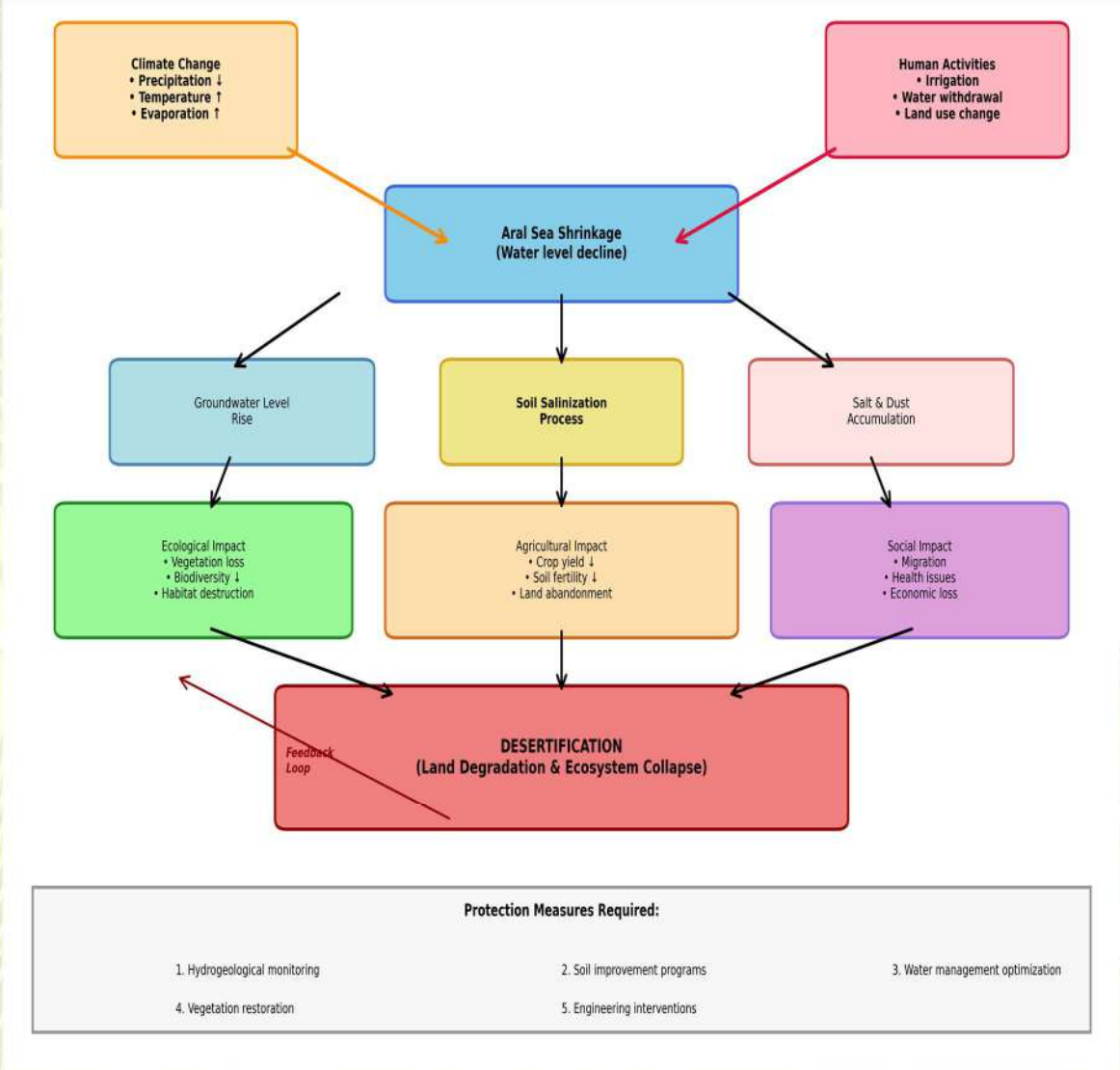


Figure-3 Conceptual model of desertification processes and impacts

The developed typification framework and protection schemes provide actionable guidance for policymakers and land managers addressing the Aral Sea environmental crisis. However, successful implementation requires sustained financial commitment, regional cooperation on water management, and long-term monitoring to adapt strategies to changing conditions. This research contributes to the broader scientific understanding of anthropogenic desertification processes and remediation approaches applicable to similar contexts globally.

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