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**GIS-BASED HYDROMODULAR ZONING OF AGRICULTURAL
LANDS UNDER EXTREME ECOLOGICAL CONDITIONS (A CASE
STUDY OF CHIMBAY DISTRICT, NORTHERN KARAKALPAKSTAN)**

Abstract: This article addresses the critical issues of monitoring and mapping land resources in the northern districts of the Republic of Karakalpakstan, with a specific focus on the Chimbay district. Against the backdrop of the Aral Sea ecological catastrophe, where irrigated agriculture faces unprecedented challenges due to soil salinization, rising groundwater levels, and water scarcity, this study develops a comprehensive methodology for hydromodular zoning using Geographic Information Systems (GIS).

Keywords: Geographic Information Systems (GIS), hydromodular zoning, Chimbay district, land reclamation, irrigated agriculture, groundwater, soil salinization, Aral Sea region, Karakalpakstan, sustainable land management.

ГИС-ОСНОВАННОЕ ГИДРОМОДУЛЬНОЕ РАЙОНИРОВАНИЕ СЕЛЬСКОХОЗЯЙСТВЕННЫХ ЗЕМЕЛЬ В ЭКСТРЕМАЛЬНЫХ ЭКОЛОГИЧЕСКИХ УСЛОВИЯХ (НА ПРИМЕРЕ ЧИМБАЙСКОГО РАЙОНА, СЕВЕРНЫЙ КАРАКАЛПАКСТАН)

***Аннотация:** В данной статье рассматриваются актуальные вопросы мониторинга и картографирования земельных ресурсов северных районов Республики Каракалпакстан, с особым акцентом на Чимбайский район. На фоне экологической катастрофы Аральского моря, где орошаемое земледелие сталкивается с беспрецедентными проблемами, вызванными засолением почв, повышением уровня грунтовых вод и дефицитом водных ресурсов, в настоящем исследовании разработана комплексная методология гидромодульного районирования с использованием геоинформационных систем (ГИС).*

***Ключевые слова:** Географические информационные системы (ГИС), гидромодульное районирование, Чимбайский район, мелиорация земель, орошаемое земледелие, грунтовые воды, засоление почв, Приаралье, Каракалпакстан, устойчивое управление земельными ресурсами*

Introduction

The Republic of Karakalpakstan, an autonomous republic within Uzbekistan, is experiencing one of the most severe ecological crises of the twenty-first century. The desiccation of the Aral Sea, once the fourth-largest inland water body on Earth, has created a new desert—the Aralkum—and triggered a cascade of environmental degradation processes that threaten agricultural sustainability, public health, and economic development across the region. Among the most affected areas are the northern districts of Karakalpakstan, including Chimbay, Karauzyak, Moynaq, and Taxtako'pir, where the combination of rising saline groundwater tables, soil salinization, and diminishing freshwater resources for irrigation has pushed agricultural systems to the brink of collapse.

The Chimbay district, located approximately 50-60 kilometers south of the former Aral Sea shoreline, exemplifies the challenges facing this region. Agriculture remains the dominant land use and primary source of livelihood for the district's predominantly rural population, yet the productivity of irrigated lands has declined precipitously over the past three decades. Studies indicate that secondary salinization affects 70-75% of irrigated lands in the northern districts, with annual

crop yield losses ranging from 30-50% for salt-sensitive crops such as cotton and vegetables. The situation is exacerbated by inadequate drainage infrastructure, inefficient irrigation practices, and the absence of spatially explicit land management guidelines that account for the heterogeneous reclamation conditions across the landscape.

Hydromodular zoning represents a scientifically grounded approach to addressing these challenges. This method involves the spatial delineation of agricultural territories into zones with homogeneous reclamation conditions based on key parameters including groundwater depth and mineralization, soil mechanical composition, salinity levels, and irrigation system characteristics. When implemented effectively, hydromodular zoning enables land managers to match crops to site-specific conditions, optimize irrigation scheduling, target reclamation investments, and prevent further land degradation. However, traditional zoning methods relying on manual mapping and limited field observations are inadequate for capturing the spatial complexity and dynamic nature of reclamation conditions in the Aral Sea region.

Geographic Information Systems (GIS) offer a powerful solution to these limitations. By integrating diverse spatial datasets—from soil maps and groundwater monitoring networks to remote sensing imagery and digital elevation models—GIS enables the quantitative analysis of environmental parameters and the generation of high-resolution zoning maps that reflect real-world heterogeneity. This study applies GIS technology to develop a hydromodular zoning scheme for a representative agricultural area in Chimbay district, with the dual objectives of: (1) establishing a replicable methodology for land resource assessment in data-scarce environments; and (2) generating practical recommendations for crop selection and irrigation management that can enhance agricultural sustainability in the face of ongoing environmental degradation.

Materials and Methods

The study was conducted in the P.Seytov agricultural massif of Chimbay district, located in the northwestern part of Karakalpakstan (approximately 42°55' N, 59°45' E). The massif covers 4,500 hectares of irrigated land, representative of the broader reclamation conditions across Chimbay district. The climate is sharply continental: mean January temperature is -8°C, mean July temperature is 28°C, and annual precipitation averages only 100-120 mm, falling primarily in spring. Potential evapotranspiration exceeds 1,200 mm annually, creating a substantial irrigation requirement for crop production.

The natural vegetation consists of desert-adapted halophytes such as *Salsola* spp., *Artemisia* spp., and *Tamarix* spp., but these have been largely replaced by agricultural crops including cotton (*Gossypium hirsutum*), winter wheat (*Triticum aestivum*), alfalfa (*Medicago sativa*), and vegetables. Irrigation water is supplied through the Amu Darya river via the Kizketken and Pakhtakor main canals, which are unlined and suffer significant seepage losses. Drainage is provided by a network of collector-drains that discharge into natural depressions, but many drains are silted and non-functional.

The following datasets were compiled for the study period 2021-2024:

Soil data: A systematic soil survey was conducted at 156 sampling points across the massif, with samples collected from depths of 0-30 cm and 30-100 cm. At each point, soil type was classified according to the Uzbekistani soil classification system, mechanical composition was determined by the pipette method, and total dissolved solids (salinity) was measured by electrical conductivity (EC) of a 1:5 soil-water extract. Soil pH, organic matter content, and exchangeable sodium percentage were also analyzed.

Groundwater data: Water level and mineralization data were collected from 24 observation wells distributed across the massif, with measurements taken monthly from March to October (irrigation season) and bimonthly from November to February. Groundwater depth was measured to the nearest centimeter using an electric sounder, and samples were analyzed for electrical conductivity, major ion

composition (Ca^{2+} , Mg^{2+} , Na^+ , K^+ , Cl^- , SO_4^{2-} , HCO_3^-), and total dissolved solids.

Irrigation data: The locations and characteristics of irrigation canals, field ditches, and drainage collectors were digitized from topographic maps at 1:25,000 scale. Water delivery schedules and flow rates were obtained from the local water management authority (Uzsuvtaminot). On-farm irrigation practices were documented through farmer surveys ($n=87$) covering cropping patterns, irrigation application depths, and perceived constraints.

Topographic data: A digital elevation model (DEM) with 10-meter resolution was derived from topographic maps and validated with differential GPS measurements at 45 ground control points.

All spatial analyses were performed using ArcGIS 10.6 software (ESRI, Redlands, CA, USA). The methodological workflow consisted of five sequential steps:

Step 1: Data preprocessing and standardization. All spatial datasets were projected to UTM zone 41N (WGS84 datum). Raster layers were generated for each parameter at 30-meter cell resolution using inverse distance weighting (IDW) interpolation for point data (groundwater depth, salinity) and vector-to-raster conversion for polygon data (soil type, mechanical composition). To ensure comparability, all parameter values were standardized to a common 0-1 scale using min-max normalization.

Step 2: Parameter weighting. The relative importance of each parameter for hydromodular zoning was determined using the Analytic Hierarchy Process (AHP), a multi-criteria decision-making technique that structures complex problems hierarchically. A panel of five soil scientists and irrigation engineers with expertise in the Aral Sea region performed pairwise comparisons of the four parameters (groundwater depth, soil salinity, mechanical composition, irrigation system type) based on their perceived influence on reclamation status. The

resulting weights (Table 1) were validated through consistency ratio calculations ($CR < 0.10$).

Table 1: AHP-derived weights for hydromodular zoning parameters

Parameter	Weight	Consistency Ratio
Groundwater depth	0.42	0.06
Soil salinity	0.31	0.06
Mechanical composition	0.18	0.06
Irrigation system type	0.09	0.06

Step 3: Calculation of reclamation status index (RSI). For each 30-meter cell, the RSI was calculated as the weighted sum of the four standardized parameters. Higher RSI values indicate more favorable reclamation conditions (deeper groundwater, lower salinity, lighter texture, more efficient irrigation), while lower values indicate degraded conditions requiring intervention.

Step 4: Zonation. The RSI raster was classified into three zones using the natural breaks (Jenks) optimization method, which minimizes within-zone variance while maximizing between-zone variance. Zone boundaries were smoothed using a 3x3 median filter to remove isolated pixels.

Step 5: Validation. Zonation results were validated against independent field data not used in model calibration, including yield data for cotton (n=42 fields) and wheat (n=38 fields). Statistical significance of yield differences between zones was tested using one-way ANOVA with post-hoc Tukey HSD tests ($\alpha = 0.05$).

3.4 Irrigation Regime Optimization

For each zone, optimal irrigation regimes were developed using the FAO CROPWAT 8.0 model, which implements the Penman-Monteith equation for reference evapotranspiration (ET_0) calculation and the crop coefficient (K_c) approach for crop evapotranspiration (ET_c). Climate data (temperature, humidity, wind speed, sunshine hours) were obtained from the Chimbay meteorological station for the period 2000-2024. Crop coefficients for local varieties were

calibrated using field monitoring of soil moisture depletion in 12 representative fields per zone.

The leaching requirement (LR) for each zone was calculated as:

$$LR = EC_{iw} / (5 * EC_e - EC_{iw})$$

where EC_{iw} is the electrical conductivity of irrigation water (dS/m) and EC_e is the critical threshold EC for the target crop (dS/m). For Zone I, where EC_{iw} averages 2.1 dS/m and soil salinity requires leaching, additional winter-flood leaching applications of 3,500-4,000 m³/ha were prescribed.

Results

Groundwater depth. Interpolation of observation well data revealed pronounced spatial variation in groundwater depth across the study area. The deepest groundwater (>5 m) occurred in the northern sector, where higher elevation and better natural drainage create more favorable conditions. Shallow groundwater (0-3 m) dominated the central and western sectors, corresponding to lower topographic positions and proximity to the main irrigation canal where seepage contributes to waterlogging. The area-weighted mean groundwater depth was 3.4 m, with 28% of the area having groundwater shallower than 2 m during the peak irrigation season (July-August).

Soil salinity. Soil salinity exhibited strong correspondence with groundwater depth (Pearson's $r = -0.73$, $p < 0.001$). Severely salinized soils ($EC > 8$ dS/m in saturated paste extract) were concentrated in areas with groundwater < 2 m, where capillary rise concentrates salts in the surface horizon. Moderately salinized soils ($EC 4-8$ dS/m) occupied transitional zones, while non-saline soils ($EC < 2$ dS/m) were restricted to well-drained northern areas with deeper groundwater. The dominant salt type was chloride-sulfate throughout the study area, with sodium comprising 65-80% of exchangeable cations.

Mechanical composition. Soil texture varied from heavy clay (clay content $> 40\%$) in the central depression to sandy loam (sand content $> 50\%$) along the eastern terrace. Heavy-textured soils, which constitute 52% of the study area, have

low hydraulic conductivity and high water-holding capacity but are prone to waterlogging and difficult to leach. Light-textured soils (18% of area) drain readily but require more frequent irrigation.

The RSI classification produced three distinct hydromodular zones (Figure 1, Table 2). The spatial pattern reflects the underlying topography, with zones arranged concentrically around the central low-lying area.

Table 2: Characteristics of hydromodular zones in the P.Seytov massif

Parameter	Zone I (High risk)	Zone II (Moderate risk)	Zone III (Favorable)
Area (ha)	1,250	2,100	1,150
Proportion (%)	27.8	46.7	25.5
Groundwater depth (m)	0-3 (mean 1.8)	3-5 (mean 4.1)	>5 (mean 6.3)
Groundwater TDS (g/L)	5.2-8.4 (mean 6.8)	3.1-5.0 (mean 4.2)	1.8-2.9 (mean 2.3)
Soil salinity (EC, dS/m)	8-15 (mean 11.2)	4-8 (mean 5.8)	<2 (mean 1.4)
Mechanical composition	Heavy clay (clay 45-55%)	Clay loam (clay 25-35%)	Sandy loam to loam
Irrigation system	Unlined earthen canals	Mixed (canals + pipes)	Lined canals + pipes
Drainage condition	Poor-functioning	Partially functioning	Well-functioning

Zone I (High Salinity Risk Zone). This zone occupies the central and western lowlands, representing the most degraded reclamation conditions. Groundwater remains within 2 meters of the surface throughout the growing season, creating continuous upward salt flux. Surface soil salinity exceeds 10 dS/m EC in the dry season, inhibiting germination and reducing crop growth. The heavy clay texture impedes leaching: even large application depths (2,000 m³/ha) penetrate only the upper 30-40 cm before redistributing laterally. Existing drainage collectors are mostly silted and non-operational, as indicated by ponded water in field depressions and white salt crusts on the surface.

Zone II (Moderate Salinity Risk Zone). This transitional zone surrounds Zone I on the east and south, occupying mid-elevation positions. Groundwater depth fluctuates seasonally from 3 to 5 meters, being shallower in spring (snowmelt + canal filling) and deeper in late summer (crop water uptake). Soil salinity in the root zone (0-60 cm) remains within tolerable limits for moderately salt-tolerant crops (EC 4-6 dS/m) under normal irrigation, but secondary salinization can develop rapidly if irrigation is excessive or drainage is neglected. Soils have favorable physical properties for water management: clay loam texture provides adequate water-holding capacity while allowing sufficient percolation for leaching.

Zone III (Favorable Zone). Located in the northern and northeastern parts of the massif on slightly elevated terrain, Zone III represents the best reclamation conditions. Deep groundwater (>5 m) eliminates capillary rise as a salinization mechanism, and natural drainage to the north prevents water accumulation. Soil profiles are generally non-saline throughout, with the exception of minor surface accumulation in micro-depressions where evaporation concentrates salts. The lighter texture facilitates deeper percolation of irrigation water, enabling effective leaching of any salts that do accumulate. Existing drainage collectors are maintained and discharge to an inter-collector drain that flows northward out of the massif.

Yield monitoring confirmed the ecological and agronomic relevance of the zoning classification (Table 3). For cotton, average yield in Zone III (3.8 t/ha) was 73% higher than in Zone I (2.2 t/ha). Wheat followed a similar pattern, with yields declining from 5.1 t/ha in Zone III to 3.2 t/ha in Zone I. The yield differences between zones were statistically significant for both crops ($p < 0.001$, ANOVA followed by Tukey HSD). Notably, within-zone yield variability was lowest in Zone I (CV = 12% for cotton), reflecting the uniformly poor conditions, and highest in Zone II (CV = 21%), reflecting the transitional nature where site-specific management can produce widely divergent outcomes.

Table 3: Crop yield by hydromodular zone (mean \pm SD, n fields)

Crop	Zone I	Zone II	Zone III	Overall
Cotton yield (t/ha)	2.2 \pm 0.26a	3.1 \pm 0.65b	3.8 \pm 0.52c	3.1 \pm 0.80
Wheat yield (t/ha)	3.2 \pm 0.41a	4.2 \pm 0.71b	5.1 \pm 0.63c	4.2 \pm 0.89
Relative yield (% of Zone III)	58% (cotton), 63% (wheat)	82% (cotton), 82% (wheat)	100% (cotton), 100% (wheat)	-

Different superscript letters indicate significant differences between zones ($p < 0.05$, Tukey HSD).

4.4 Optimized Irrigation Regimes

CROPWAT modeling produced zone-specific irrigation schedules that balance crop water requirements with leaching needs and water availability constraints (Table 4). The key principle underlying these schedules is that water application should be matched not only to crop evapotranspiration but also to the leaching requirement dictated by soil salinity and irrigation water quality.

Zone I: The high leaching requirement (LR = 0.28) reflects both poor water quality ($EC_{iw} = 2.1$ dS/m) and low salt tolerance of most cash crops. A two-phase irrigation strategy is recommended: (1) winter-flood leaching (3,500-4,000 m³/ha) applied in December-January when evaporation is minimal, using the full irrigation allocation to push salts below the root zone; and (2) growing-season irrigation at 8- to 10-day intervals, not by calendar schedule but by soil moisture tension (irrigate when tension reaches 50 kPa at 20 cm depth). This approach prevents the buildup of salts between irrigations while avoiding waterlogging from excessive applications.

Zone II: Salts can be managed through grower-season leaching without a dedicated winter flood. The recommended schedule matches irrigation to the 60% depletion of available water (irrigate when tension reaches 40 kPa), with two "flushing irrigations" during the season—one at peak vegetative growth and one at

early boll development—that apply 25% more water than ET_c to push accumulated salts downward.

Zone III: Standard deficit irrigation (80% of ET_c) is sufficient, as natural precipitation (limited as it is) and deep percolation prevent salt accumulation. Irrigation frequency can be reduced to 12- to 14-day intervals, decreasing labor costs and reducing waterlogging risk.

Table 4: Recommended irrigation regimes by hydromodular zone

Parameter	Zone I	Zone II	Zone III
Cotton schedule			
Leaching requirement	0.28	0.12	0.04
Winter leaching (m ³ /ha)	3,500-4,000	0-1,000	0
Vegetation irrigation (m ³ /ha)	6,000-6,500	5,500-6,000	4,500-5,000
Total annual (m ³ /ha)	9,500-10,500	5,500-7,000	4,500-5,000
Irrigation frequency (days)	8-10	10-12	12-14
Wheat schedule			
Leaching requirement	0.20	0.08	0.02
Winter leaching (m ³ /ha)	2,500-3,000	0	0
Vegetation irrigation (m ³ /ha)	4,500-5,000	4,000-4,500	3,500-4,000
Total annual (m ³ /ha)	7,000-8,000	4,000-4,500	3,500-4,000
Water savings vs. current practice (%)	15-20%	10-15%	5-10%

Discussion

Traditional hydromodular zoning in Uzbekistan, as codified in Soviet-era guidelines, relied primarily on expert judgment and limited field observations, typically mapping zones at the scale of entire irrigation systems (hundreds to thousands of hectares) without capturing within-system heterogeneity. The GIS-

based approach developed in this study represents a significant advancement by enabling zoning at the field scale (30-meter resolution), where management decisions are actually implemented. This higher resolution has practical consequences: in the study area, 22% of fields straddled zone boundaries under traditional zoning (i.e., were classified incorrectly), leading to inappropriate irrigation recommendations for portions of those fields. Under the new scheme, each field is assigned to a single zone, enabling uniform management prescriptions.

The water savings potential identified in this study (10-20% of current applied volumes) is substantial given the regional water scarcity. The Amu Darya, which supplies irrigation water to Karakalpakstan, has seen its flow reduced by 50-70% since 1960 due to upstream diversion, and climate change projections indicate further reductions of 10-30% by 2050 (Micklin, 2016). Implementing zone-specific irrigation scheduling could free water for environmental flows to the Aral Sea remnant, maintain agricultural productivity with less water, or expand irrigated area without increasing total diversion.

However, realizing these savings requires institutional changes. Currently, water is allocated to Water Consumer Associations (WCAs) based on historical entitlements rather than crop water requirements, creating incentives to use full allocations even when not needed. Transitioning to demand-based allocation calibrated to evapotranspiration and leaching requirements—as enabled by the zoning maps—would align water distribution with agronomic needs. This shift would require investments in flow measurement infrastructure and training for WCA staff in modern irrigation scheduling.

Several limitations of this study should be acknowledged. First, the analysis focused on a single massif within Chimbay district; while the massif was selected for representativeness, extrapolation to the entire district should be validated with additional field data. Second, the zoning scheme is static, yet groundwater levels and soil salinity exhibit strong seasonal and interannual dynamics. Future research

should develop a dynamic zoning approach that updates zone boundaries in near-real time using remote sensing of soil moisture and vegetation indices. Third, the economic analysis (returns per zone) was limited to yield data; inclusion of input costs (seed, fertilizer, labor, water fees) would enable net profitability comparisons. Fourth, social factors—land tenure security, farmer access to credit, extension service quality—were not incorporated but likely influence adoption of recommended practices.

Conclusions

This study developed a GIS-based methodology for hydromodular zoning of irrigated agricultural lands in the Chimbay district of northern Karakalpakstan, a region experiencing severe land degradation due to the Aral Sea ecological crisis. The key findings and conclusions are:

The study area exhibits pronounced spatial heterogeneity in reclamation conditions, with three distinct zones identified: high-risk Zone I (27.8% of area) requiring intensive leaching and salt-tolerant crops; moderate-risk Zone II (46.7%) suitable for traditional cash crops with improved water management; and favorable Zone III (25.5%) where standard practices are adequate.

Current irrigation practices do not account for this heterogeneity, leading to waterlogging and salinization in Zone I (excessive application) and yield-limiting water stress in Zone III (insufficient application). Zone-specific irrigation regimes developed in this study could reduce water application by 10-20% while maintaining or increasing yields.

The GIS-based zoning methodology is replicable and scalable, requiring only standard soil maps, groundwater monitoring data, and digital elevation data that are available or can be generated for most irrigation systems across Karakalpakstan. The cost of implementing the methodology (estimated at \$8-12 per hectare for data collection and analysis) is modest relative to the potential benefits of improved water productivity and reduced land degradation.

Validation against independent cotton and wheat yield data confirmed the agronomic relevance of the zoning classification, with yield differences between zones of 40-70% that were statistically significant ($p < 0.001$).

Institutional reforms, including demand-based water allocation and capacity building for Water Consumer Associations, are necessary to translate zoning maps into improved on-farm management.

The methodology and findings from this study contribute to the scientific basis for sustainable land management in one of the world's most environmentally stressed regions, with potential applications across the Aral Sea basin and other arid zones where water scarcity and soil salinization threaten agricultural livelihoods.

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