Managed aquifer recharge (MAR) with a naturally based approach for Kazakhstan's water sustainability

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Managed Aquifer Recharge (MAR)

Managed Aquifer Recharge (MAR) is a targeted water management system that involves replenishing aquifers with various water sources, such as snow, floodwater, stormwater, treated wastewater, industrial, and non-potable surface water, for subsequent storage for future use or environmental benefits. This MAR method is getting popular worldwide as sustainable solutions to mitigate the water shortage problems, especially in arid and semi-arid regions [1,2].

Why MAR for Kazakhstan?

Kazakhstan, a country with a vast territory and diverse, often inefficient, water use methods and technologies, experiences significant seasonal variations in precipitation, creating challenges in water resource management. Situated at the end of several transboundary river basins, Kazakhstan has problems with surface water, connected with its dependence from neighboring countries. High water losses and pollution create challenges for Kazakhstan's sustainable development. Climate fluctuations, characterized by increased flood peaks in early spring and severe droughts in summer, further exacerbate these problems. During spring floods, residents of Kazakhstan often struggle to cope with the excess flood water, attempting to dispose of it, often try to pass the flood water away somehow, transferring the flood problems to the neighbors at lower elevations. Without well-established, rational programs for conserving floodwater near their homes and communities for later use in the summer these flood water passing actions are irrational. During droughts the same local people may have critical water shortages issues, which impacts the local sustainability in the rural farms' sustainability. The MAR application expansion could be a more efficient and sustainable approach for many Kazakhstan's regions to improve water security/ MAR allows replenishment of groundwater resources and can support sustainable water reuse practices expansion throughout Kazakhstan. By strategically capturing and filtering excess water during periods of flood water abundance, MAR can reduce both flood risks and conserve water for summer droughts [1-4]. The localized MAR technologies that combine snow and floodwater harvesting with runoff management can be widely implemented throughout Kazakhstan. This can be achieved through the introduction of forest shelterbelts, contour strip land organization, sequentially connected in the final section to the retention ponds, effectively creating a distributed network of water storage ponds with reasonable flow rates for storing floodwater and recharging groundwater aquifers (Figs. 1-4)

Snow flood water accumulatios

Melting snow floods are one of the main emergency disaster event issues in Kazakhstan. The implementation of efficient water collection systems for snowmelt and flood relocation could be one of the key strategies for improving water sustainability in most Kazakhstan's regions. This strategy should be rationally implemented by following Nature, respecting the water's natural flow movement [4]. Minimal adjustments would be reasonable to adapt for the Nature terrain, by following the local topography, avoiding direct confrontation with Nature by building the big dams against direct movement of the big amount of flood water. The Natural water movements streams would be rational to keep, with the basic adaptation activities and allowing the melted snow to move and be stored gradually, before potential widespread big flooding may happen [4]. This strategy would allow control to the potential movement of the big amount of water, to help snow melting activities, by directing and accumulating water for the further seepage into underground aquifers with connected MAR technologies. The snow flood collection system could be designed based on the terrain, the local topography by using various types of retention ponds. Below is a basic scenario for a snow flood collection in the retention pond during the early spring period.

Figure 1. The snow flood water collection system shows water movement during the early spring in the retention pond. *Snowmelt Runoff Channel (Top-Center)*: *Snowmelt Runoff Channel (Top-Center)*: A clear, winding channel is visible at the top, actively transporting muddy-brown water from the surrounding fields towards the retention pond. The banks of this channel and adjacent areas are outlined with residual white snow, indicating the source of the meltwater. *Retention Pond (Center-Large Circular Pond)*: The dominant feature is the large, circular "Retention Pond." It is filled with a significant volume of brownish, turbid water, characteristic of snowmelt runoff carrying suspended soil. Crucially, large, irregular patches of white ice and melting snow are floating on the pond's surface,

visually emphasizing the early spring conditions. The pond's primary role is to collect and hold this large influx of water, mitigating flood risks and storing water for future agricultural use. *Contoured Farmland (Throughout):* The vast agricultural fields surrounding the pond are depicted as bare, dark gray-brown earth. Distinct Contoured Farmland patterns are evident as subtle, sweeping lines across the landscape. These contours play a vital role in directing the snowmelt runoff efficiently towards the collection channel and minimizing soil erosion [3,4].

Figure 2. The snow flood water collection system, showing the potential design during the late spring - early summer in the farmland retention ponds system. *Snowmelt Water Collection Channel (Top-Center)*: A visible channel at the top of the image indicates where snowmelt water is initially gathered from the surrounding fields. This channel directs the water towards the main processing area. *Settlement Pond (Left-Large Pond)*: The first large circular pond on the left is the Settlement Pond. Here, the initial floodwaters, which may contain sediment and debris from the fields, are allowed to settle. Heavier particles sink to the bottom, clarifying the water before it moves to the next stage. *Retention Pond (Right-Large Pond)*: Adjacent to the settlement pond is the Retention Pond. This pond serves as a larger reservoir for storing the partially clarified water. It ensures a continuous supply for irrigation or further treatment, regulating the flow downstream. *Biomass Ponds (Smaller Ponds at Bottom-Right): T*wo smaller circular ponds are Biomass Ponds. These ponds are designed to cultivate aquatic plants or

microorganisms (biomass) that can naturally filter and purify the water, potentially removing excess nutrients or pollutants. This is a biological treatment stage. *Subsurface Aquifer (Below the Ponds)*: The Subsurface Aquifer is beneath the pond system. This suggests that the collected and treated water can either be used for direct irrigation or allowed to infiltrate the ground to recharge local groundwater reserves, providing a long-term water source. *Farmland and Contour Strips (Background)*: The surrounding landscape features expansive green fields with visible Contour Strips. These are farming practices where crops are planted in rows that follow the contours of the land, helping to reduce soil erosion and manage water runoff more effectively, guiding it towards the collection system.[3.4]

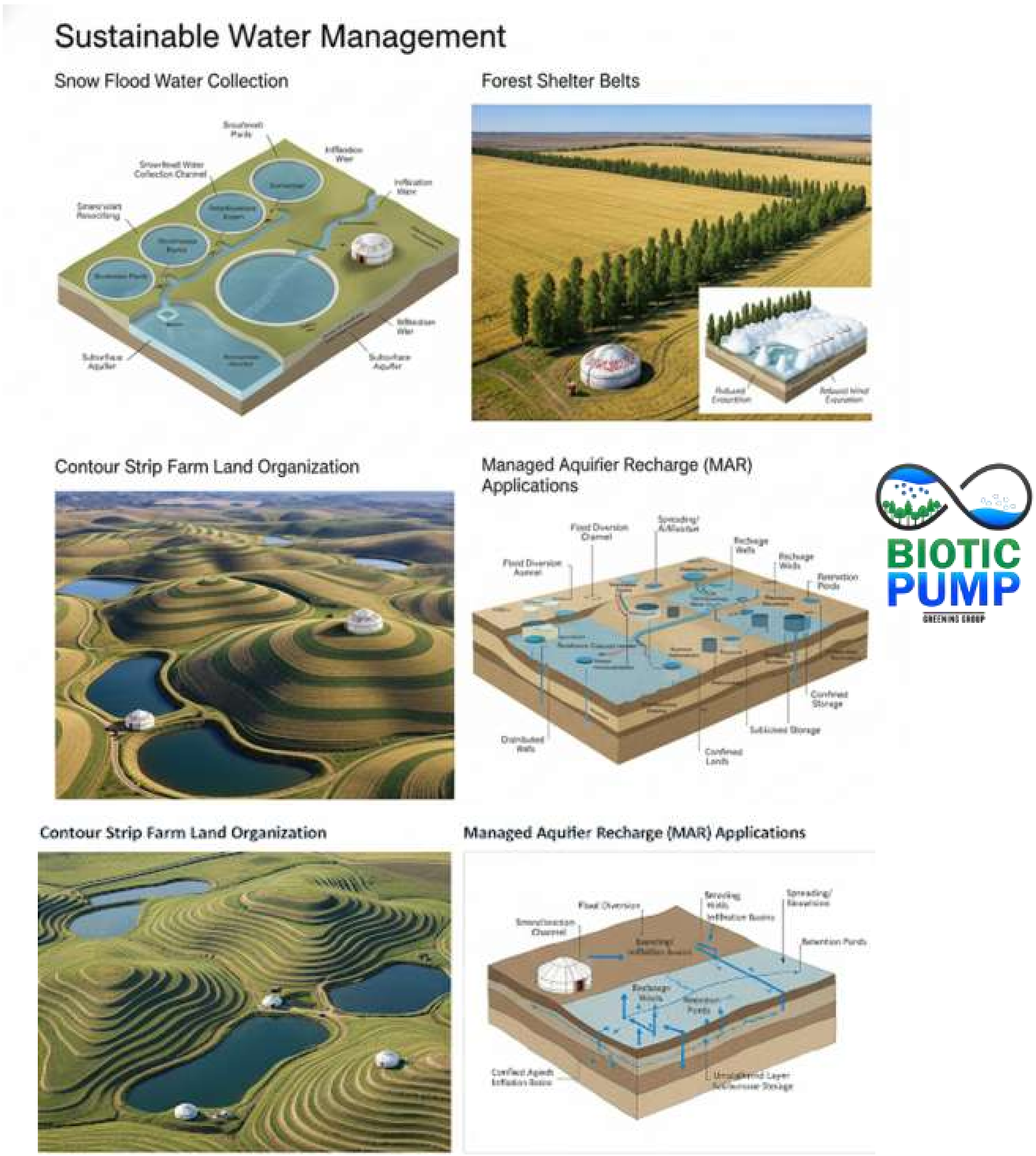


Figure 3. Snowmelt is a major contributor to spring floods in Kazakhstan. Implementing effective snow

flood water collection systems is crucial. This involves creating structures that can capture, and store melted snow before it causes widespread flooding, allowing for controlled infiltration into aquifers. Incorporating the almost forgotten Kazak tradition to use movable yurts into the Kazakh landscapes could give more flexibility to adapt into Nature, by respecting Nature. Similarly, as Canadian Indians respect the water desire in movements, adapt to the Natural topography, it could be less costly, instead of the big engineering constructions on the flood zones against the natural flood water movements, Indians respect nature and the movement of water [3,4]

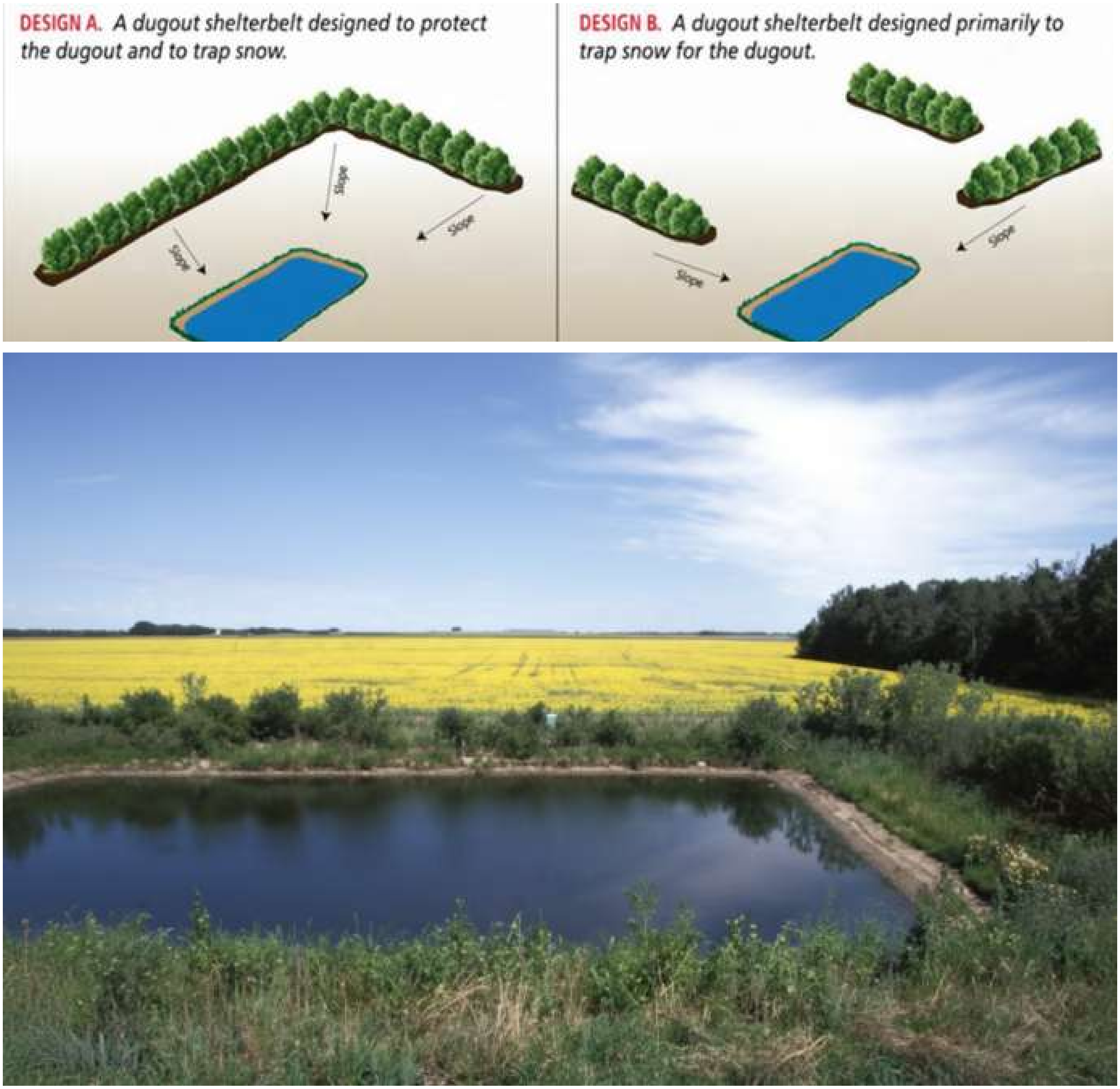


Figure 4. Forest shelter belts play a dual role in water management: reducing wind erosion and enhancing snow accumulation. The proper designed tree rows can provide the maximum available snow collection and direct the right runoff water to the dugout, retention pond. Generally, trees should be planted on the north and west sides of a dugout, retention ponds to trap snow and to reduce evaporation caused by prevailing winds. Shelterbelts on the south and east sides may also be an effective snow trap where winds contribute to large snow accumulations [3-7]

Figure 5. Snowmelt and spring runoff can be an important water source for dugouts and retention ponds. Strategically placed shelterbelts can trap significant amounts of snow for the eventual filling of a dugout, retention pond. By strategically planting trees and shrubs in rows, these belts can significantly slow down wind speeds, preventing valuable topsoil from being blown away. More

importantly for water management, shelter belts can trap snow, leading to a more even distribution and slower melt, which in turn facilitates better infiltration into the soil. Shelterbelts create microclimates that reduce evaporation from the soil surface, further conserving moisture. In winter, they act as natural snow fences, accumulating snowdrifts that, upon melting, slowly release water into the surrounding agricultural lands. Contour strip farming combined with planting different crops in alternating strips along the contours of the land is highly effective in preventing soil erosion on sloped terrain, and in managing water runoff. By following the natural elevation lines, contour strips reduce the velocity of water flow, allowing more time for water to infiltrate the soil rather than running off [3-7].

Benefits of MAR for Kazakhstan's Agriculture

- **Increased Water Security:** Reduces reliance on variable surface water supplies, creating a buffer against droughts and climate variability.
- **Groundwater Replenishment:** Recharges depleted aquifers, reversing trends of groundwater table decline and combating over-abstraction.
- **Improved Water Quality:** Natural filtration through soil and aquifer materials can remove pollutants, improving the quality of recharged water for agricultural use.
- **Reduced Evaporation Losses:** Storing water underground minimizes surface evaporation inherent to reservoirs and open canals.
- **Reliable Support for Irrigation:** Provides a reliable source of water for crop irrigation, especially during dry seasons and extended irrigation periods, enhancing agricultural productivity and resilience.
- **Environmental and Economic Gains:** Supports ecosystem health by maintaining baseflow in rivers and wetlands, reduces pumping costs in the long term, and fosters sustainable agricultural growth.
- **Reducing transboundary dependency:** Kazakhstan is located at the end of several transboundary river basins, where are the neighbors' countries often unpredictable. The neighbors may release the flood water when they have emergency flood risk issues by diverting floods away, by creating problems for the neighbors, who are living in the lower elevated areas, vice versa, the neighbors may hold water during the peak drought summer season. Kazakhstan could be decreasing its transboundary dependency on the water resources from the neighbors by creating a local flood water collection with reasonable expenses, by avoiding the expensive big dams' constructions , by following the Natural topography and introducing the contour strip land organization, setting up the chain of the retention's ponds, connected to MAR technologies.

Challenges and Considerations for MAR in Kazakhstan

- **Hydrogeological Assessment:** Thorough studies are needed to identify suitable sites with appropriate aquifer characteristics and infiltration rates.
- **Water Quality:** The quality of source water for recharge must be carefully monitored and, if necessary, treated to prevent aquifer contamination. TVET support for the local expertise skills improvement in MAR implementation are needed for Kazakhstan's regions and villages, to analyze water quality, including for schoolchildren, with similar TVET programs that are in the Koksu Polytechnic College in Zhetysu Oblast promotion based on the US farm schoolchildren

TVET activities https://youtu.be/2vi75468Ohg

- **Infrastructure Development:** Requires infrastructure improvement with the proper geodesy farmland topography survey investigations for water diversion, conveyance, and recharge facilities for MAR.
- **Regulatory Framework:** Development of clear policies and regulations for MAR implementation, water rights, and quality standards. The proper incentives, including financial support, tax breaks, tax reductions, the taxes substitute to implement MAR in local regions by industry and local farmers to engage the snow collection, flood water conservation would be reasonable to adapt
- **Capacity Building:** Training local experts and stakeholders in MAR design, operation, and maintenance by studying international expertise similar MAR activities, https://floodmar.org/ , https://www.inowas.com/.

Kazakhstan's farmers land sustainability improvement with soil, geology, MAR water retention

Land degradation issues are getting complicated. Kazakhstan's land use has sharply deteriorated over several decades, necessitating comprehensive assessment and restoration. Farmlands in Kazakhstan are grappling with multiple challenges related to climate change, intense anthropogenic distractions, aggressive industrial agricultural practices involving monoculture crop production, Soil depletion is widespread in Kazakhstan due to the flood erosion and drought expansion, causing desertification, and intensive pesticides, nitrate, phosphate applications. The sustainability of farmlands improvement, including the soil, geology, and MAR water retention assessment would be reasonable to expand all over the Kazakhstan farmland territories. Contour-strip land organization with forest shelterbelts topography design preparation could be some of such programs to improve Kazakhstan's farmlands sustainability. Many farms in Kazakhstan poorly implement the snow flood water collection and soil moisture retention technologies alongside with protective forest shelter belts applied on agricultural lands. The cause of these issues could be related to the poor incentive to adapt more Nature-based solutions to improve the farmland sustainability, which requires time and preliminary investments. Most Kazakhstan's farmers are required to produce the agricultural products during the short period of time; most bank credits are given for the short period of time. The long-term bank credits with reasonable percentage rating are complicated to receive in Kazakhstan. The previous big subsidies, which were used during the former soviet period, for agricultural land snow retention, forest shelters belts support programs, soil moisture retention forestry improvement activities were decreased dramatically during the last several decades in Kazakhstan.

The nature-based methods for forest plantation along contour strips, topography-based design landscape are rarely applied or are absent in many rural areas, farmlands these days in Kazakhstan. The land use issues resulted in the loss of the soil moisture protective functions and a reduction in agricultural efficiency. Kazakhstan's agrochemical soil fertility analysis, hydrogeology assessment, water resource potential evaluation would be reasonable to provide on the permanent base with expansion of the Nature-based solutions. Geodesy geomatics tools would be reasonable to expand in the practical applications by expanding the dual education college based localized Technical and Vocational Education and Training (TVET) programs all over the farmland regions in Kazakhstan. Kazakhstan's farmlands topography investigation with digital model elevation (DEM), digital terrain models (DTM) preparation and potential retention pond's location identification for managed aquifer recharge (MAR) introduction would be reasonable to expand for the flood mitigation activities locally in the rural regions by the local activities, framers themselves. The proper dual TVET support with financial incentives for the development of the forest shelterbelts are also important to expand all over the Kazakhstan regions. The combination of effective water accumulation methods, considering topography, with the development of protective forest shelter belts should enhance the land use strategies for sustainable development in Kazakhstan. This strategy is expected to reduce soil erosion, promote moisture accumulation, by improving the soil quality to be as sponges in water collection, and increase crop yields.

Kazakhstan's Natural Water Cycle restoration locally on the small rural areas

The disruption of natural connections within the terrestrial water cycle, including changes in evaporation, transpiration, and atmospheric moisture convergence, has a substantial impact on the water balance, biodiversity, and stability of soil systems all over Kazakhstan's territories. A range of studies demonstrates that the local changes in vegetative cover can improve restoration of the small streams and rivers [8-18]. A decrease in transpiration due to deforestation leads to reduced rainfall in the Amazon. At the same time, as the opposite example, forest restoration on China's Loess Plateau first decreased and then intensified atmospheric moisture convergence [19–27]. The Natural Water Cycle restoration locally is presented in the diagrams below (Figures 6 - 10).

Figure 6. Restoration of the Natural Water Cycle, modified from [28–30]. Afforestation restores the natural water cycle: moisture evaporating from leaf surfaces increases atmospheric humidity, which

initiates cloud formation and increases precipitation. This process, in turn, enhances moisture convergence and creates a positive feedback loop where forest masses stabilize and even amplify the local and regional water cycle A crucial aspect lies in the fact that atmospheric dynamics vary depending on the initial state of the atmosphere: in a dry atmosphere, an increase in transpiration merely redistributes moisture, whereas in an atmosphere close to saturation, evapotranspiration is capable of simultaneously increasing both precipitation and moisture influx. Thus, tree plantations improve the soil quality, prevent soil degradation, decrease the landscape destruction, and work on the self-sustaining mechanism of moisture circulation, ensuring the long-term sustainability of ecosystems [28-30].

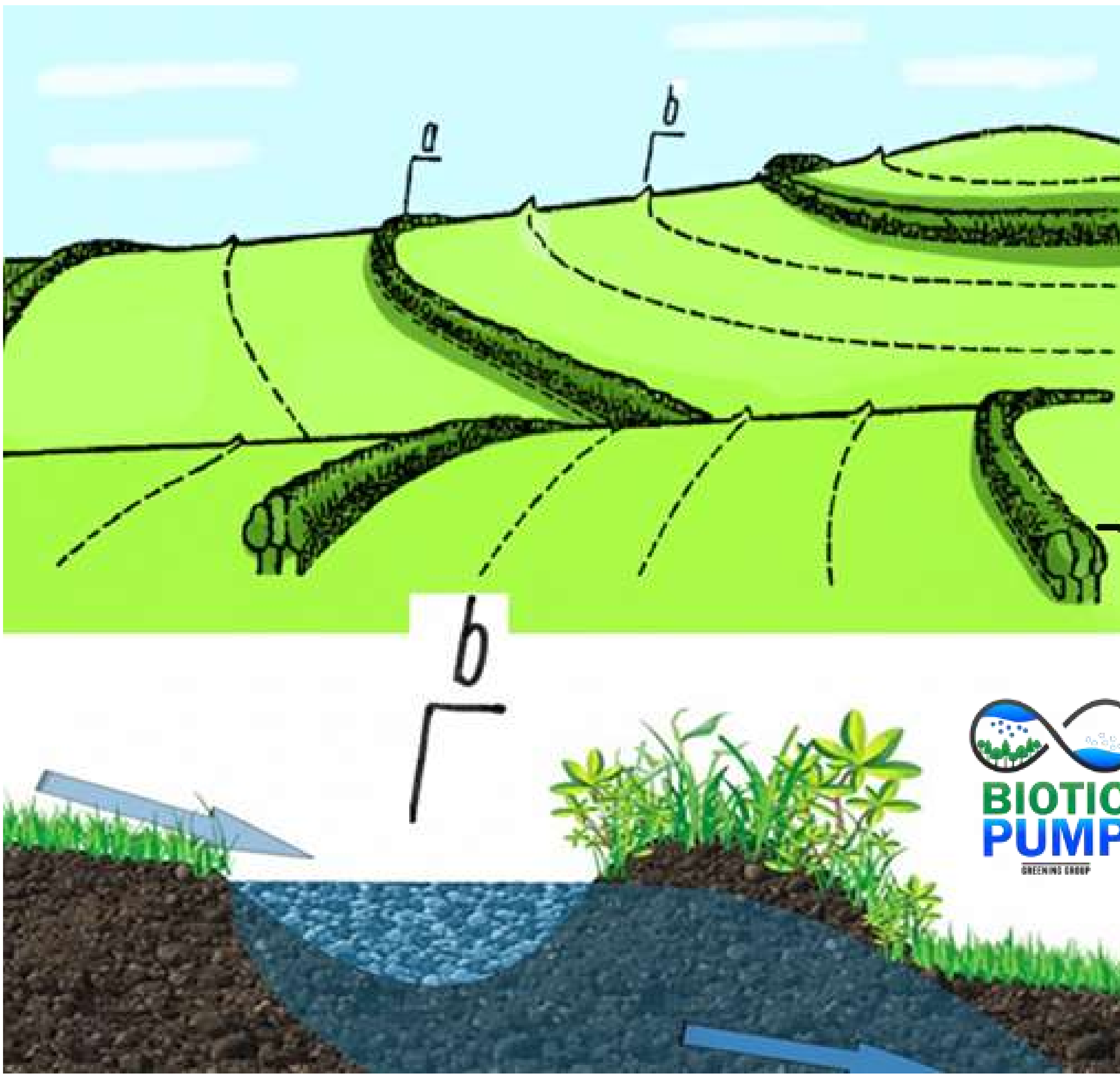


Figure 7. Arrangement scheme of forest shelterbelts (a) berms with small less than 40 cm ditches; (b) for contour-strip land organization, to improve the water retention, soil moisture capacity to be used as sponges, modified from [28–30]. Depending on the slope of the terrain, the contour strips can be 500 to 50 meters wide. Along the strip boundaries, water-retaining seeded embankments with wide bases and water-absorbing ditches filled with various organic waste materials are installed, replacing the missing forest litter and steppe felt. On the water-retaining embankments, shelterbelts of organic waste, the stems remain, leaves of the harvest crops are established at intervals of 500 to 250 meters. Intensive

biological decomposition processes occur within the ditch, the temperature rises, and the number of earthworm burrows increases. The purpose of improving soil is to absorb accumulated water, to work as the filter and the sponge system. Operating year-round, the good quality organic soil is ready to receive precipitation, flood water, to store water as sponges, simply this is a natural soil-sponge. This natural hydrological regime is implemented in natural biocenosis. This main process is associated with surface hydrology from the entire set of natural processes that exist in biocenoses. The width of the strips depends on climatic, environmental, soil conditions, the slope angle and aspect, the amount and nature of precipitation, the snow-flood characteristics, and the depth of soil freezing [28-31].

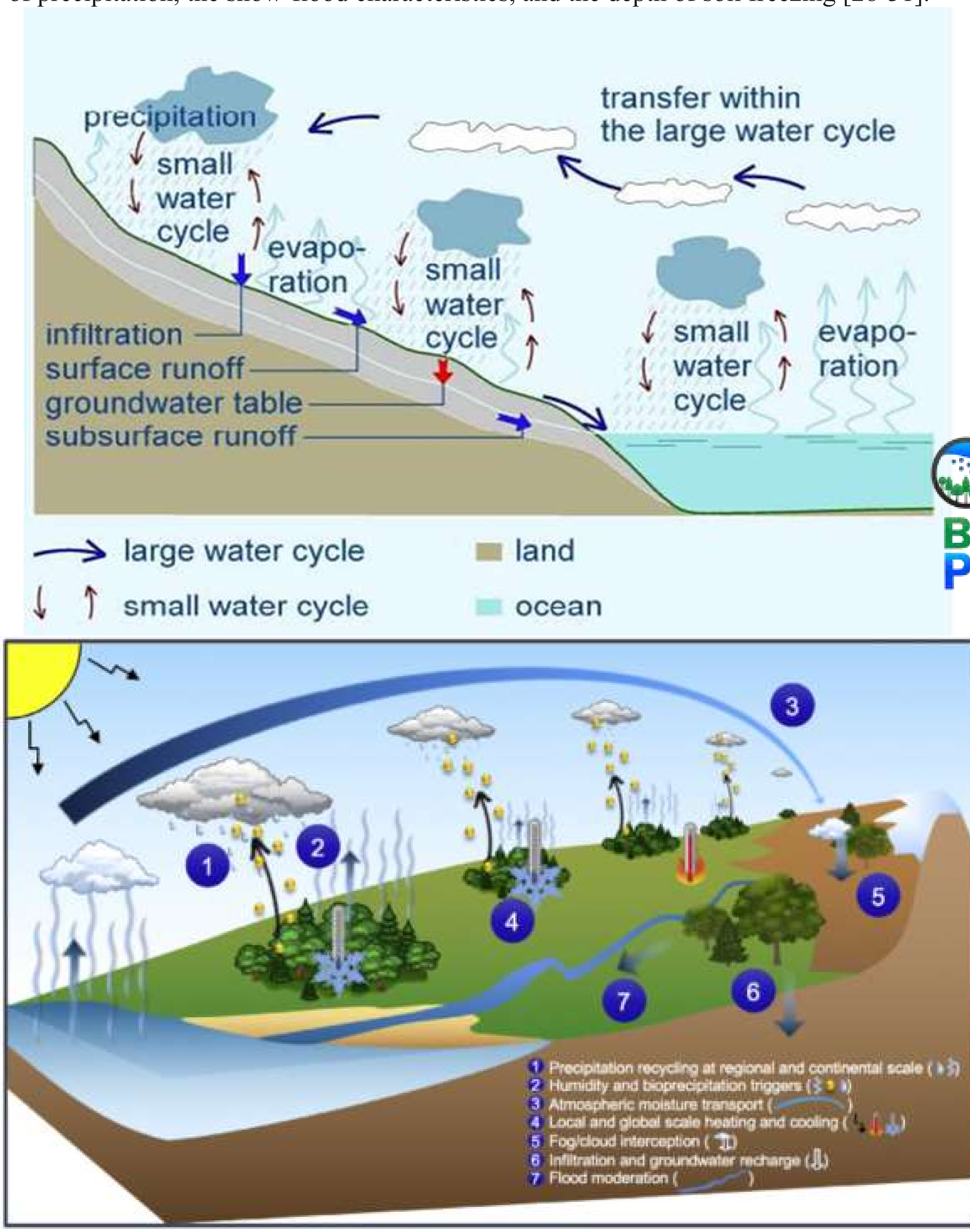


Figure 8. Combination of forestry with the localized wetland area creates the biotic pump circulation system driven by biological processes. Trees can influence atmospheric processes to cycle rainfall taken up by trees

and back to the atmosphere for further cycling. Evapotranspiration creates low atmospheric pressure, creating a suction effect to draw in water vapor from the atmosphere. Increased amounts of evapotranspiration cause a reduction in atmospheric pressure as clouds form, which will subsequently cause moist air to be drawn to regions where evapotranspiration in high amount [32,33]

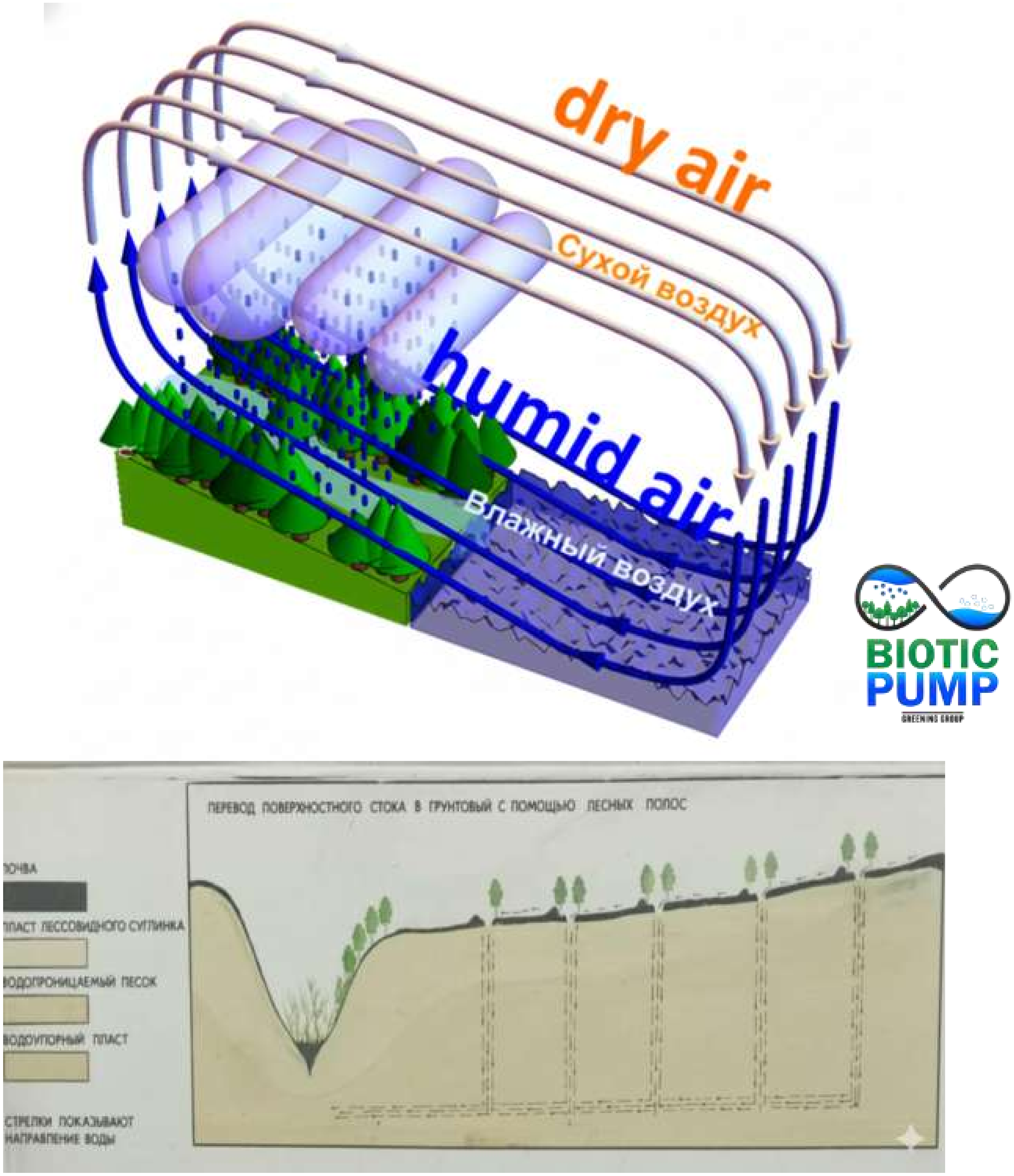


Figure 9. Biotic pumps work on the wetland areas combined with trees. Water attracts water. Trees keep the wetlands soil area with the moisture capacity to attract clouds humidity. Sustainable land management, contour strip trees planning, and soil-sponges' approaches will work on the proper biotic pumping efforts [32,33].

Figure 10. Trees are rain makers through evapotranspiration activities. Trees produce hydroscopic microorganisms within their leaves in volatile organic matter. These microorganisms and particles drift up into the atmosphere, forming a microenvironment like cation-anion microparticles, providing precipitation nuclei needed to condense water vapor into droplets forming clouds and then rain. Micro energy, like positive "+" energy, attracts micro minus "-" energy, like a magnet, creating a microparticle of precipitation. Trees release chemical compounds, called volatile organic compounds (VOCs), which can form aerosol particles that act as cloud condensation nuclei (CCN). These hygroscopic particles attract water vapor, allowing it to condense and form clouds, which eventually lead to precipitation. The microorganisms that live on or in leaves also contribute to this process. *Trees emit VOCs:* Trees release a large variety of VOCs into the atmosphere. The type and number of VOCs emitted depend on factors like the tree species, season, and environmental conditions. *VOCs form particles:* These VOCs can react with other atmospheric chemicals like ozone layers and form new aerosol particles. *Microorganisms on leaves:* Microbes on the surfaces of leaves are also a source of aerosols and contribute to the atmospheric particle load. *Particles become CCN:* The resulting particles are tiny, often solid or liquid specks that are highly effective at attracting water molecules, making them hygroscopic. *Cloud formation:* These particles serve as the "seeds" for clouds by providing a surface on which water vapor can condense to form tiny droplets. *Rainfall:* As these droplets grow and become saturated, they fall as rain [34]

Precipitation Regimes in Kazakhstan

Precipitation is various in the different areas of Kazakhstan. However, the most annual runout from snowmelt, around 70-80%, from the annual total 300-400 mm [35,36]. It means technologies related to the flood water, the earlier spring water collection programs, the snow flood water collection system, with the farmland retention ponds connected to MAR will be reasonable to expand for Kazakhstan (Figure 11).

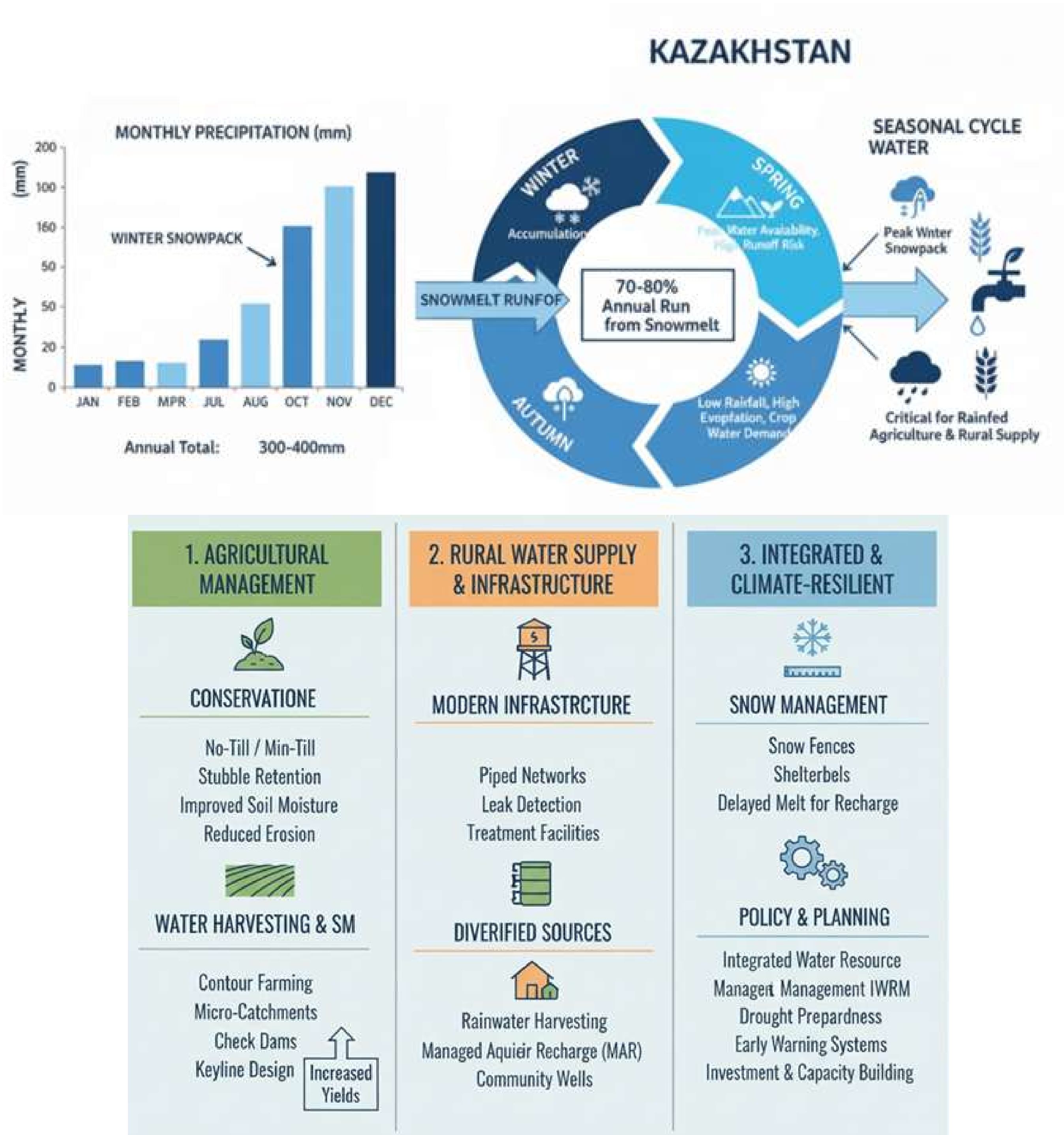


Figure 11. Kazakhstan's precipitation regimes are highly variable, with the annual total around 350 mm. Around 75 % of annual run is from snowmelt, flood water, which directs to the development of the rational snow flood water collection system, with the farmland retention ponds connected to MAR, agricultural infrastructure improvement activities [35, 36].

The current major points of water losses within the hydrological system for agricultural needs in Kazakhstan, summarized and compiled from [37, 38].

Stage	Input Source	Utilization Pathway	Status/Challenge
I. Source	Snow/Rain/Meltwater	Precipitation Input	Highly variable, low totals, peak flow in spring, snow melt poorly collected.
II. Collection/Capture	Surface Runoff	1. River/Reservoir Storage	High loss from inefficient conveyance (seepage/evaporation), poor soil storage.
	Soil Infiltration	2. Soil Moisture (Rainfed)	High loss from surface runoff and high evaporation, condense poor quality soil.
	Deep Infiltration	3. Groundwater Recharge	Slow, often limited by high soil compaction, lack of soil-sponges' strategies .
III. Allocation	Stored Water	Agricultural Demand (63% share)	Low Water Use Efficiency (WUE); reliance on the outdated flood canal irrigation approach.
	Extracted Water	Rural Supply Demand	Infrastructure Leakage and poor treatment; outdated, seasonal unreliability
IV. Outcome	Water Use	Crop Yield/Water Access	High dependency on annual moisture; yield instability; inefficient water use.

Remote Sensing and GIS support approach for MAR introductions in Kazakhstan

Landscape heterogeneity, variations in soil properties, and differences in the hydrological response of sites require proper investigations in setting up and selecting locations for planting and groundwater replenishment. In this regard, increasing attention is being drawn to Managed Aquifer Recharge (MAR) methods, which are considered an effective tool for integrating ecosystem restoration with water resource management [19–20]. Modern approaches to mapping suitability zones for MAR are getting manageable to design with reasonable expenses and efficient time use by applying the Geographic Information Systems (GIS), Remote Sensing (RS) data. GIS-RS are combined for multi-factor model analysis, including input data such as topography, soil, geology, hydrological regime, and climatic parameters [21]. This approach makes it possible to identify sustainable interaction models between natural and socio-economic systems, forming useful designs for the rational land use strategies to make the farmland more sustainable. The integration of the forest contour-strip land organization with the MAR methodology increases opportunities for land use sustainability strategies. On the one hand, tree and shrub strips along the relief contours enhance infiltration efficiency and reduce erosion, strengthening the potential for groundwater replenishment. On the other hand, a systematic analysis using GIS and RS allows for the identification of proper zones and areas to be designed more efficiently, both in terms of water balance and preventing ecosystem degradation. This interdisciplinary approach meets modern challenges by combining the achievements of ecology, hydrology, and geoinformation technologies to develop strategies for sustainable landscape restoration. The GIS RS data are analyzed often by the Analytical Hierarchy Process (AHP) method to identify territories with high potential for groundwater replenishment. The most promising areas for organizing MAR areas, as well as assessing the weight and ranking of various geospatial factors depending on their influence on the effectiveness of infiltration and groundwater accumulation are identified. The land use integrated with the analysis of topography, soil, and hydrogeology for the localized MAR locations and the integration of forest shelterbelts contributes to the refinement of land use strategies for sustainable development. This strategy has been successfully employed globally but requires promotion in Kazakhstan. In Russia's Chernozem zone, the restoration of shelterbelts combined with contour-strip land organization has significantly reduced wind and water erosion, improved the water balance, and increased cereal crop yields by 15–25%. A comprehensive approach, including soil recultivation and slope terracing, showed particularly high effectiveness [39–41]. In the Canadian Prairies, MAR technologies are actively used in conjunction with shelterbelts and pasture systems. Such solutions have improved the soil's water-holding capacity, reduced seasonal moisture deficits, and enhanced the productivity of agricultural lands, especially under unstable precipitation regimes [42–44]. In the northwestern regions of China, the integration of shelterbelts, terraced slopes, and MAR systems has reduced soil salinization and restored agricultural land productivity. The combination of agrarian landscape measures and MAR technologies has proven highly effective in water resource management and adapting agriculture to frequent droughts [45–47]. The complex application of contour-strip land organization with MAR technologies and the introduction of forest shelterbelts contributes to the refinement of land use strategies for sustainable development with effective adaptation to climate change, where spring floods alternate with summer drought periods [45–47]. The GIS RS data combined with (AHP) have started to apply for the research work by mapping the potential for managed aquifer recharge in Kazakhstan [48]. MAR remains relatively underutilized in Kazakhstan despite its potential to address water scarcity issues, particularly those related to seasonal fluctuations in water availability. The multi-criteria decision analysis framework, five distinct physical criteria were integrated and visualized within a GIS to delineate the intrinsic potential for MAR. The intrinsic MAR potential map was overlaid with remote sensing data identifying potential water sources and water utilization patterns. This overlay facilitated the identification of priority areas with potential for further evaluation for MAR implementation (Figure 12).

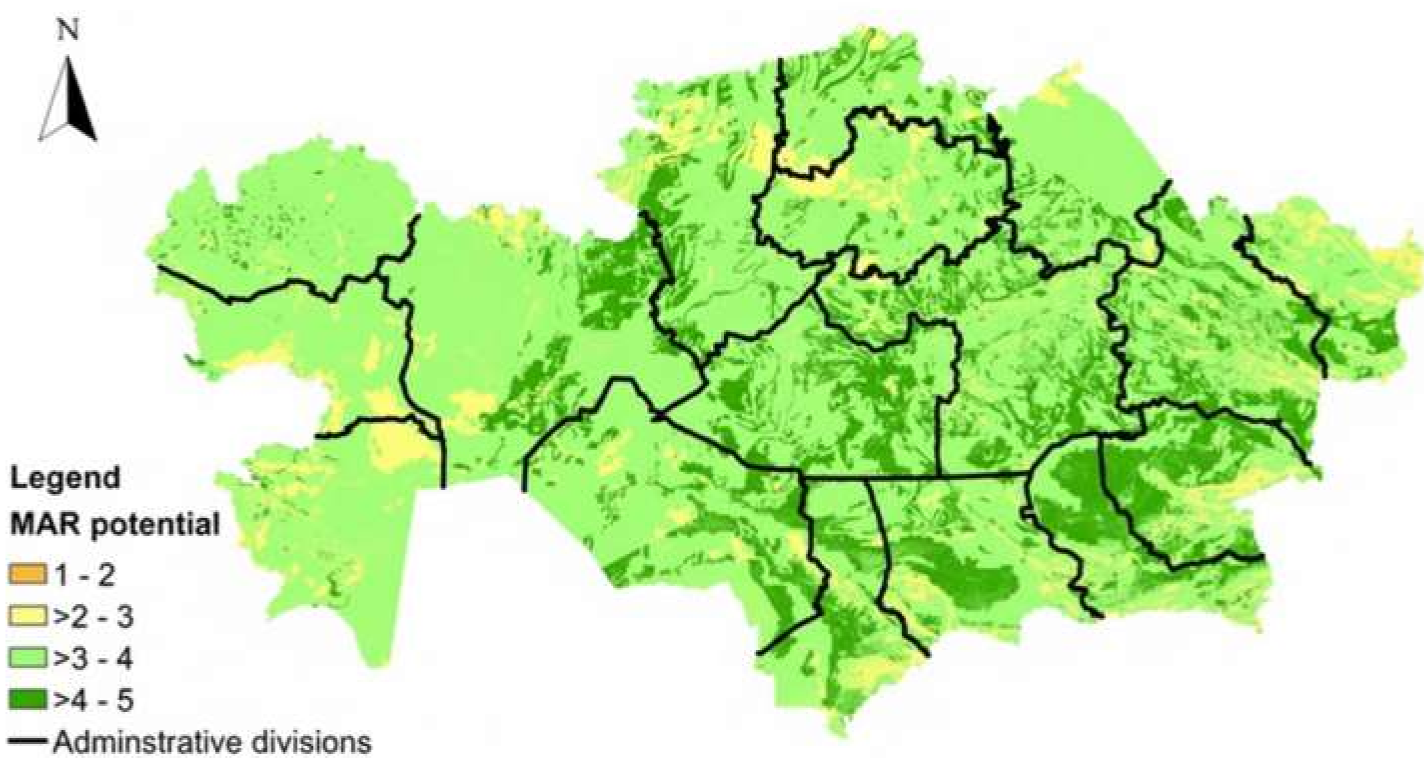


Figure 12. Intrinsic map of MAR potential for Kazakhstan [48] with an index rating from 1 to 5 by applying the criteria weighting with pairwise comparison method on the INOWAS platform, https://www.inowas.com/

The group of researchers from Kazakh Agrarian University [49] have developed and applied the RS-GIS based methodology for the snow amount calculations, flood water estimations by snow-water equivalent assessment (SWE) and MAR location identifications for the North Kazakhstan region (Figure 13,14).

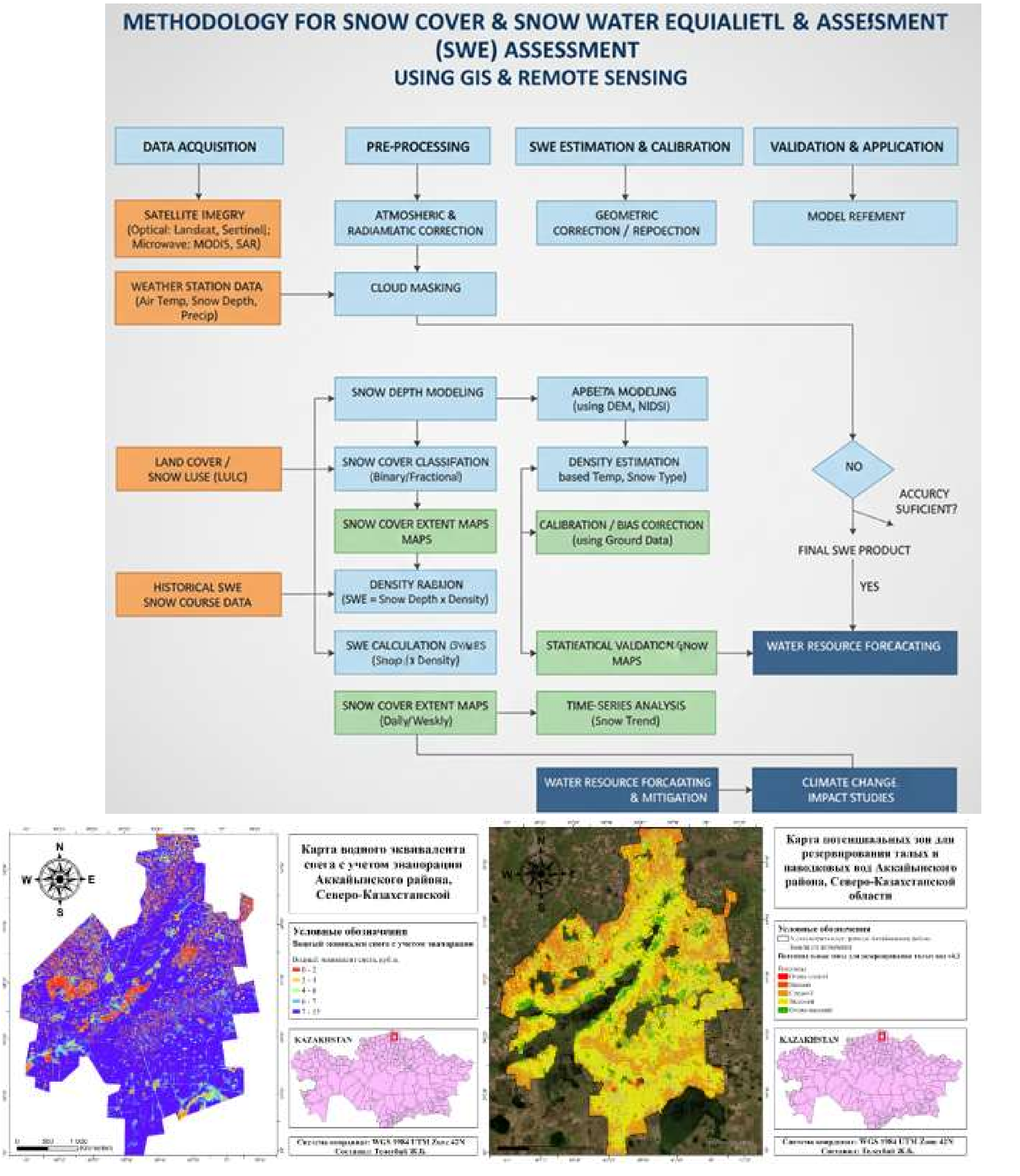
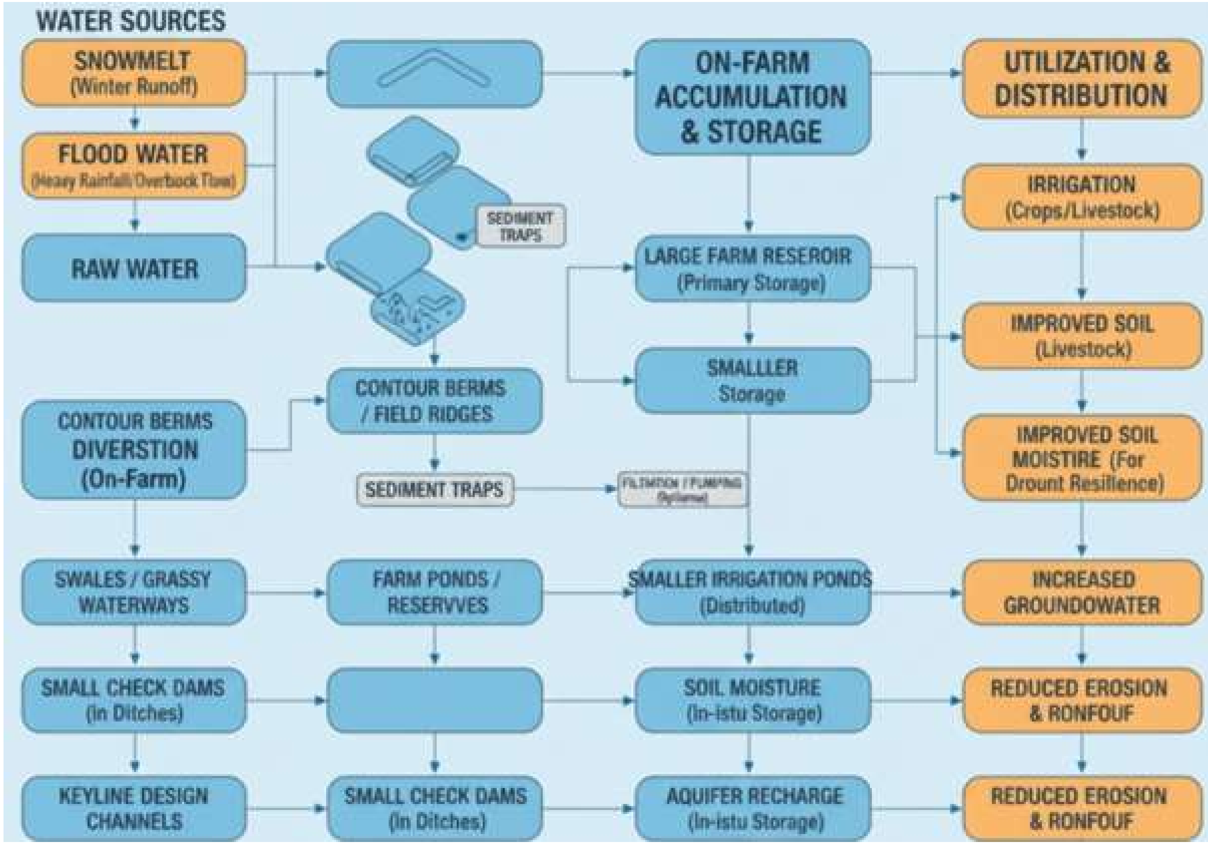


Figure 13. RS-GIS based methodology for the snow amount calculations, flood water estimations by snow-water equivalent assessment (SWE) and MAR location identifications for the North Kazakhstan region [49]



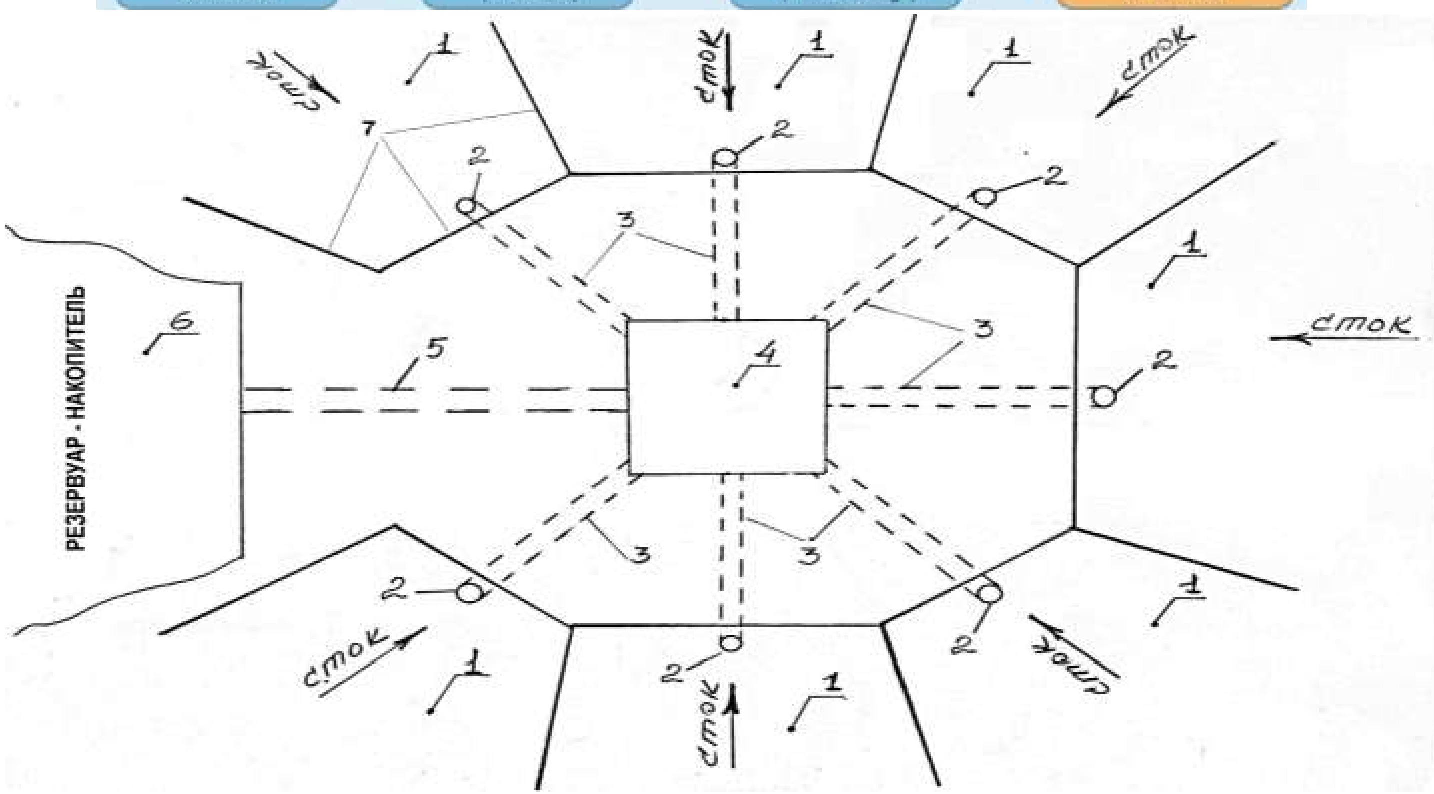


Figure 14. Technological scheme for melted snow flood water collection and accumulation: 1 – waterproof material (such as geomembrane); 2 - water wells; 3 – underground pipelines; 4 – water intake well; 5 – underground channel, 6 – storage tank; 7 – snow retention shields [49]

Expanding Nature-based sustainability with international cooperation

Many countries increase their special attention to adaptation of nature-based solutions to improve ecosystems, to improve soil retention capacity as sponges, and to increase the water resources sustainability. Among these solutions are the traditional practices of contour-strip land organization, which involve the placement of tree and shrub plantings along the contours of the relief. This practice reduces soil erosion by forming contour-aligned ridges that act as barriers to surface runoff, decreasing the flow velocity and increasing infiltration into the small depressions created by crop rows. Contour farming has become widespread globally as an effective method for controlling soil erosion and preventing the siltation of water bodies. The primary goal of filter strips is to reduce the number of suspended solids and sediment in the runoff. These measures stabilize the hydrological regime and contribute to the restoration of soil fertility and local bio productivity [50-54].

The Korean Mongolian cooperation programs in land sustainability improvement could be reasonable to expand. Kazakhstan works on the program to plant 3.5 million trees [55], while Mongolia is promoting a 300 times larger program to plant 1 billion trees [56]. Mongolia is intensively studying the experience of other countries, including South Korea's expertise in promoting the Korea-Mongolia project for the restoration of the green belt, creating a distributed network of cultivation sites adapted to Mongolia of different climates, different soils, and local breeding plants with hybrids of Korean trees. South Korea is funding this US$10 million program of a network of tree cultivation sites along with the training of Mongolian locals [57]. South Korea uses Mongolian groundwater, which has large underground water reserves, but groundwater has a high alkalinity up to pH 8.6. Technologies for softening water from pH 8.6 to pH 6.5, favorable for vegetation, are carried out based on ion exchange, sodium-cation based on chemical reactions of ion exchange (ions that form water hardness, including calcium, magnesium). The water softened by the replacement ions, added to the water. Mongolian government invests 1% of GDP in this program on the 1 billion trees [58] program implementation and has created incentives for the Mongolian mining industry companies to invest and support Mongolian farmers in the tree planting activities locally in their farmlands.

The Mongolian 1 billion trees [56] program is connected to the water resources programs; a project of 333 storage water ponds [59] is in the simultaneous development with 1 billion trees [56].

The Czech Mendel University of Brno in cooperation with Canadian partners from the University of Manitoba, the Mongolian University of Science and Technology, the German Mongolian Institute for Resources and Technology, work on the field of natural sciences, the degradation of forest ecosystems, degradation of permafrost, desertification, environmental contamination. The main goal is to help Mongolian afforestation, mitigate desertification, and improve sustainability in nature protection [59].

Mongolian large program of 1 billion trees is very complicated and requires water, this is a reason why Mongolia works on the water supply preparation with South Korea [57], and in conjunction with 333 lakes, water storage ponds [58]. These project programs are complex and require both a lot of financial effort and the involvement of the local Mongolian population. Mongolia, in addition to studying the Korean and Czech expertise, is also studying the Bhutan's experience, which has extensive experience in promoting nature-oriented programs, contour-strip organization of lands and involving the population in the processes of conservation and restoration of Nature. The Planted Forests Program is a key conservation initiative of Bhutan to sustainably manage forests in the face of acute challenges from climate change, pollution and biodiversity loss. Since 1947, the Royal Government of Bhutan has given priority to environmental protection, including through various afforestation activities. As of June 30, 2024, about 20,161 hectares of forest plantation have been established in Bhutan, providing forest cover in 69.71% of Bhutan's territory, exceeding the constitutional limit of 60%, and allowing it to achieve the status of a carbon-negative region. At the same time, a sample assessment of planted forest programs in several regions and forest departments in Bhutan showed an average tree survival rate of only 56%. The low survival rate is attributed to the lack of care, maintenance and monitoring after planting Bhutanese trees. In Bhutan, it is mandated that any afforestation proposals submitted by central or local governments must include a comprehensive Five-Year Tree Care and Maintenance Plan [60]. Funding for simply planting trees without an evidence-based 5-year tree survival plan is rejected in Bhutan.

Mongolia is studying Canada's experience in involving the local population in trees programs from the childhood, respectful attitude to the trees from the childhood, trees love cultivation programs, like the British Petroleum (BP) Birthplace Forests [61], where children are more responsible for trees from birth, care about the survival of trees like caring for siblings (Figure 15).

Figure 15. The programs of Canada, Bhutan, which were adapted by Mongolia, to involve the population in caring for Nature from early childhood are identical, especially in the initial phase of tree survival up to 5 years. If the tree was able to grow within 5 years, then the tree can grow on its own, using its root system. This is by analogy, to raise the child until the age of 18, till adulthood. The BP Birthplace Forests were launched by BP Canada to celebrate every newborn baby by planting a tree in their honor [61].

Australia has a well-developed agrarian farming support system with a personalized service system in the remote rural areas, including indigenous aboriginal people, with regulated attention to the protected wetland system. The current Australian policy was initiated in the '90s. Since 2000, water consumption per crop cultivation has decreased rapidly [62,63]. Over ten years, the water use indicator has reduced by 2.5 times. At the same time, the agrarian production output has not undergone significant changes in Australia. The gross income from the agrarian business has continued to grow in Australia. Kazakhstan is missing such an efficient water consumption program; the agrarian production output is directly related to the consumption volume of water. Agriculture is moving towards resource depletion, drainage of swamps and land desertification. The surface and groundwater network facilities information system are poorly developed in Kazakhstan, compared to Australia. The system of surface and underground water resource facilities is interconnected and all data transparent and available for everybody in Australia. People have more incentives to use water more efficiently. Even in water crisis periods, farmers may purchase water from those who have used water more efficiently, recycled water in Australia. People have more incentives to collect water during the flood seasons, heavy precipitation, and develop underground managed aquifer recharge (MAR) technologies to reduce water losses due to evaporation. This strategy allows the mitigation of natural disasters and floods, by storing water with low losses, and using water during droughts. In Kazakhstan, water resources are considered less valuable in comparison with energy resources and industry activities. The ownership of water resources, separation of technical and valuable potable drinkable water is practically absent and poorly regulated in Kazakhstan. Water in Australia is an asset and a means of earning money. In Australia, every citizen has the right to own a certain amount of water resources. The water of the typical basin is the property of every person who lives in its catchment area. Each resident has the right to a certain amount of water. It becomes rational for engineering companies to build water facilities to preserve water resources during floods, protect water and then offer the collected water on the market to those regions where there is demand [62,63]. In Kazakhstan, the basin-based community system and ownership of water resources by the ordinary people of a particular basin is missing. Each farmer is trying to use water from the shared Kazakh basin as much as possible without incentives to restore or keep water. Water is underestimated as a resource in Kazakhstan . Ordinary Kazakh people are missing incentives for saving water to profit from efficient usage. Creating conditions for ordinary people to earn money by saving water will allow more efficient use of the water resources in Kazakhstan. Also, Kazakhstan governmental budget carries significant expenses for the emergency flood-drought events. It will be reasonable to set up the proper water insurance business and decrease the governmental budgeting pressure [64].

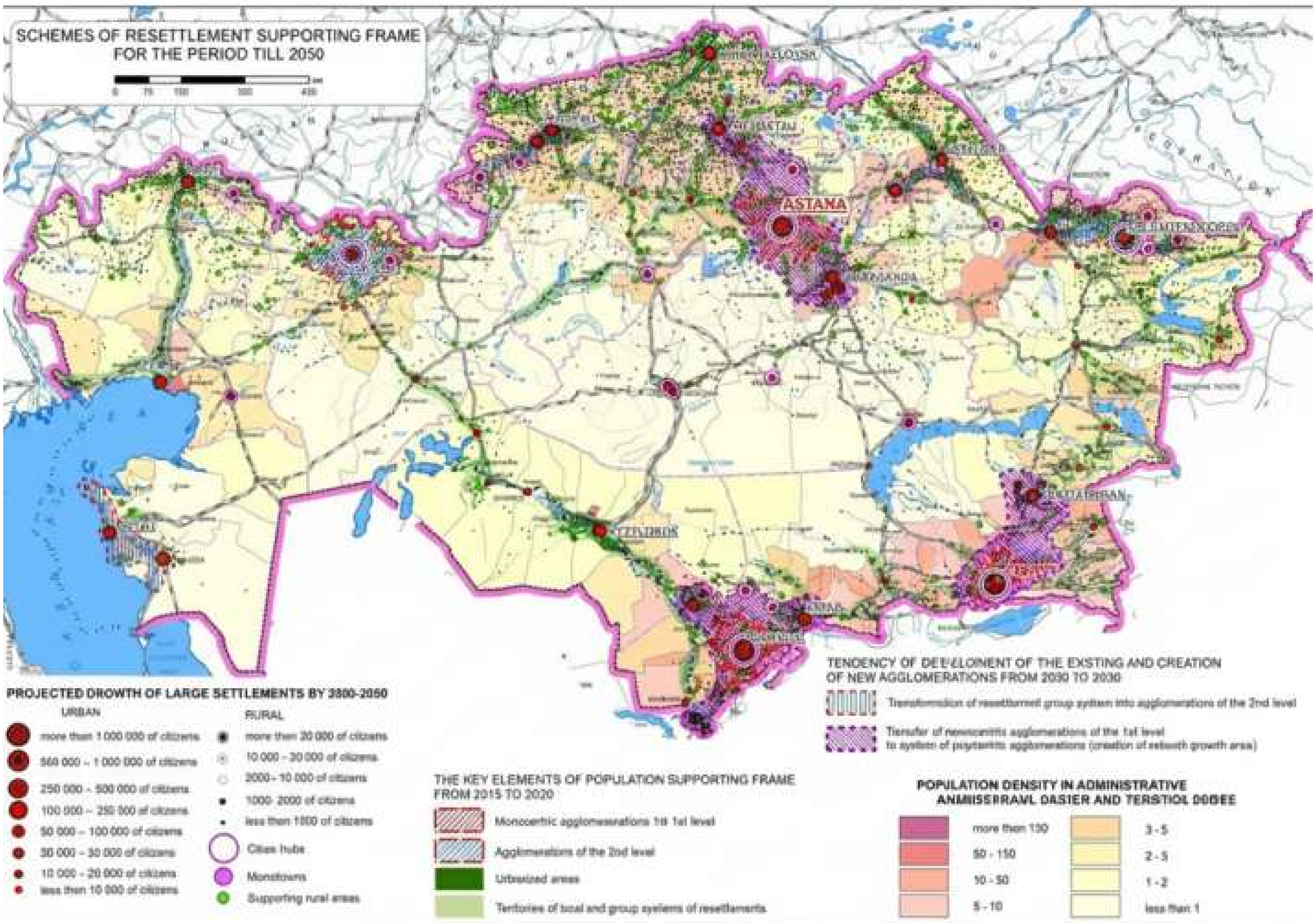
The Canada-US Red River Basin Committee [65] coordinates water project programs, including financial, efficient use of water resources, by residents, farmers, First Nations people living in the three US states of Minnesota, North and South Dakota and the Canadian province of Manitoba. Residents, farmers, First Nations people are actively involved in solving joint projects of programs for the efficient use of water resources. Civil societies for the protection of natural interests, flora, and fauna, actively participate in water resource management. Strong local capacity of water technicians in managing their water resources with financial and technical training technicians in the affiliated colleges provide Technical and Vocational Education and Training (TVET) services on the permanent base. Permanent user-friendly lifelong blended learning related to water issues are provided for everybody within the Canada-US river basin. The rural region libraries are used intensively for regular meetings, seminars, booklets-leaflets promotional activities [65]. The Canada-US Basin Committee maintains all databases open and accessible to everyone. Information on each project and the group leading the project on an open website. For example, in the basin, residents, farmers decided to take LIDAR, Light Detection and Ranging - Remote Sensing, high-resolution images of 50 cm, to create topographic maps, digital elevation models, land planning for farmers, modeling floods and droughts. $5 million was spent on this, with a portion of $3 million from local farmers and $2 million from the provincial state administrations. Open access LIDAR data is available for everybody to download. Available training programs on the use of LIDAR are open to everyone, with modeling programs on climate change forecasting and adaptation [65]. For the effective use of accumulation of drainage and flood waters, the basin committee uses intensive modeling and, in consultation with farmers in Canada and the USA, determines the region where it will be optimal to create small reservoirs for replenishing underground aquifers, to mitigate floods, Flood-MAR [66].

The International Network of Basin Organizations https://www.inbo-news.org/ would be very helpful for Kazakhstan, very beneficial for the Ministry of Water Resources and Irrigation of the Republic of Kazakhstan to join and become an active member. It's difficult for Kazakhstan to directly resolve basin issues with China, but by participating in the Network of Basin Organizations https://www.inbo-news.org/, Kazakhstan can communicate and negotiate more efficiently, at lower financial costs, and in a more civilized manner through such a network. Kazakhstan's President K-Zh.K. Tokayev is expanding the UN Regional Center for Sustainable Development Goals for Central Asia and Afghanistan. https://www.akorda.kz/ru/prezident-kasym-zhomart-tokaev-i-generalnyy-sekretar-antoniu-guterrish-posetili-regionalnyy-centr-oon-v-almaty-373245. This initiative provides significant opportunities for local communities in Kazakhstan's villages to participate more actively in promoting sustainable programs for Kazakhstan. Kazakhstan faces challenges with specialists in water resources and basin management. Despite the challenges facing water resources, industry and all residents of Kazakhstan are turning to President Tokayev and the Ministry of Water Resources and Irrigation of the Republic of Kazakhstan to address local basin issues related to water resources, floods, and droughts. At the same time, through participation in the International Network of Basin Organizations (https://www.inbo-news.org/), Kazakhstan can optimize budget expenditures by engaging local populations in addressing their local challenges at the basin level, studying international experience, and promoting natural solutions for climate change adaptation and ecosystem restoration at the basin level. Local expertise in villages and training in Kazakhstan's colleges is poorly developed to support UN programs initiated by President Tokayev, including promoting basin management at the local level and the ability to spend budget funds rationally at the local level to address local flood and drought issues. In his address on the implementation of strategically important state objectives, President Kassym-Jomart Tokayev noted that "70% of Kazakhstani employers are dissatisfied with the skills of our college graduates." Considering these challenges, President Tokayev designated 2025 the Year of Working Professions to strengthen professional development programs. To engage local populations in local basin management programs, for the Ministry of Water Resources and Irrigation of the Republic of Kazakhstan will be rational to join the International Network of Basin Organizations (https://www.inbo-news.org/) to promote nature-based solutions for climate change adaptation and ecosystem restoration at the basin level, support President Tokayev's initiatives to advance UN sustainable programs in Kazakhstan, and promote basin-based programs for local village residents of Kazakhstan so that local residents can effectively spend budget funds on flood and drought programs using nature-based technologies. The rural colleges in Kazakhstan, like the State Budgetary College "Koksu Polytechnic College" of the Education Department of the Zhetisu Region could be involved in such programs. The International Network of Basin Organizations (INBO) provides different types of TVET support, including the Nature-based Solutions and Innovative Finance https://www.inbo-news.org/events/webinar-on-nature-based-solutions-and-innovative-finance/, https://zhetysutv.kz/ru/koksuskij-politehnicheskij-kolledzh-prinimaet-opyt-zarubezhnyh-kolleg-dlya-

podgotovki-speczialistov-po-vodnym-resursam-45855/, https://youtu.be/2vi75468Ohg

Hungary is actively involved with the International Network of Basin Organizations (INBO) through the EURO-INBO regional network and by participating in events and initiatives focused on integrated water resource management at the basin level, https://unece.org/media/news/385244, https://unece.org/water-global-workshop-2023-budapest,

Kazakhstan is targeted to build a new city of Alatau-Singapore on the shores of the Kapchagay reservoir in the Almaty region (Figure 1).



Drawing 16. Forecasts increase urbanization Kazakhstan to 2050 years

The challenges facing this Alatau-Singapore city construction project include the bare, empty soil, and poor vegetation growth in the Kapchagay area which will require a large amount of water. Water will be taken from the Kapchagay reservoir, the Ili River basin, which is the main source of water for Balkhash Lake, providing approximately 70% of the Balkhash inflow. The upstream of the Ili River basin is in China, where China takes about 70 % of the Ili River's water. China's water uses from the Ili River in combination with Kazakhstan's Alatau-Singapore city construction on the Kapchagay reservoir shore may dry up the Ili River, which could lead to the Balkhash Lake shrinking and drying up, similarly what has happened to Aral Lake, and what may happen to the Caspian Lake also. The Alatau-Singapore city construction, promoting the intensive urbanization of the Almaty region, is an unsustainable strategy for Kazakhstan. Bhutan, Slovakia, the Czech Republic, Hungary, Canada, Mongolia, in the same situations, are trying to decrease urbanization, trying to support more rural regions, to live on the whole territories of their countries with incentives to develop their entire countries territories. The Balkhash Basin sustainability on the border between China and Kazakhstan (Figure 17) conducted with publication in Sustainability journal 2025 Environmental Science: Duisebek, B.; Senay, G. B.; Ojima, D.S.; Zhang, T.; Sagin, J.; Wang, X. Evaluating the Performance of Multiple Precipitation Datasets over the Transboundary Ili River Basin Between China and Kazakhstan. Sustainability 2025, 17, 7418. https://doi.org/10.3390/su17167418

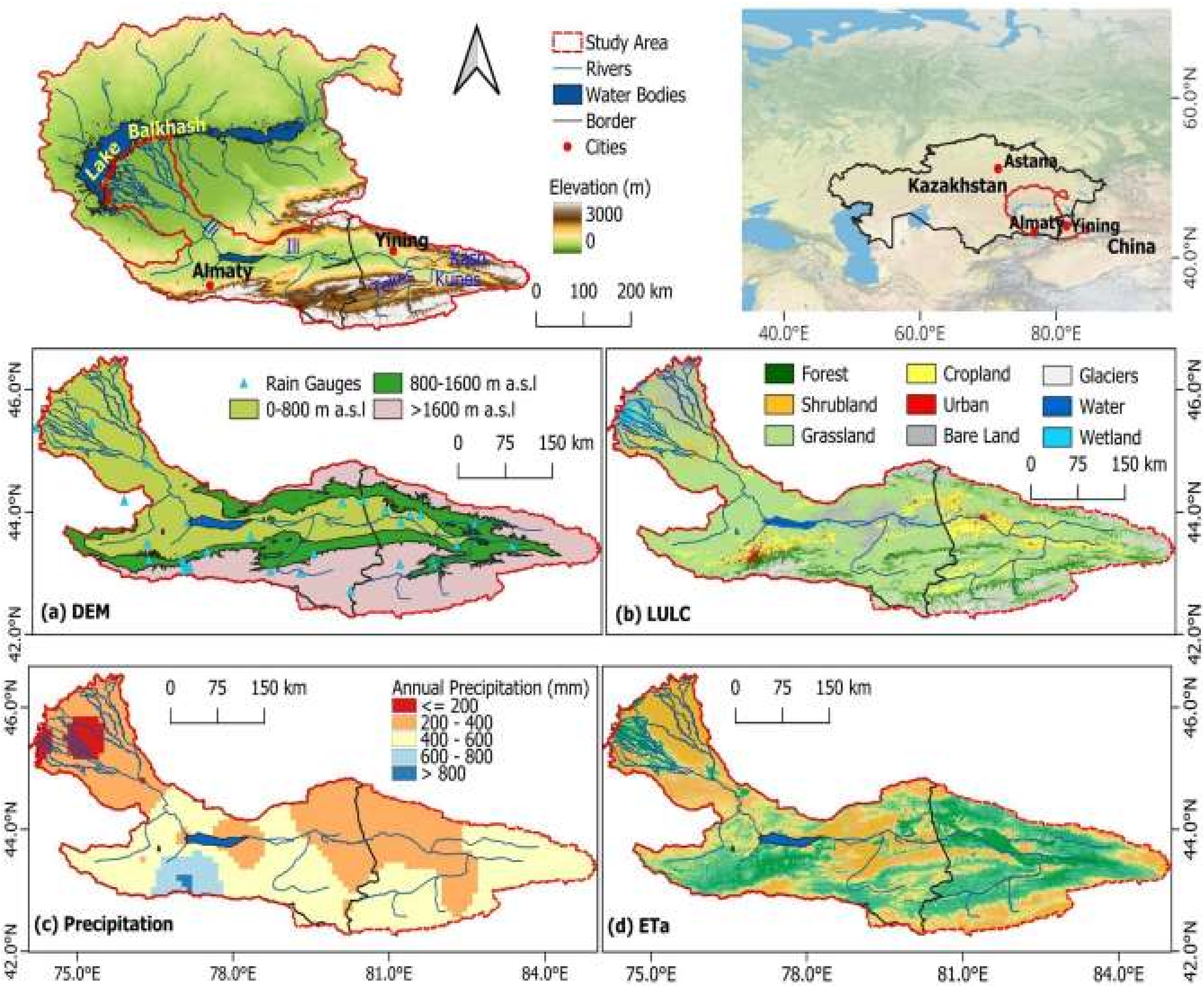


Figure 17. Balkhash Lake Basin Sustainability 2025 journal [67].

Kazakhstan may have difficulties convincing China in using less water in the upstream area of the Ili River Basin. Similarly, it could be difficult to change the Alatau-Singapore city contraction activities in the Kapchagay Reservoir area, Almaty region. By facing these difficulties, it is proposed to implement a program to restore the water levels of small rivers in the Balkhash basin in Kazakhstan without relying on the Ili River basin (Figure 18) by adapting the contour strip land organizations, Biotic Pumps methods applications. These efforts should help to keep Balkhash Lake with water sources supply from the small internal Kazakhstan subbasins with at least 30% of Balkhash annual water supply.

This strategy would increase predictability and improve Balkhash Lake sustainability. This strategy is also important for ensuring the guaranteed water supply for the nuclear power plant, which is planned for construction on the Balkhash Lake shores.

Figure 18. Balkhash Lake inner subbasin small rivers, without the Ile River. where the contour strip land organizations, Biotic Pumps methods applications are proposed to apply to improve the Balkhash Lake sustainability.

TVET support programs would be reasonable to introduce with MAR Biotic Pump programs for the rural regions, colleges on water resources and water quality analysis, similar to what works in other countries, including the United States and Canada. The dual TVET with real-world examples from existing programs may be more practical to adapt. A good example of such an approach is the "Know Your Well" program led by Professor Daniel Snow, Nebraska Water Center, USA. “Know Your Well” is a collaborative citizen science program training high school students how to sample and test well water quality. Students collect water samples, test them in the classroom, and compare their results with tests conducted at the University of Nebraska Water Sciences Laboratory. The Nebraska rural region’s water wells have been tested for nitrate, nitrite, metals, pesticides, and coliform bacteria. Rural schools farm students have collected land use and other data to help determine vulnerability to contamination in the rural farm areas. Well owners are supplied with test results and provided with information to help them evaluate their water quality. With assistance from key partnerships around the Nebraska state, “Know Your Well” is helping well owners and future water scientists in Nebraska know more about groundwater in Nebraska state. A similar program is under development at the Koksu Polytechnic College, Zhetisu Oblast, Kazakhstan, https://www.youtube.com/watch?v=2vi75468Ohg&t=14s . Balkhash Lake basin sustainability could be improved by adapting the small river restoration program with Biotic Pump methods. The main task would be reasonable to increase with TVET, "Know Your

Well" type of program incentives for the farmer's school children's involvement to study more the local water resources. This initiative from the Koksu Polytechnic College, within the two small rivers Bizhe and Mukanchi, small tributaries of the Karatal River in the Balkhash basin, could be further expanded to other regions of the Balkhash basin (Figure 19).

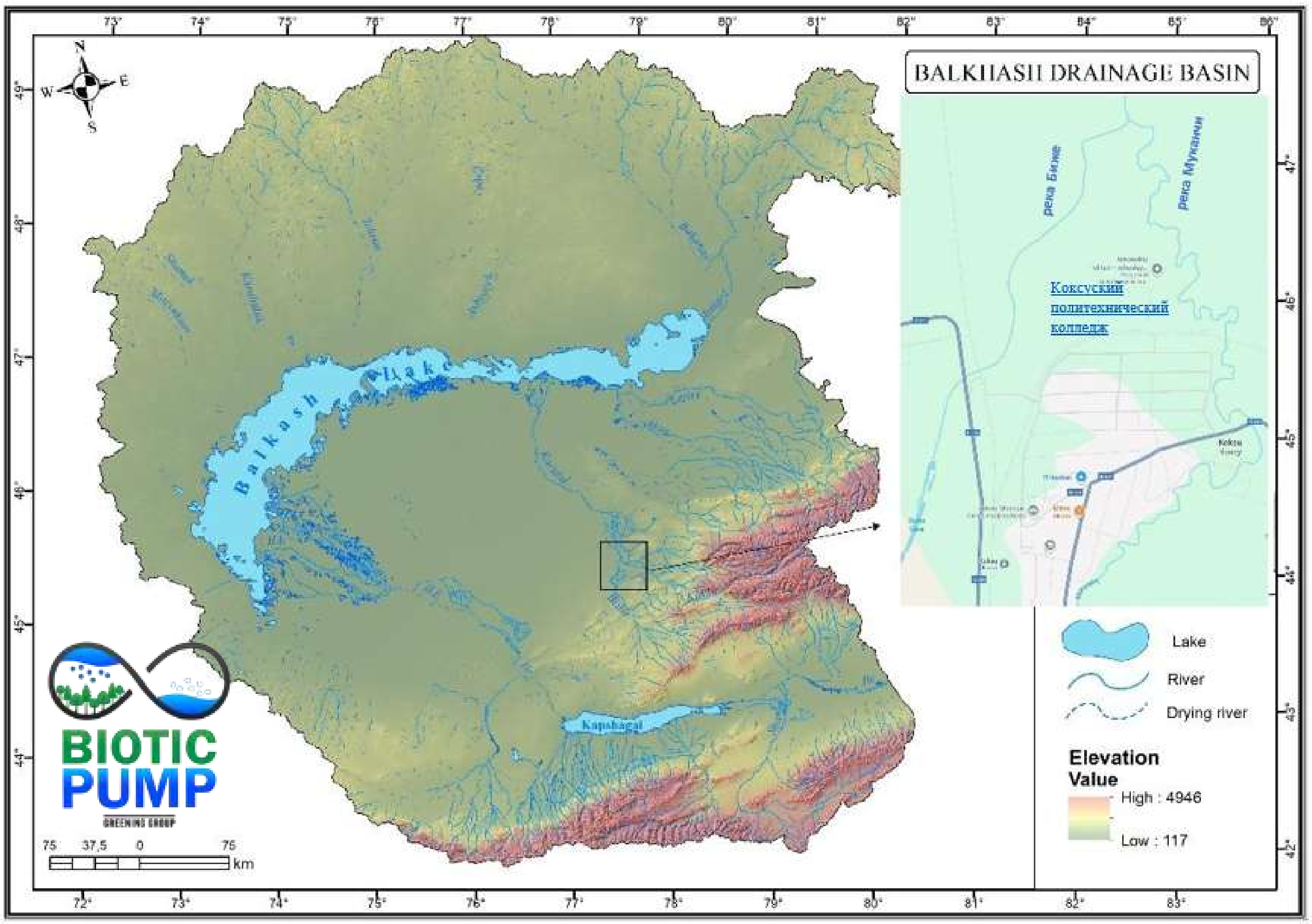


Figure 19. "Flood-MAR-Kaz", https://flood-mar.kz/ , with "Know Your Well" program adaptation for Koksu Polytechnic College, https://www.youtube.com/watch?v=2vi75468Ohg&t=14s , within the Bizhe and Mukanchi rivers, small tributaries of the Karatal River, Balkhash Lake basin.

These efforts are directly connected to the Kazakhstan's President K-Zh.K. Tokayev initiatives in expanding the UN Regional Center for Sustainable Development Goals for Central Asia and Afghanistan. https://www.akorda.kz/ru/prezident-kasym-zhomart-tokaev-i-generalnyy-sekretar-antoniu-guterrish-posetili-regionalnyy-centr-oon-v-almaty-373245. To support this UN program the more localized TVET programs would be reasonable to adapt to improve the basin management at the local level to mitigate the flood and drought issues. In his address on the implementation of strategically important state objectives, President Kassym-Jomart Tokayev noted that "70% of Kazakhstani employers are dissatisfied with the skills of our college graduates." Considering these challenges, President Tokayev designated 2025 the Year of Working Professions to strengthen professional development programs.

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