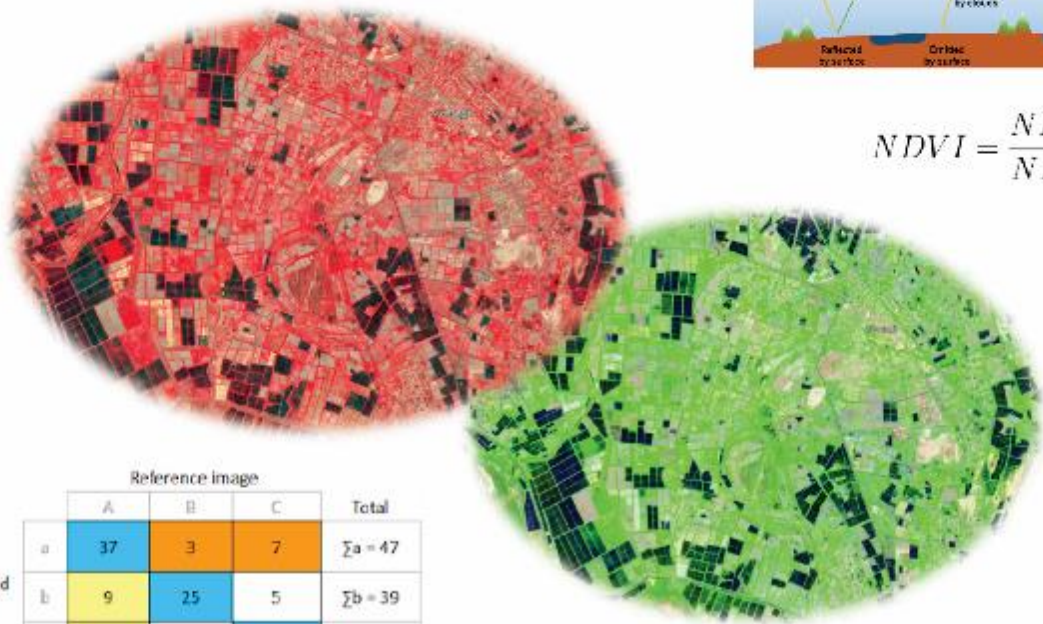
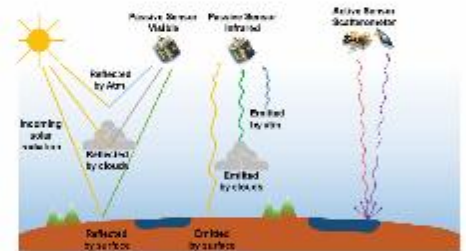


*Ecologically oriented regional development in the Aral Sea region program
Increasing water use efficiency in the Aral Sea Region*

Geodatabase and Atlas: Karakalpakstan

*Zafar Gafurov, Sarvarbek Eltazarov, Tulkun Yuldashev,
Kakhramon Djumaboev, Sherzod Zaitov and Shavkat Kenjabaev*



$$NDVI = \frac{NIR - RED}{NIR + RED}$$

		Reference image			Total
		A	B	C	
Classified image	a	37	3	7	Σa = 47
	b	9	25	5	Σb = 39
	c	11	2	43	Σc = 56
Total		ΣA = 57	ΣB = 30	ΣC = 55	N = 142

About GIZ

The German Society for International Cooperation (GIZ), as a service provider in the field of international cooperation for sustainable development and international education work, is dedicated to shaping a future worth living around the world. Having over 50 years of experience in a wide variety of areas, including economic development and employment promotion, energy and the environment, and peace and security, GIZ provides tailor-made, cost-efficient and effective services for sustainable development. GIZ has two registered offices in Germany, one in Bonn and one in Eschborn, near Frankfurt am Main. GIZ also operates from about 90 offices around the globe, some of which shared with other German development organisations.

About IWMI

The International Water Management Institute (IWMI) is an international, research-for-development organization that works with governments, policymakers, farmers, civil society, water managers, development partners and businesses to solve water problems and scale up solutions. Through partnership, IWMI combines research on the sustainable use of water and land resources, knowledge services and products with capacity strengthening, dialogue and policy analysis to support implementation of water management solutions for agriculture, ecosystems, climate change and inclusive economic growth. Headquartered in Colombo, Sri Lanka, IWMI is a Research Center of CGIAR with offices in 15 countries and a global network of scientists operating in more than 55 countries.

About the “Ecologically oriented regional development in the Aral Sea region program”

Since 2020, the project has been supporting two Central Asian states (Kazakhstan and Uzbekistan) to improve the capacity of organisations and individuals, with the aim of enabling them to make climate-adapted and ecologically oriented investment decisions. For further details about the project, visit: <https://www.giz.de/en/worldwide/93488.html>.





Geodatabase and Atlas: Karakalpakstan

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Gafurov, Z.; Eltazarov, S.; Yuldashev, T.; Djumaboev, K.; Zaitov, S.; Kenjabaev, S. 2024. *Geodatabase and atlas: Karakalpakstan*. Colombo, Sri Lanka: International Water Management Institute (IWMI). 54p. doi: <https://doi.org/10.5337/2024.225>

/ spatial databases / atlases / digital elevation models / satellite imagery / maps / land cover / land use / water resources / water supply / water demand / water-use efficiency / irrigation systems / water authorities / irrigation canals / drainage systems / soil types / soil density / soil organic carbon / soil water content / soil salinity / sandy soils / clay soils / soil pH / climate change / meteorological stations / evapotranspiration / precipitation / temperature / winds / geographical information systems / remote sensing / Uzbekistan /

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Acknowledgments

Geodatabase and Atlas: Karakalpakstan, Uzbekistan is based on data and information generated and collected within the framework of the GIZ Program “Ecologically oriented regional development in the Aral Sea region”. Data were also obtained from published and grey literature as well as spatial analyses carried out using publicly available sources. The authors would like to thank local project partners in Karakalpakstan for their valuable inputs and feedback when preparing the material.



This Geodatabase and Atlas was put together within the framework of activities implemented under the GIZ Program “Ecologically oriented regional development in the Aral Sea region” as part of the project “Increasing water use efficiency in the Aral Sea Region” implemented by the International Water Management Institute (IWMI) in collaboration with GIZ and local partners.



This work is mapped to the CGIAR Initiative on NEXUS Gains, and grateful for the support of CGIAR Trust Fund contributors (www.cgiar.org/funders).

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Implemented by



This work was carried out as part of the GIZ funded regional project “Ecologically Oriented Regional Development in the Aral Sea Region” (ECO-ARAL) and commissioned by German Federal Ministry for Economic Cooperation and Development (BMZ).

Geodatabase and Atlas

Importance Geodatabase and Atlas

The information systems aimed at data and information management are becoming increasingly important with reference to the processes of decision making and strategic thinking in a newly emergent competitive economy setting. In addition to digital data types utilized in information systems, geospatial data have advanced significantly in recent years. Not only do these data include the geographic location of particular items on the planet, they also specify their shape and size. Spatial data including digital maps are the core component of a GIS. In order to help decision makers with the planning, design and prioritization of investment plans, these data are materialized in the form of files that are compiled into a single database.

Introduction

This Geodatabase and Atlas was developed by the International Water Management Institute (IWMI) in collaboration with regional partners as part of project activities under the GIZ project “Ecologically oriented regional development in the Aral Sea region”.

Capacity-building of micro-, small- and medium-sized enterprises as well as ministries and state agencies is one of the primary focuses of the project in order to enable their employees to make climate-adaptive and environmentally oriented investment decisions. Modern satellite imagery and technologies is one of the areas that create new opportunities for agricultural, forestry and water sector professionals to improve their skills and expertise in regional spatial planning. For instance, remote sensing techniques can be instrumental in identifying environmental or climate-related industrial risks and cases of degradation for targeted improvements at an early stage.

Data Accuracy and Reliability

This Atlas was created using open source GIS, remote sensing and other relevant information including databases, maps, research, analyses etc. publicly available from renowned international agencies, research organizations and projects.

Availability and Accessibility

The Atlas can be obtained in digital form for use by external parties. When using the Atlas, the authors and the institute should be credited.

Software Employed

This Atlas and the associated maps were created on a computer machine running Windows 10 Professional and using ArcGIS, QGIS and Google Earth Engine. End users should download the package that is most appropriate for the version of ArcGIS software that they are using. It is important to note that ArcGIS is not the only software that allows making use of the map package and associated geodatabase.

Aral Sea Basin



The Aral Sea, located in the Turan plain of Central Asia and once the fourth-largest inland sea in the world, has undergone many changes. Two major transboundary rivers, the Amu Darya and the Syr Darya, feed the Aral Sea. Their combined basin boundaries, which largely define the Aral Sea basin, cover a total area of 1.9 million km² (Xenarios et al. 2019) and extend over six countries: Kazakhstan, Turkmenistan, Uzbekistan, Afghanistan, Tajikistan and the Kyrgyz Republic. About 35 million people, two thirds of the combined population of these countries, live in the Aral Sea basin. Before 1960, about 60 billion cubic meters (BCM) (Xenarios et al. 2019) of water reached the sea annually. Today, the inflow of water has declined to 5-20 BCM annually and as a result, the level of water in the Aral Sea has dropped by almost 20 meters (m) and its area shrunk by two-thirds, from 67,000 km² in 1960 to 20,000 km² at present (Xenarios et al. 2019). The table in the following page provides some key features of the Aral Sea basin.

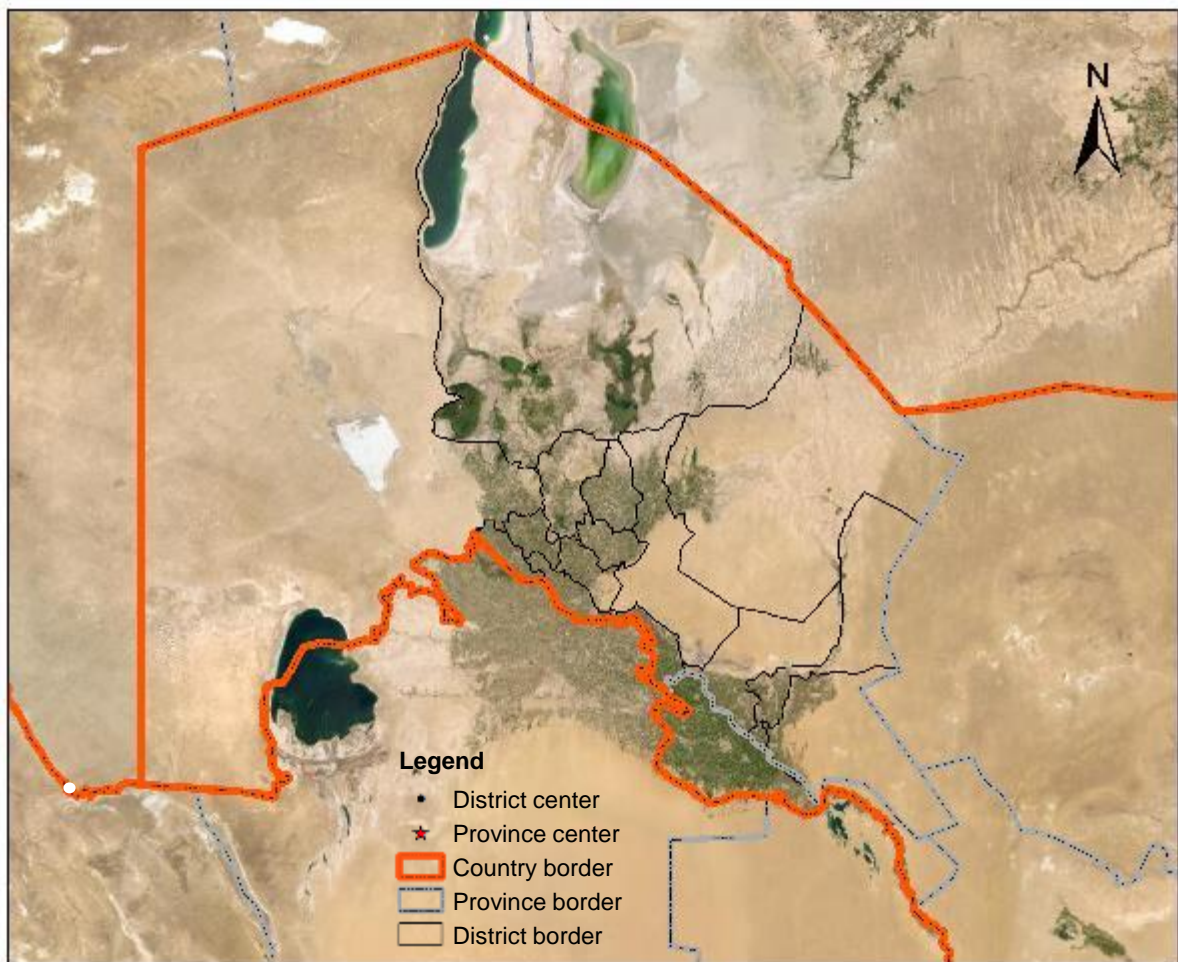
Table Key information on Aral sea basin, surface area and renewable surface water resources by basin countries

Country	Surface area		Renewable surface water resources				
	km ²	% Aral sea basin	% Country area	Amudarya (km ³)	Syrdarya (km ³)	Aral sea basin (km ³)	Aral sea basin (%)
Afghanistan	234800	12	36	6.18		6.18	5.3
Kazakhstan	540000	28	20		4.50	4.50	3.9
Kyrgyzstan	117500	6	59	1.93	27.25	29.18	25.2
Tajikistan	141670	7	99	62.90	0.40	63.30	54.8
Turkmenistan	466600	24	96	0.98		0.98	0.8
Uzbekistan	447400	23	100	4.70	4.84	9.54	8.3
Total	1947970	100.0		76.69	36.99	113.68	98.3
Aral sea basin				78.46	37.14	115.60	100.00

Source: FAO, 2003.

At present, the biggest challenges for the water sector in the region come from weak decision-making capacities of state water management organizations, and un-coordinated and competing interests of different stakeholders and public sectors across all levels of water management. These problems are the root causes resulting in bottlenecks and failures in implementing integrated water management approaches at river basin scale. Current water systems are in transformation, having the attributes of both past and present systems. However, an effective water administration needs to tackle both supply and demand needs, taking care of both the developing economy and the degraded environment (Xenarios et al. 2019).

Satellite view of study area

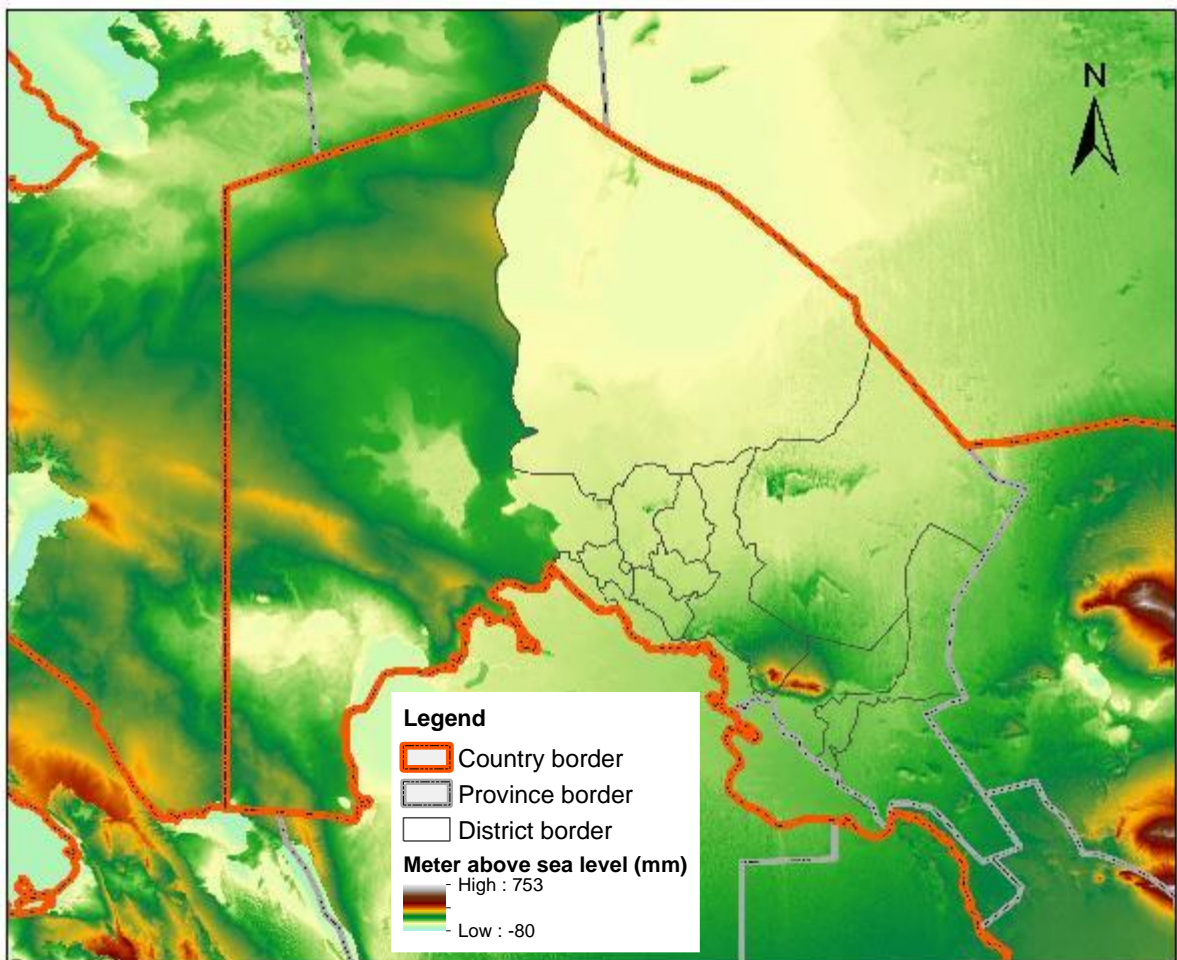


The Republic of Karakalpakstan, Uzbekistan

The Republic of Karakalpakstan is an autonomous republic within Uzbekistan located in the northwest of the country in the lower delta of the Amu-Darya River. The region borders on the Republic of Kazakhstan in the north, northeast and west; the Republic of Turkmenistan to the south and southeast; and the Navoi and Khorezm regions of Uzbekistan to the east and southeast.

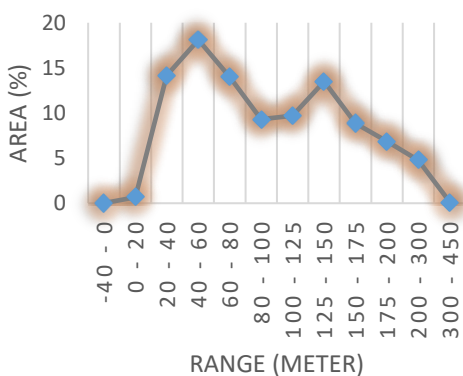
The total area of Karakalpakstan amounts to 166,561 km². The population is estimated around 1950 thousand people of which 51 percents (%) live in the rural areas (Statistics Agency 2023). Karakalpakstan is divided into 16 districts and 1 city. The capital city is Nukus. Other important towns include Khojayli, Takhiatosh, Chimboy, Kungrad and Moynaq.

Digital elevation model



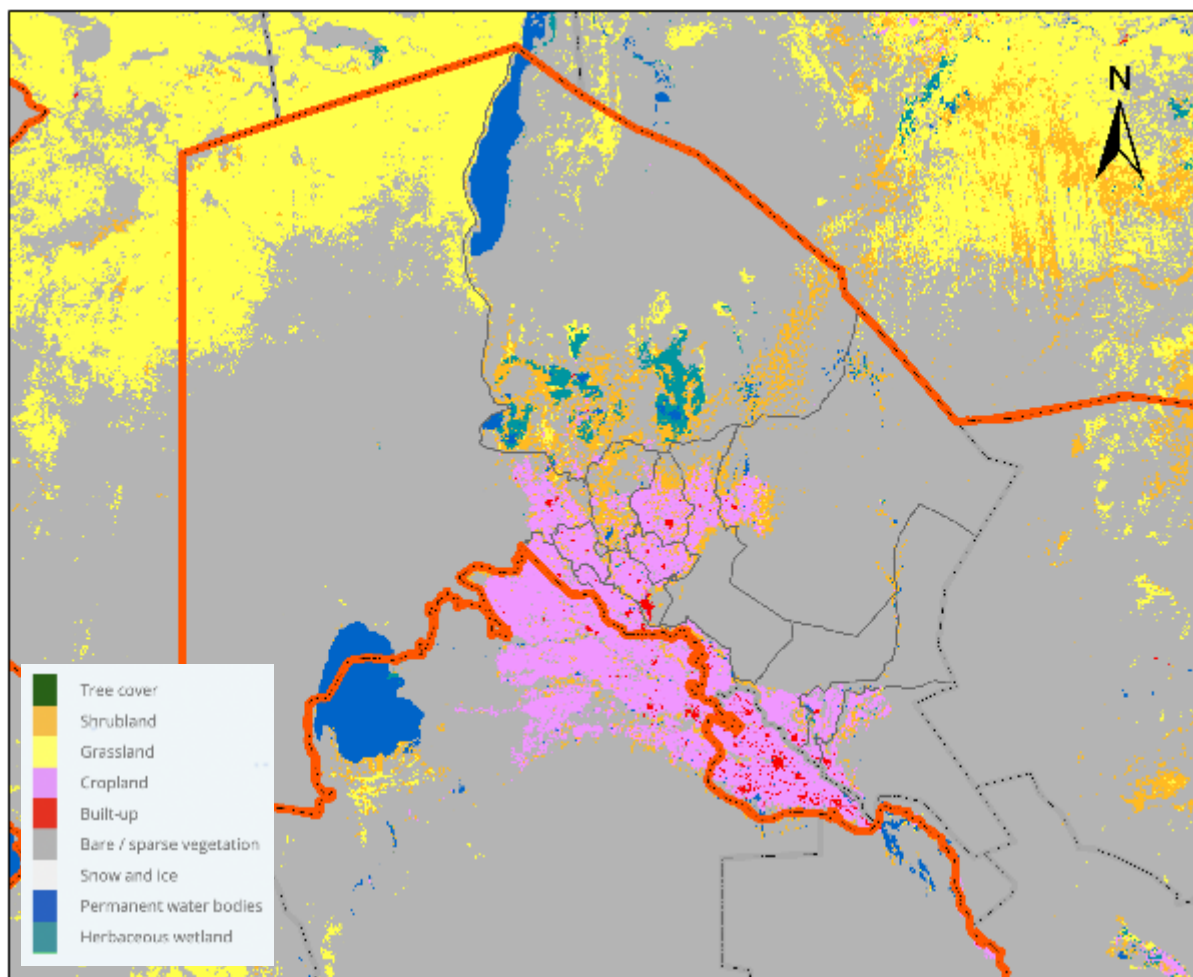
Max Elevation	450 meters
Min Elevation	-40 meters
Mean Elevation	100 meters
Mean Slope	2 degrees

The digital elevation model of the Republic of Karakalpakstan was produced using the publicly available Shuttle Radar Topography Mission (SRTM) digital elevation dataset. SRTM was originally produced to provide consistent, high-quality elevation data at near global scope. This version of the SRTM digital elevation data was processed to fill data voids, and to facilitate its ease of use.



Source: Farr et al. 2007.

Land cover and use map



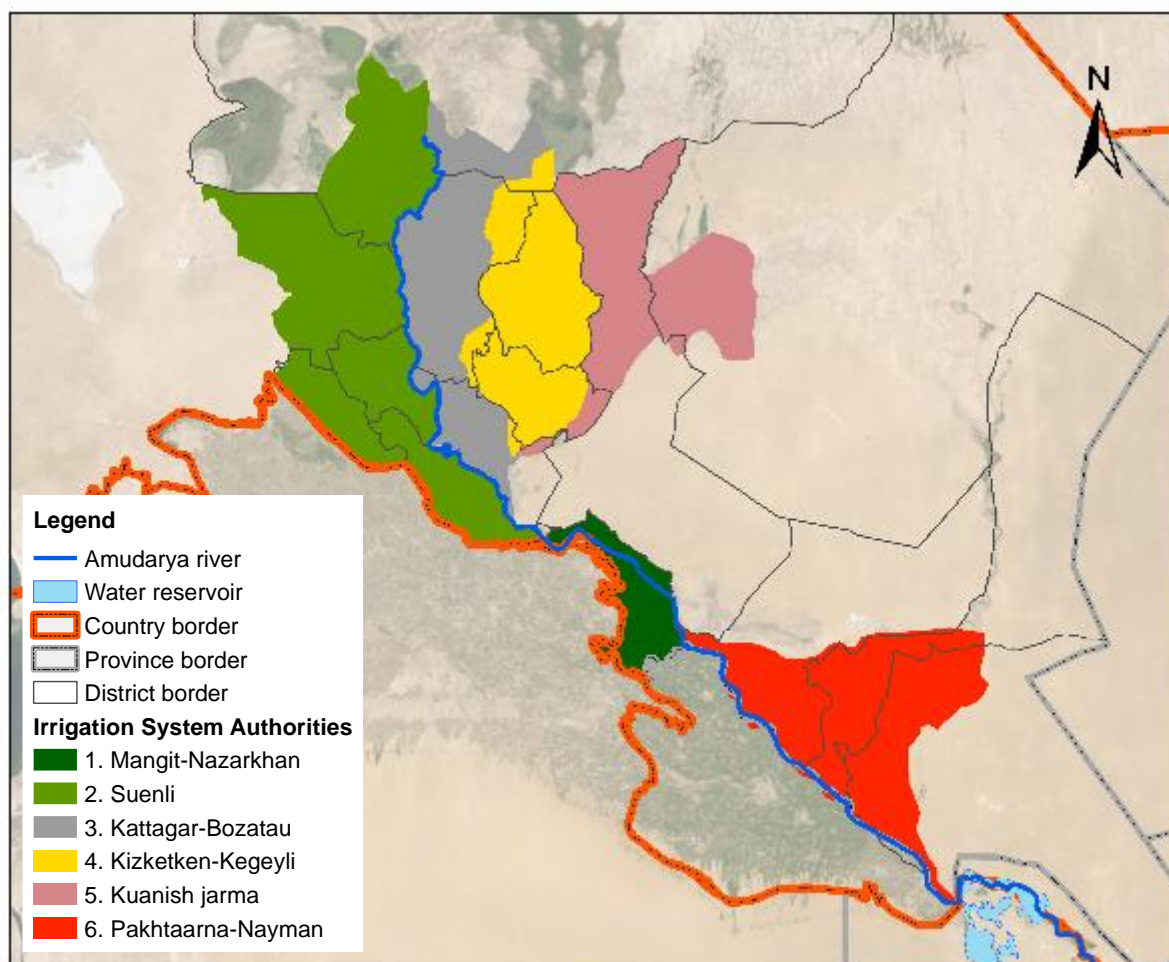
Source: ESA WorldCover product (Zanaga et al. 2021).

Class name	Approx. area(%)
Trees	0.14
Grass	0.05
Flooded Vegetation	0.53
Crops	5.41
Scrub/Shrub	67.52
Built Area	1.18
Bare Ground	22.57
Snow/Ice	0.01
Water	2.6

The total agricultural land area is about 3260 thousand hectares, of which irrigated area amounts to 500 thousand hectares (Cadastre Agency 2021).

The European Space Agency (ESA) WorldCover product provides a global land cover map for 2020 at 10 m resolution based on Sentinel-1 and Sentinel-2 data. The WorldCover product comes with 11 land cover classes and has been generated in the framework of the ESA WorldCover project, part of the 5th Earth Observation Envelope Programme (EOEP-5) of the European Space Agency (Zanaga et al. 2021).

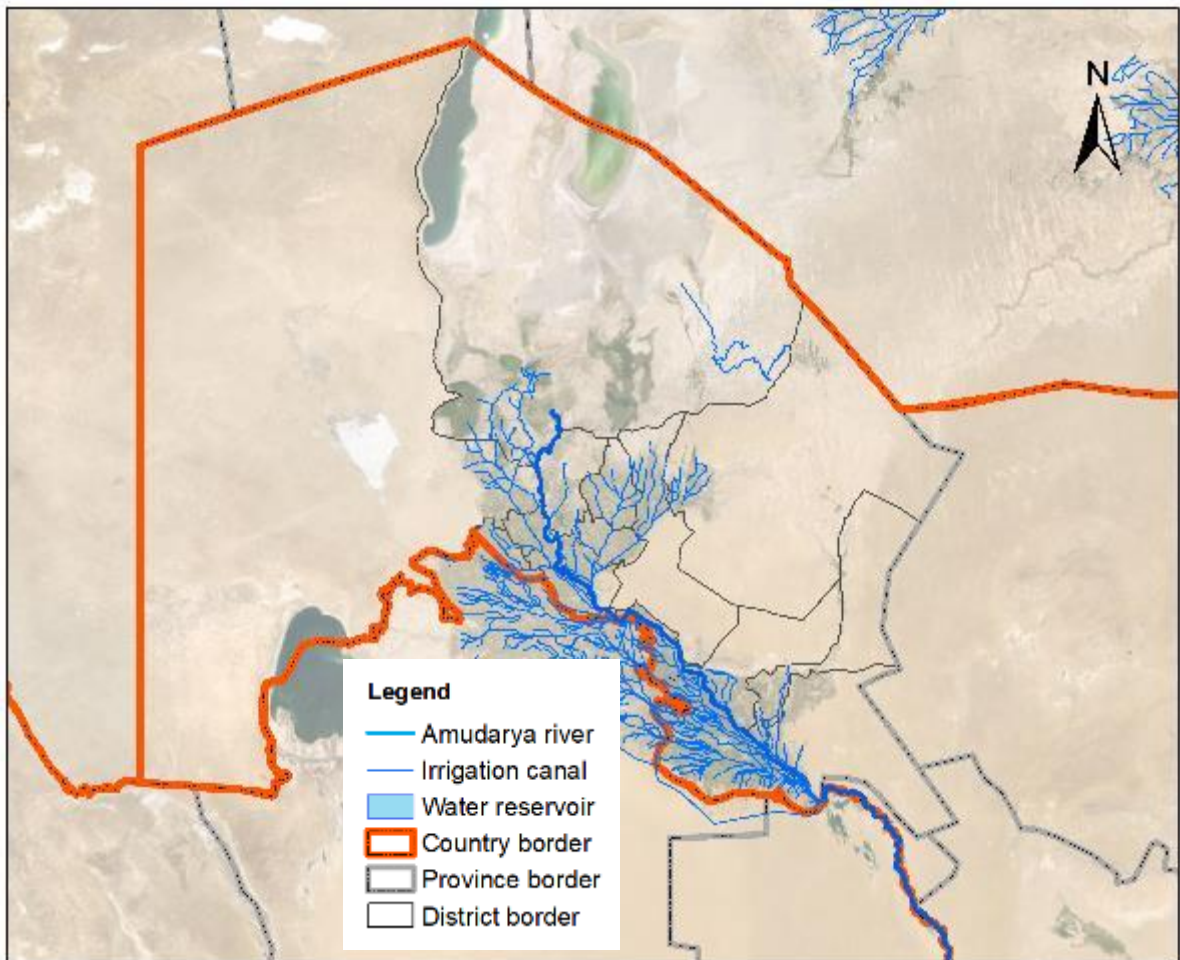
Irrigation system authorities



The institutional framework for managing water resources within Uzbekistan is complex and multi-level. The main governmental body to manage water and implement water sector policies is the Ministry of Water Resources. Further down the ladder, there are several operational management levels to allocate and manage water at cross-basin, basin and sub-basin levels including handling inter-provincial, provincial, inter-district and district water supplies. Lastly, special services of water management under district irrigation departments (DIDs) are state actors that operate at the lowest farmer and rural community level.

Karakalpakstan as an autonomous republic has its own Ministry of Water Resources to handle allocation and delivery of water resources among its six Irrigation System Authorities (ISAs) at sub-basin level and 16 DIDs at district level (Djumaboev 2021).

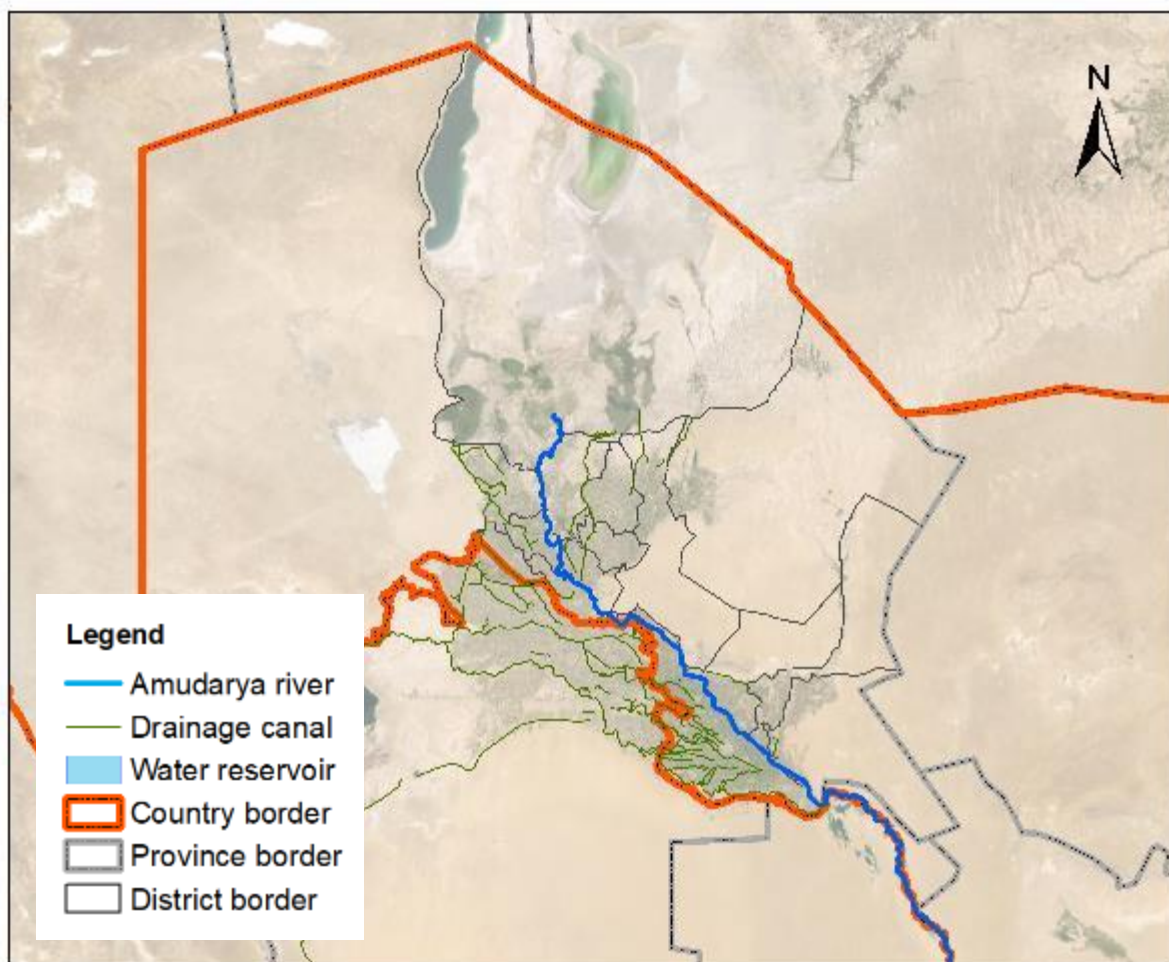
Irrigation canal networks



An extensive and complicated network of irrigation canals coupled with a mesh of drainage facilities in the region mostly originates from the Soviet era, i.e. established in the 1950 – 1970s (Sinnott 1990). Since then, however, the reliability of the system has declined significantly due to lack of maintenance and age (Ibrakhimov et al. 2004), increasing water insecurity (Müller 2006). In order to increase the productivity of irrigated areas, improve land reclamation and water supply, large-scale irrigation and land reclamation activities were carried out within the framework of the State Programs carried out in 2008-2019.

At field level there are additional water losses due to furrow irrigation which is the most common method of irrigation among farmers in Karakalpakstan and Uzbekistan, as a whole. Overall, 25-27% of water taken from the river source is lost during water conveyance along the large main canals; with additional 14-17% of water lost while reaching provincial borders along the distributary canal network. As far as water delivery losses at the boundary is concerned, they are estimated at 30% during the growing season and up to 45% of total water withdrawals at the source in the non-growing season.

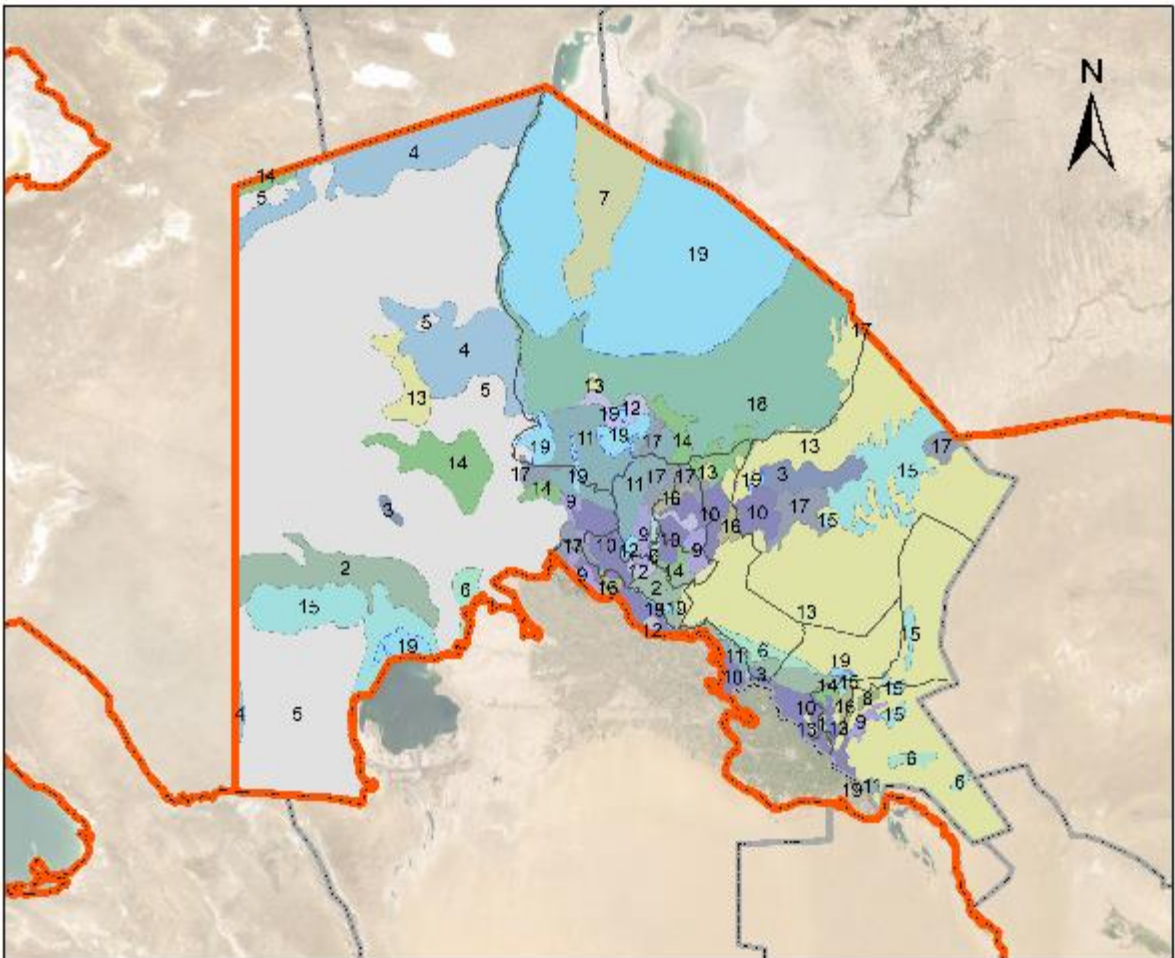
Drainage networks



The per-unit-of-area water supply during the growing season in Karakalpakstan is estimated about 14 thousand cubic meter per hectare (m^3/ha) (EBRD and IWMI 2019). Such huge amounts can be explained by underperforming irrigation systems, as a whole, and low levels of organization and skills at the demand-side, such as farmers failing to comply with proper crop irrigation techniques or cropping patterns, i.e. cultivation of rice.




The per-unit-of-area rate of accumulated drainage flows (DF) in Karakalpakstan in 2016-2018 ranged between 3-5 thousand m^3/ha amounting to 25-33% of gross water withdrawals per each irrigated hectare (e.g., 12-15 thousand m^3/ha). Also remarkable is that around 98% of all accumulated drainage flows is lost to natural depressions of which only 2% is returned back to the rivers for reuse. Net irrigation water withdrawals per each irrigated hectare for the same period ranged from 9-10 thousand m^3/ha or 67-75% of the gross irrigation water withdrawals (EBRD and IWMI 2019).

Main soil types






















Source: Celis et al. 2007.

Legend

-  Country border
-  Province border
-  District border

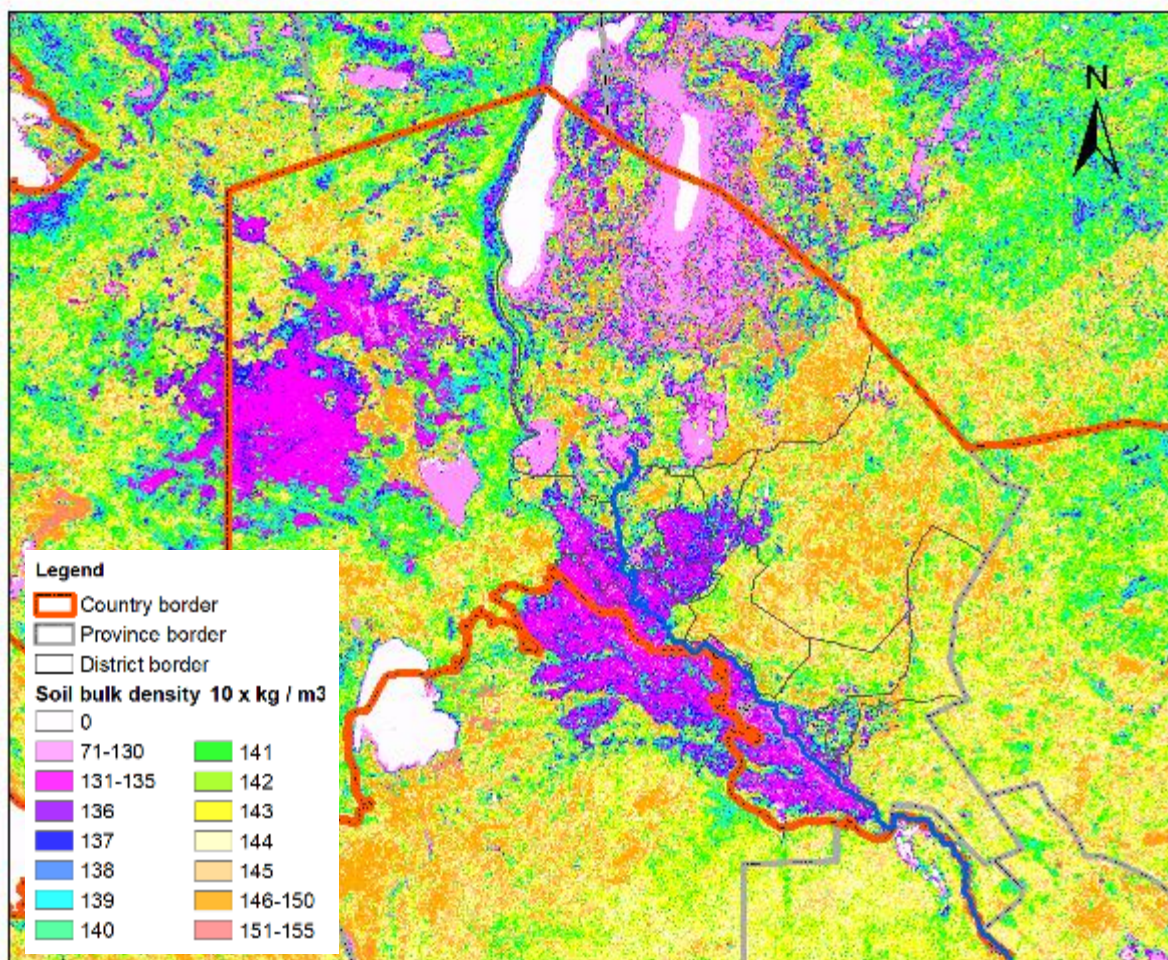
Main soil types

-  Desert sandy solonchak-like on aeolian deposits, proluvium and alluvium
-  Meadow soils
-  Meadow soils of the flood plains
-  Meadow solonchaks
-  Sands
-  Shor and other solonchaks
-  Takir-like and takirs here and there in complex with sands
-  Takir-meadow saline on alluvium
-  Takyrlike soils and takyr
-  Coastal solonchaks (including Aral)
-  Water

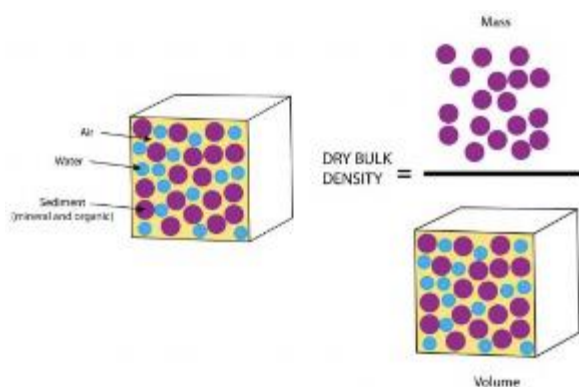
-  Grey-brown eroded skeletal on skeleton eluvium
-  Grey-brown solonchak-like loamy-sandy on eluvium of sandstone
-  Grey brown desert soils
-  Grey brown desert solonetzic soils
-  Grey brown desert weakly developed stony soils
-  Island of the dried Aral Sea
-  Meadow-oasis saline and leached loamy on alluvium
-  Meadow-takir on alluvium and proluvium with solonchaks plots

Irrigated meadow soils are the most common soil type in Karakalpakstan accounting for about 2/3 of the irrigated arable land area. Takyr soils (10%) are developed mainly on modern and ancient alluvial deposits. Large tracts of virgin takyr soils are located east of Takhtakupir, west of Kungrad and in the northern part of the Kyrkkyz massif (SoyuzNIIKHi 1992).

Soil bulk density



Source: OpenLandMap.org (Hengl 2018a).



The soil bulk density, also known as dry bulk density, is the weight of dry soil divided by total soil volume. The total soil volume is the combined volume of solids and pores which may contain air or water, or both. The average values of air, water and solid in soil are readily measured and are a useful indication of a soils physical condition.



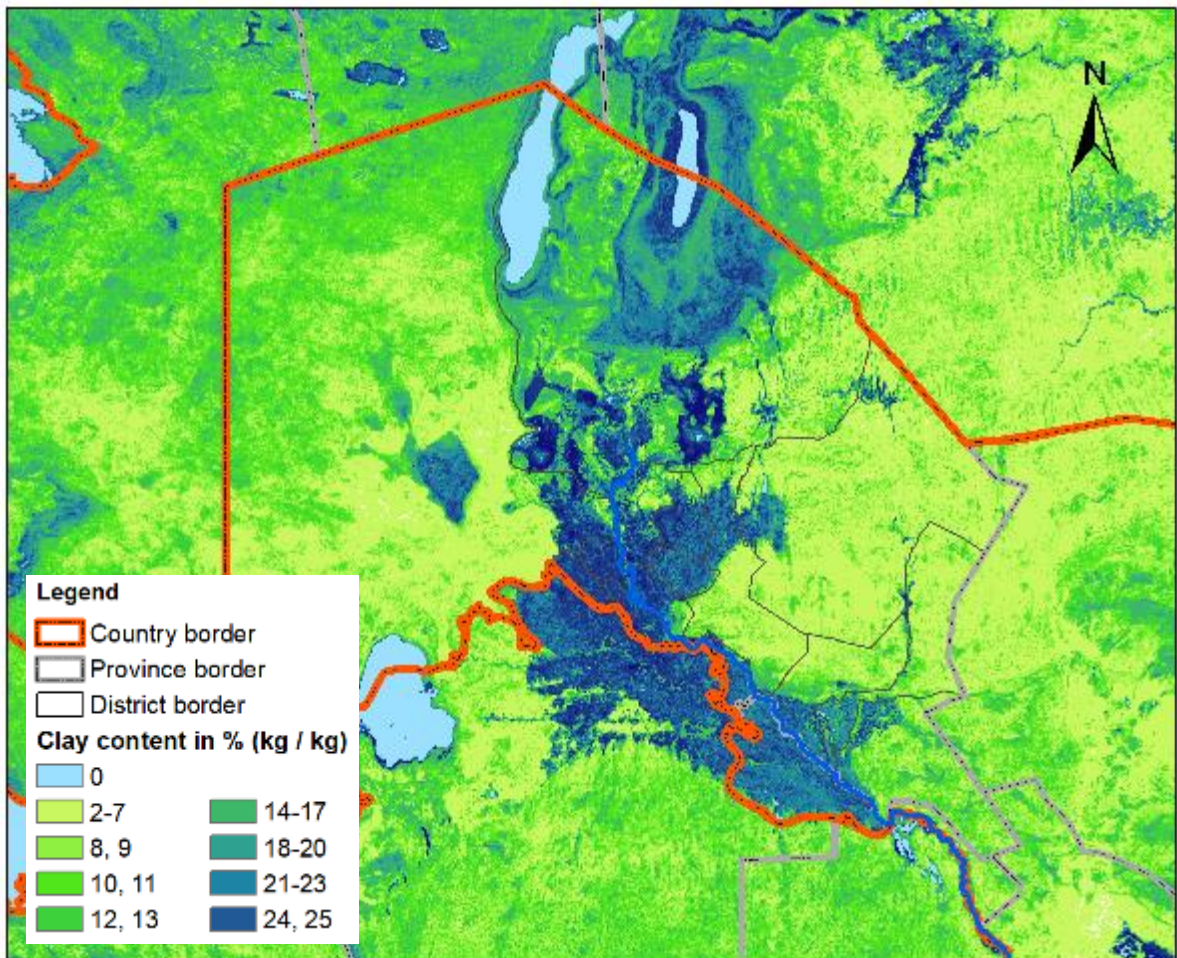
Lower bulk density
Lower weight
More pore space



Higher bulk density
Higher weight
Less pore space

OpenLandMap.org is a data portal to the world's environmental data representing land mask (land cover, vegetation, soil, climate, terrain data and similar). OpenLandMap.org is the web- mapping component of the OpenGeoHub GIS for land data (Hengl 2018a).

Clay content in soil



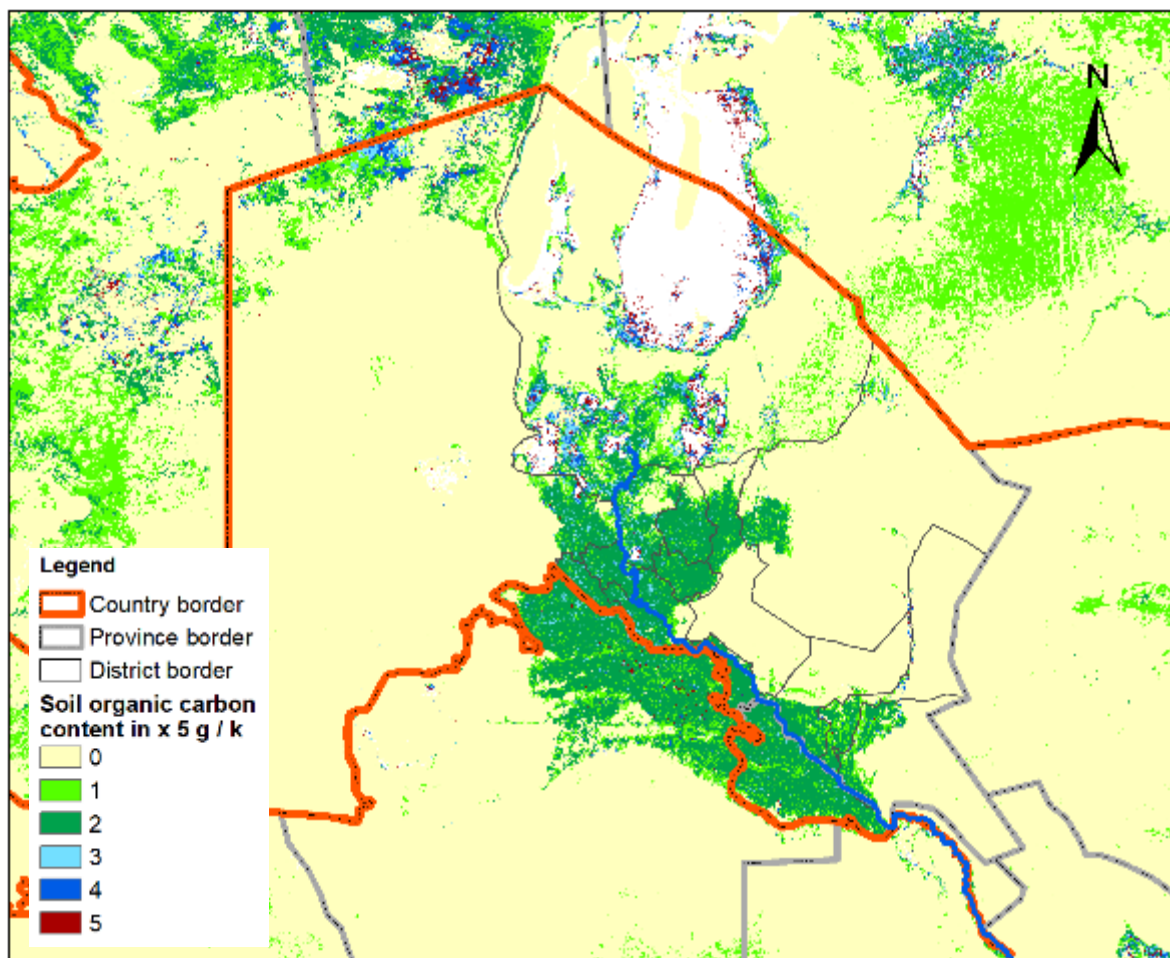
Source: *OpenLandMap.org* (Hengl 2018b).



Clay is a fundamental driver of many soil properties and in many ways defines what a soil is capable of growing and storing. The clay fraction in soils are any mineral particles less than 2 microns in size. As a result, the combined clay fraction has a significant surface area and, therefore, a large capacity for nutrient and carbon storage. The clay fraction also provides physical protection for soil microbes against predation.

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Soil organic carbon content



Source: *OpenLandMap.org* (Hengl and Wheeler 2018).

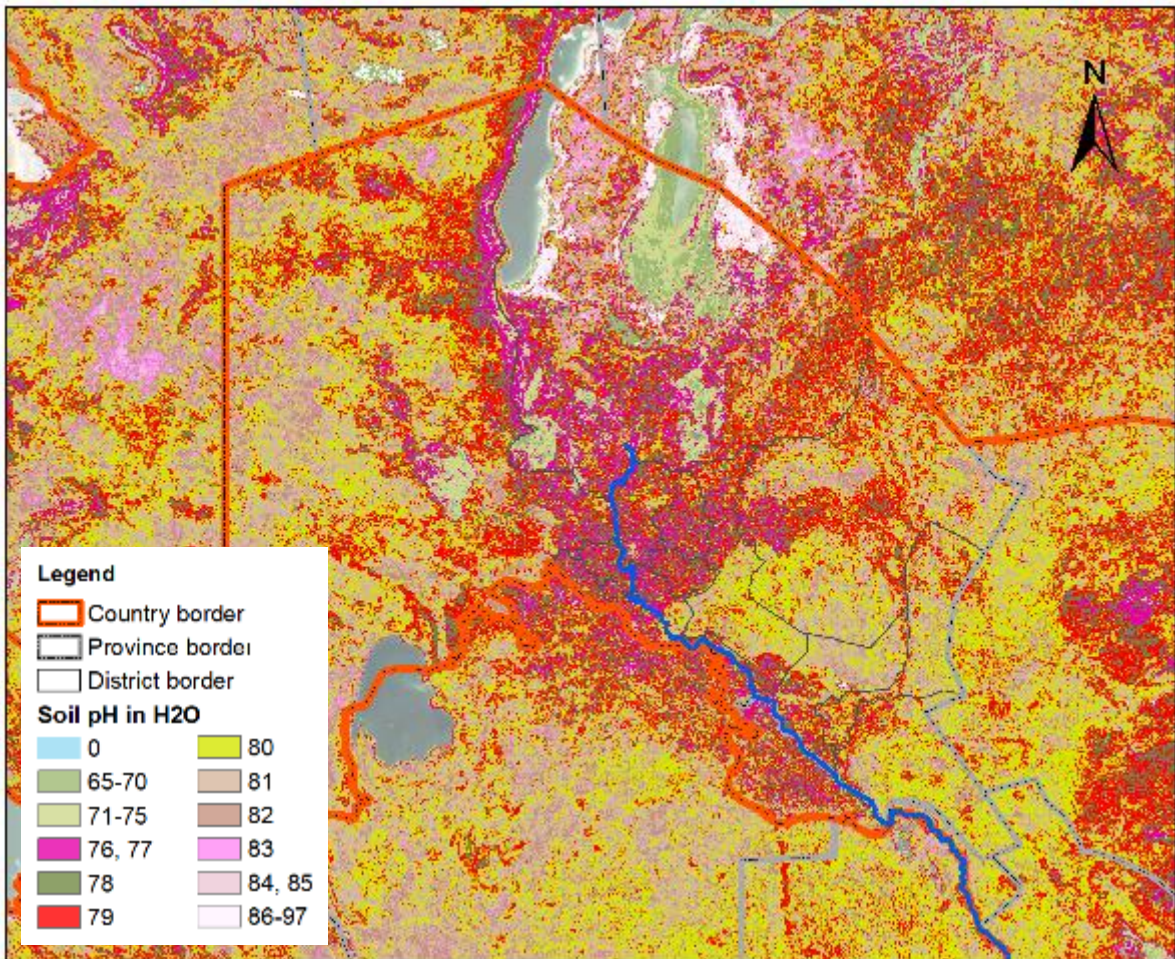


Soil organic carbon is a measurable component of soil organic matter. Organic matter makes up just 2–10% of most soil's mass and has an important role in the physical, chemical and biological function of agricultural soils.

Organic matter contributes to nutrient retention and turnover, soil structure, moisture retention and availability, degradation of pollutants, and carbon sequestration.

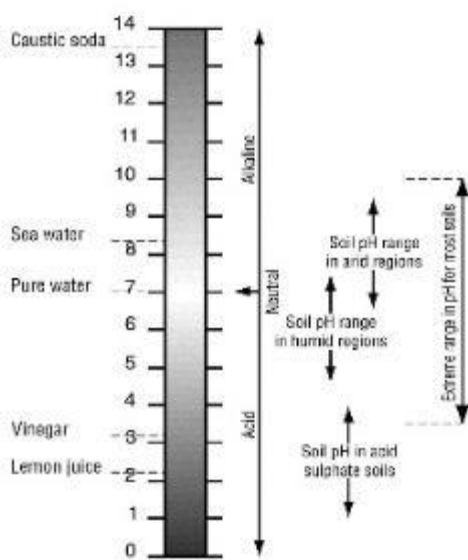
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Soil pH in H₂O



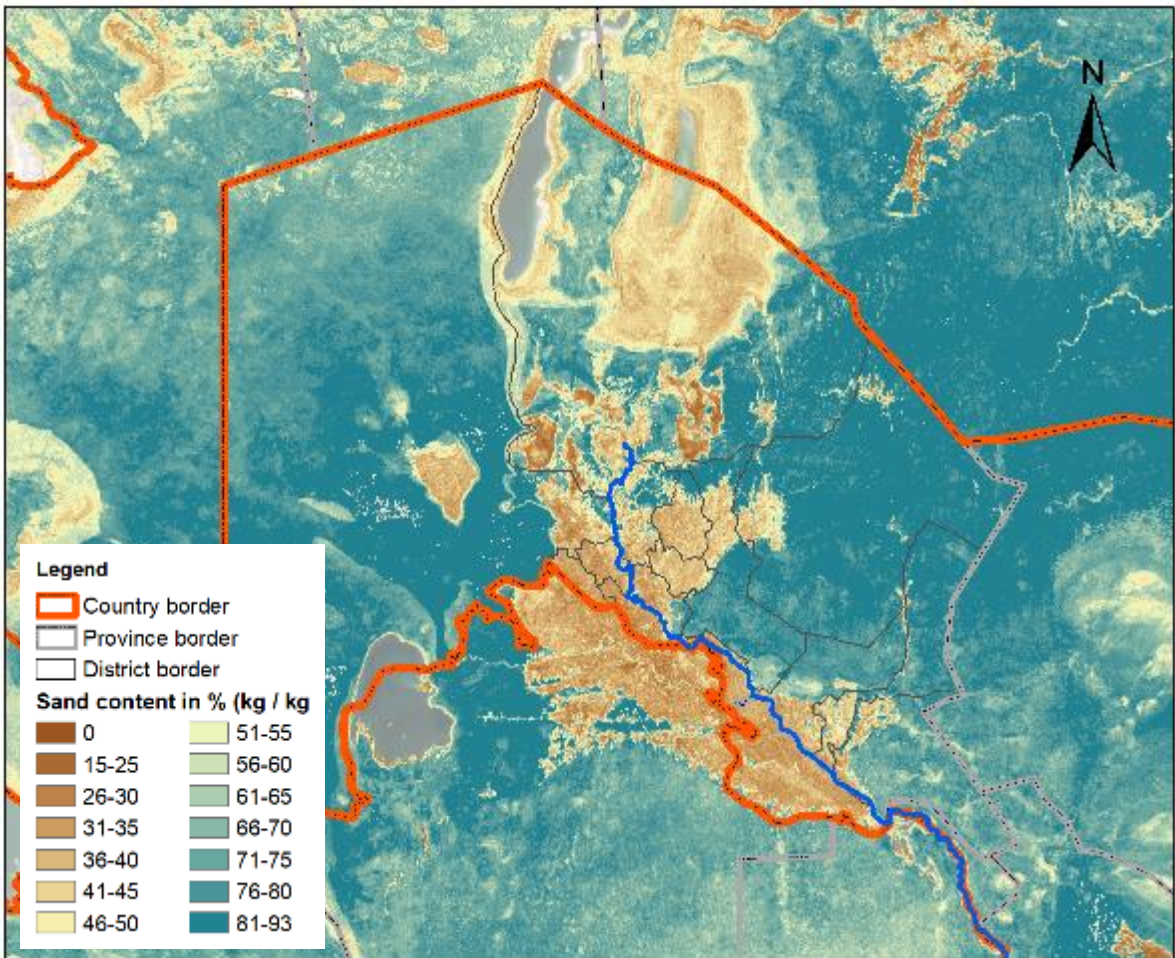
Source: OpenLandMap.org (Hengl 2018c).

Soils can be naturally acid or alkaline, and this can be measured by testing their pH value. Having the correct pH is important for healthy plant growth. Being aware of the long-term effects of different soil management practices on soil pH is also important. Research has demonstrated that some agricultural practices significantly alter soil pH.



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Soil sand content



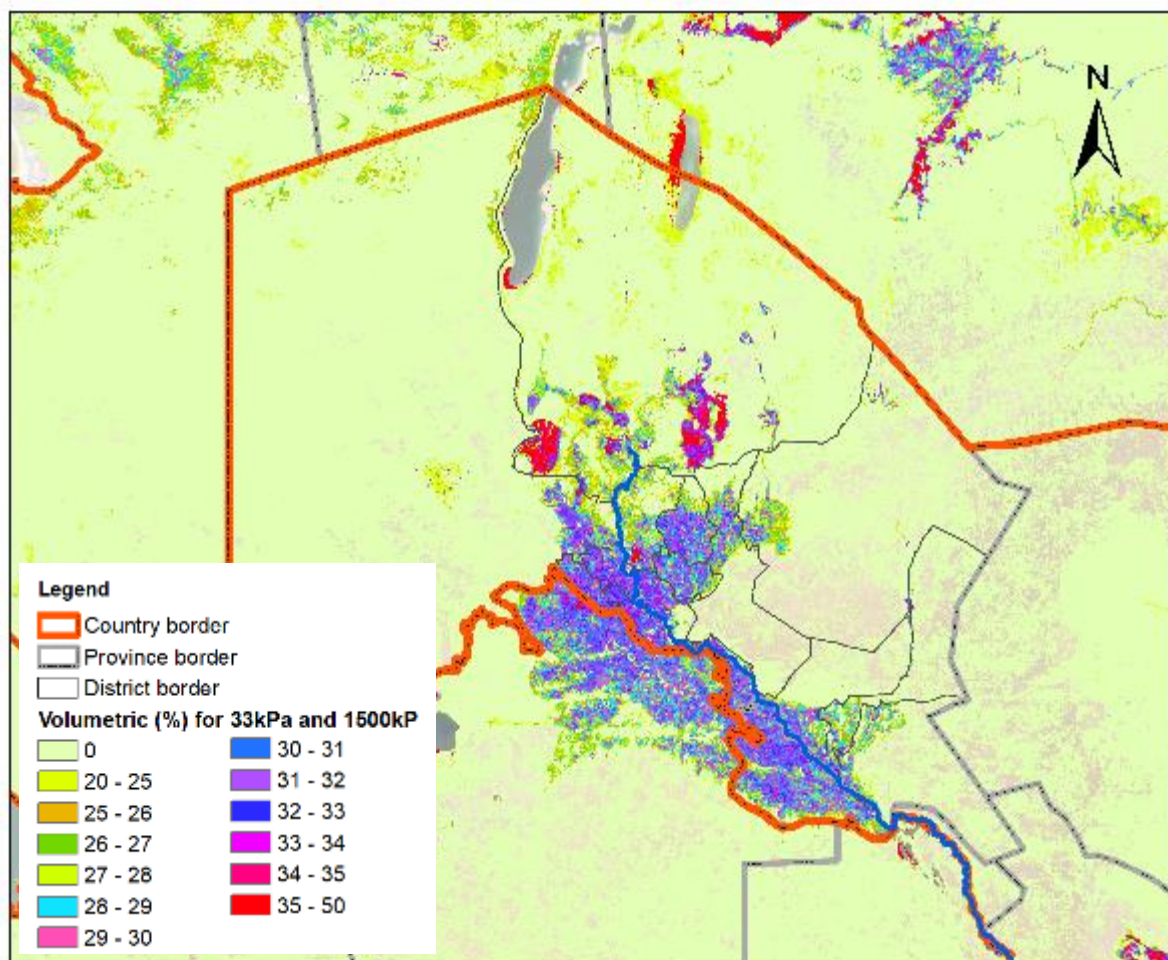
Source: *OpenLandMap.org* (Hengl 2018d).



Sand is a naturally occurring granular material composed of finely divided rock and mineral particles. A soil containing more than 85% sand-sized particles by mass is called sandy.

OpenLandMap.org is a data portal to the world's environmental data representing land mask (land cover, vegetation, soil, climate, terrain data and similar). OpenLandMap.org is the web-mapping component of the OpenGeoHub GIS for land data (Hengl 2018a).

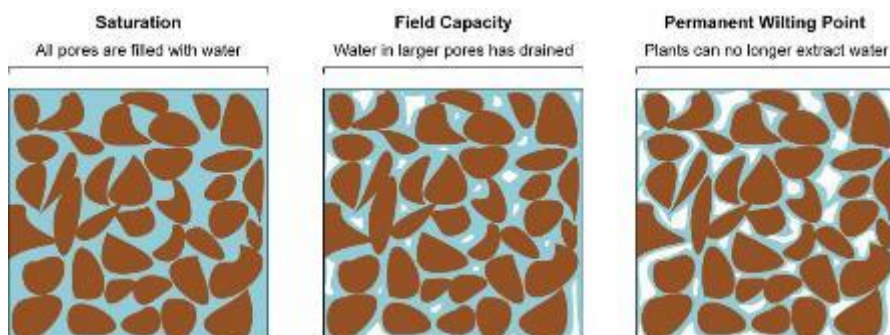
Soil water content at 33kPa



Source: *OpenLandMap.org* (Hengl and Gupta 2019).

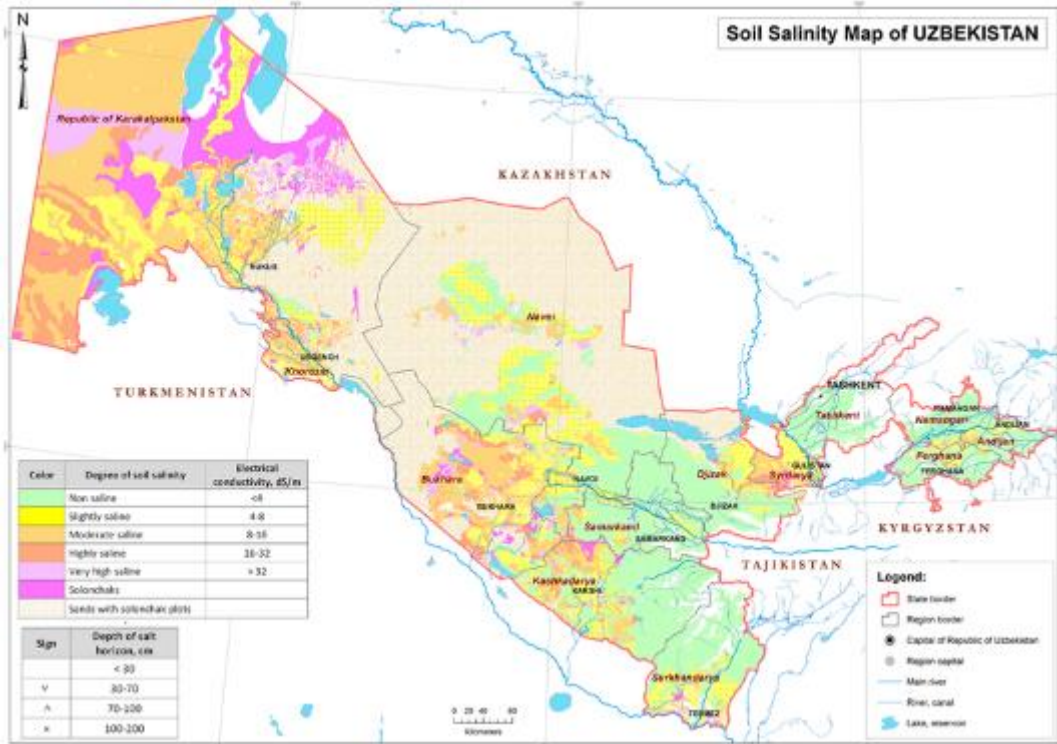
The soil water content (SWC) or soil moisture is the amount of water present in the soil. It influences plant growth, soil temperature, transport of chemicals and groundwater recharge. The two most widely used parameters for quantifying SWC or water availability for plants are i) volumetric water content; and ii) soil matric potential. Soil water content (volumetric %) for 33kPa and 1500kPa suctions predicted at 0 cm depth at 250 m resolution.

OpenLandMap.org is a data portal to the world's environmental data representing land mask (land cover, vegetation, soil, climate, terrain data and similar). OpenLandMap.org is the web-mapping component of the OpenGeoHub GIS for land data (Hengl 2018a).



Soil water content at saturation, field capacity and permanent wilting point thresholds.

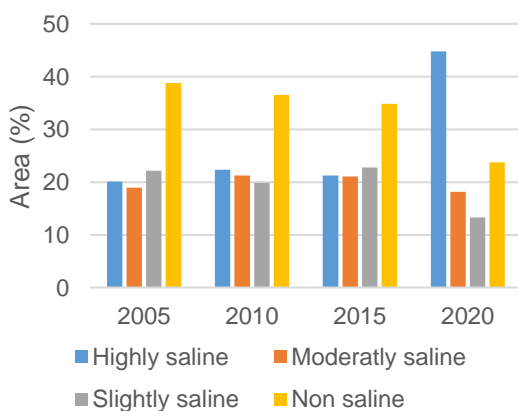
Soil salinity map of Uzbekistan



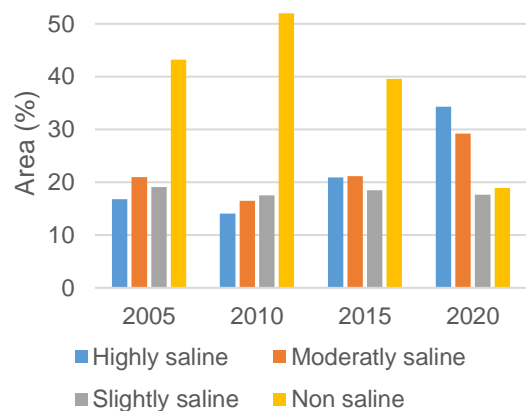
Soil salinization is one of the main environmental issues, affecting large areas in Uzbekistan. At least 46.6% of the country's irrigated areas is affected by salinization in one way or another, with 2.5% strongly saline, 13.3% moderately saline and 30.9% slightly saline (Eltazarov 2016). One of the areas most affected by soil salinization is the Republic of Karakalpakstan. Among the causes of it are underperforming drainage and irrigation systems, non-compliance with agronomic practices, on-farm water overuse, etc. The charts below and on a whole series of the pages that follow provide a comparative multi-year picture of soil salinity changes using the Vegetation Soil Salinity Index (VSSI) based on MODIS satellite imagery. For VSSI calculations and soil salinity mapping, the two 3-month reference periods of March-May and June-August are used to denote the winter and summer cropping season, respectively. The visualizations on a whole series of pages that follow are also provided for district boundaries in Karakalpakstan based on median VSSI values.

Soil salinity dynamics in Karakalpakstan province

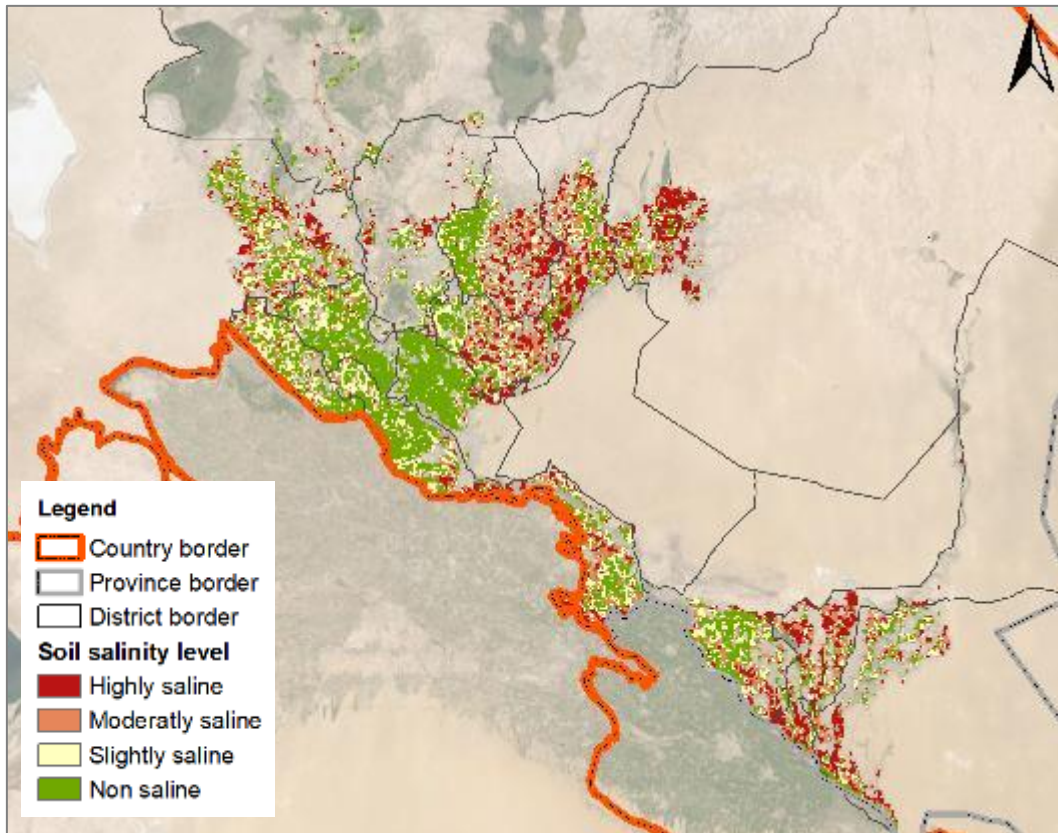
a) winter cropping season



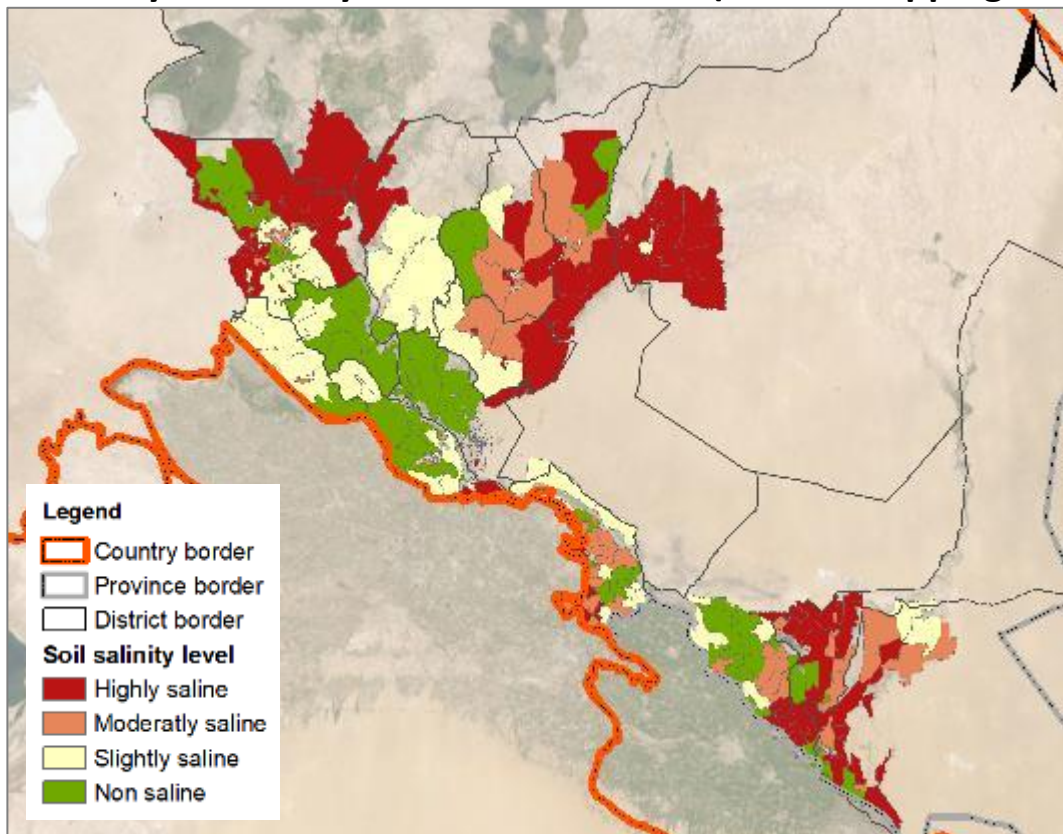
b) summer cropping season



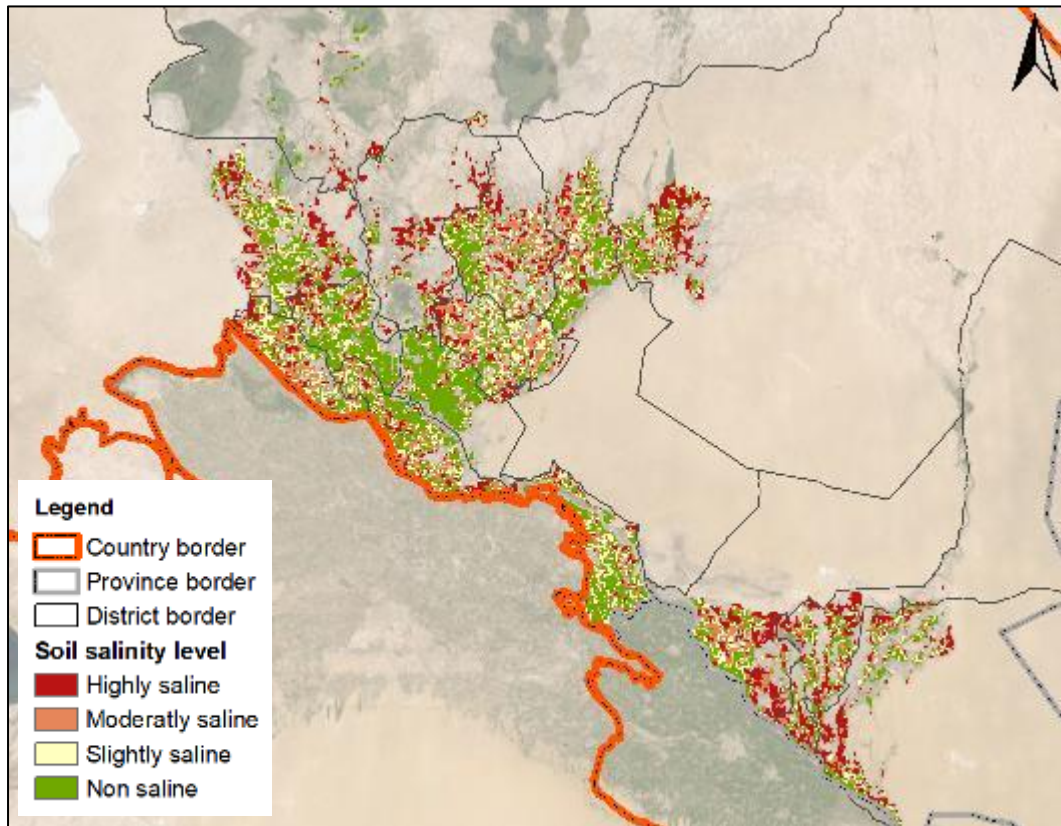
Soil salinity in 2005 (winter cropping season)



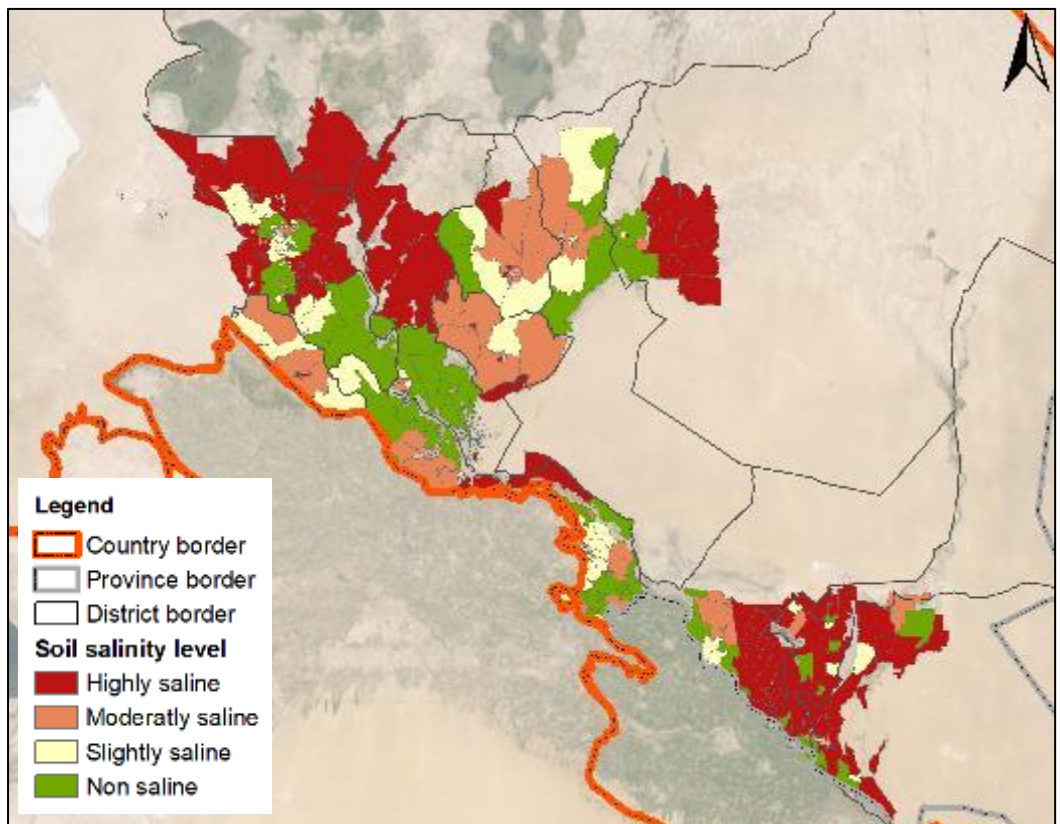
Soil salinity in 2005 by district boundaries (winter cropping season)



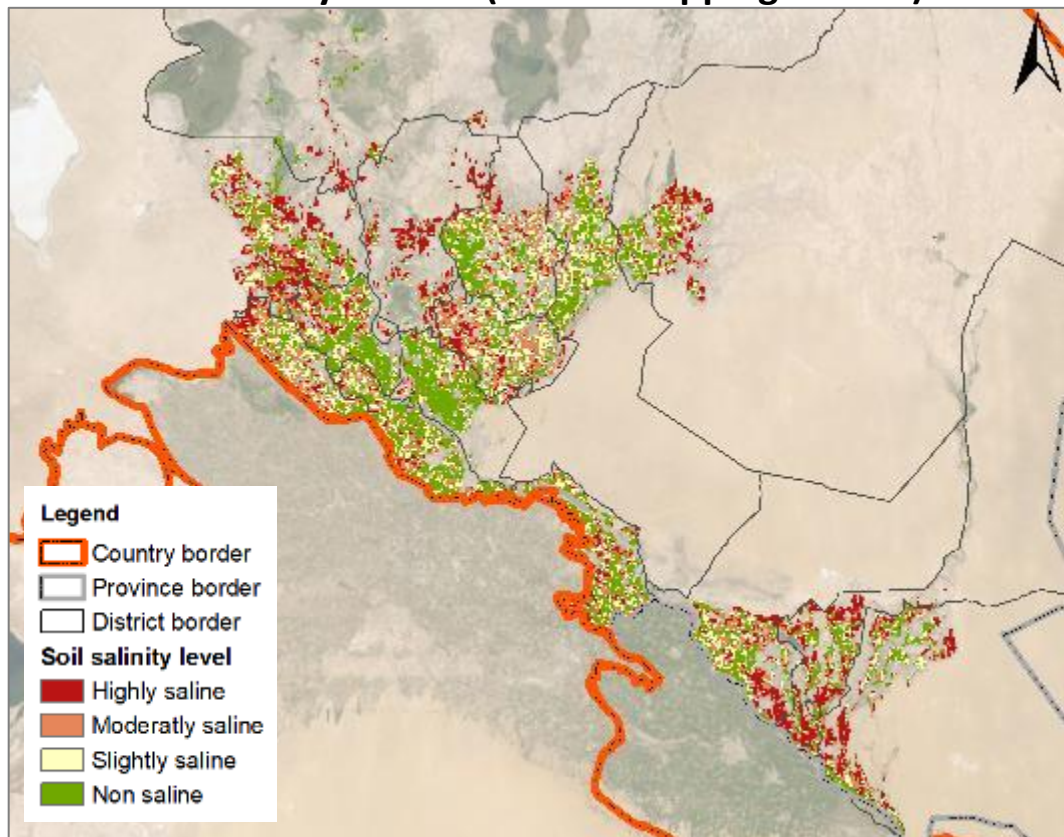
Soil salinity in 2010 (winter cropping season)



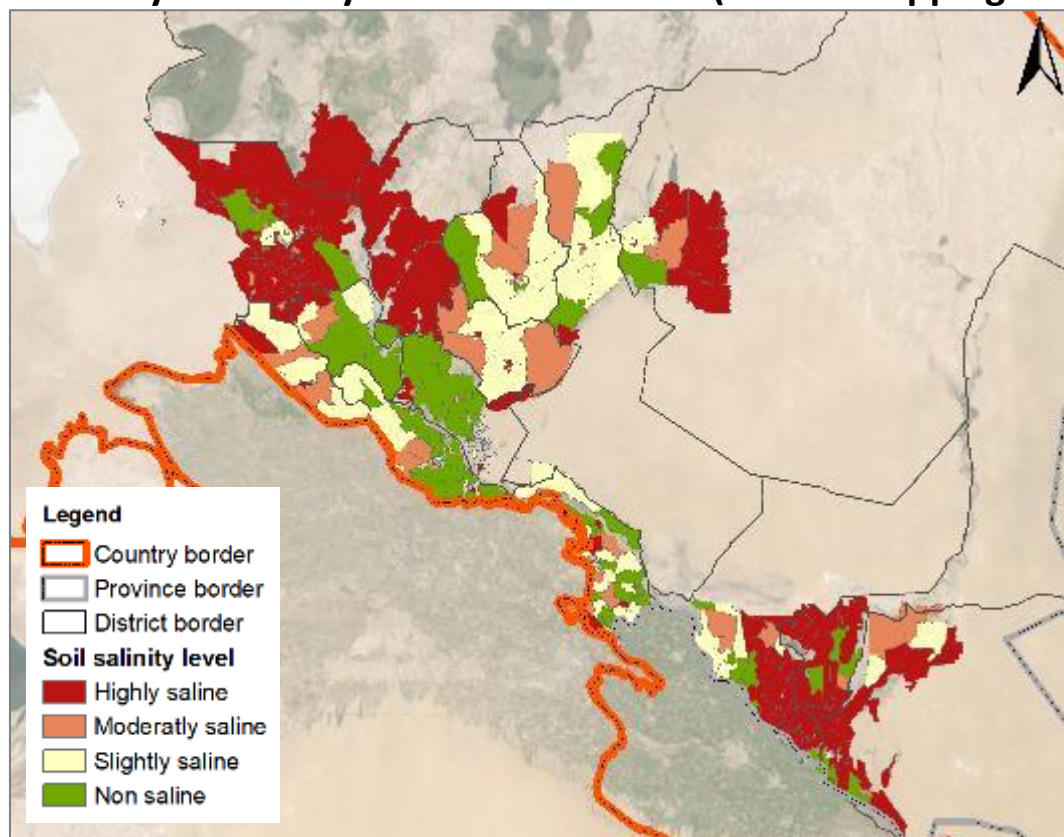
Soil salinity in 2010 by district boundaries (winter cropping season)



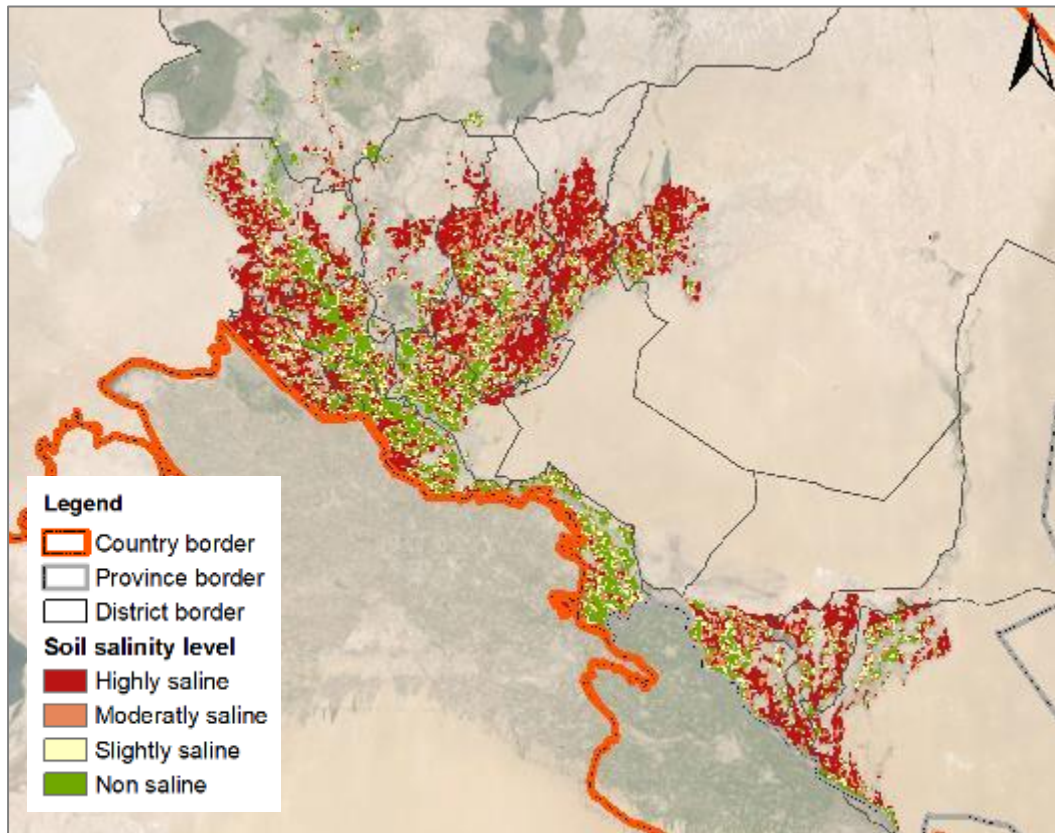
Soil salinity in 2015 (winter cropping season)



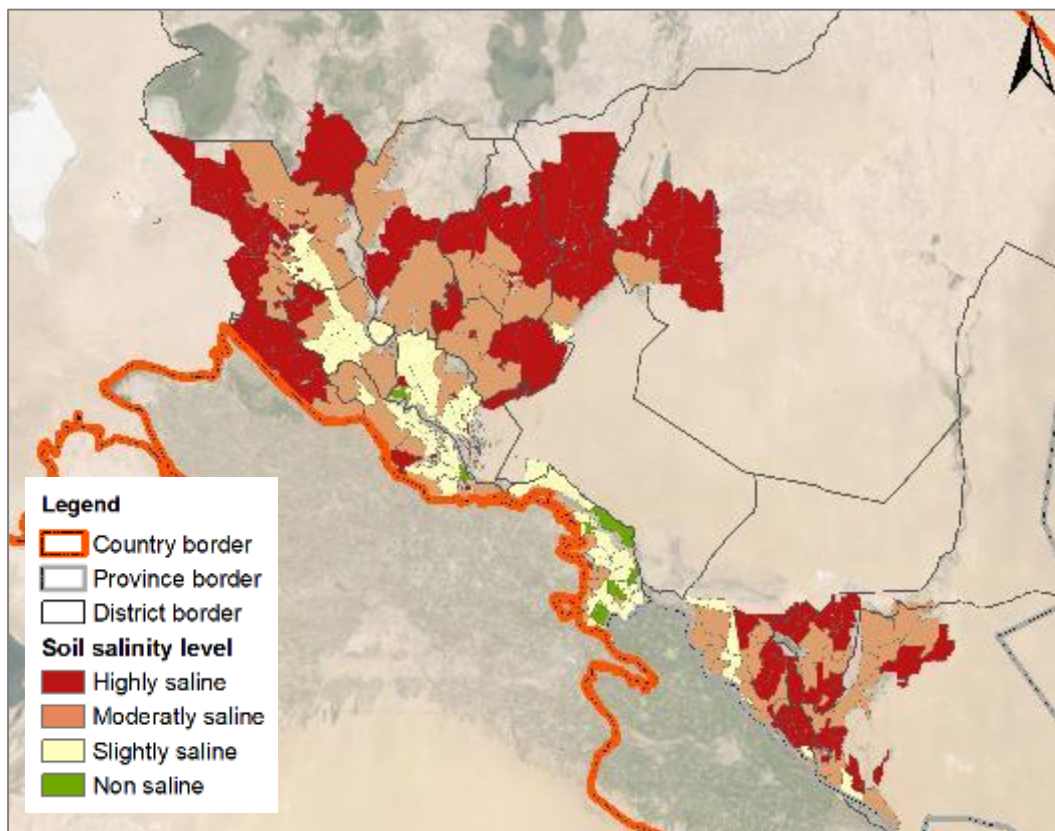
Soil salinity in 2015 by district boundaries (winter cropping season)



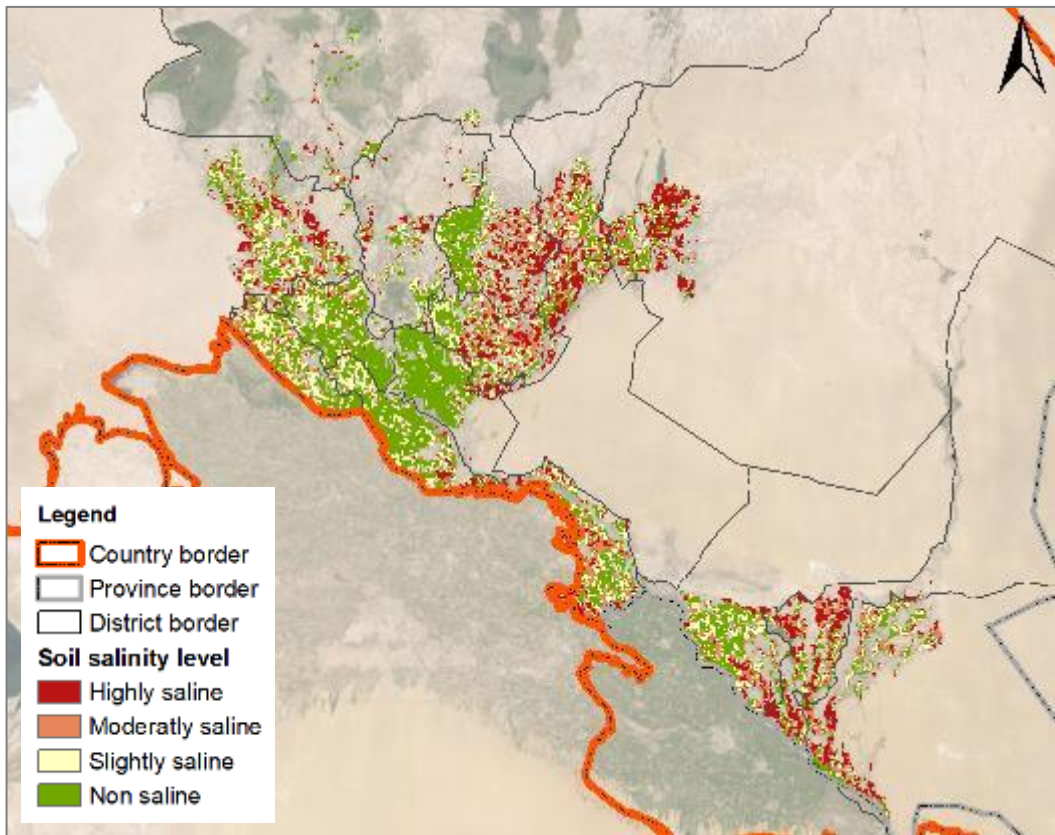
Soil salinity in 2020 (winter cropping season)



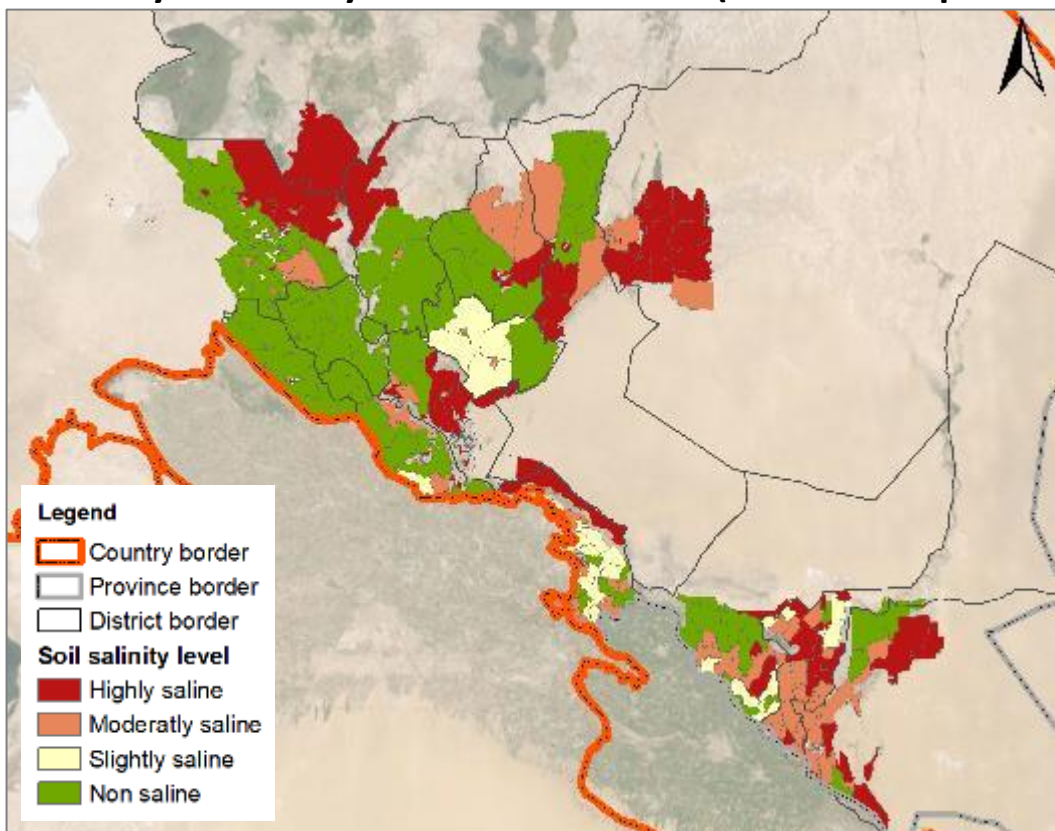
Soil salinity in 2020 by district boundaries (winter cropping season)



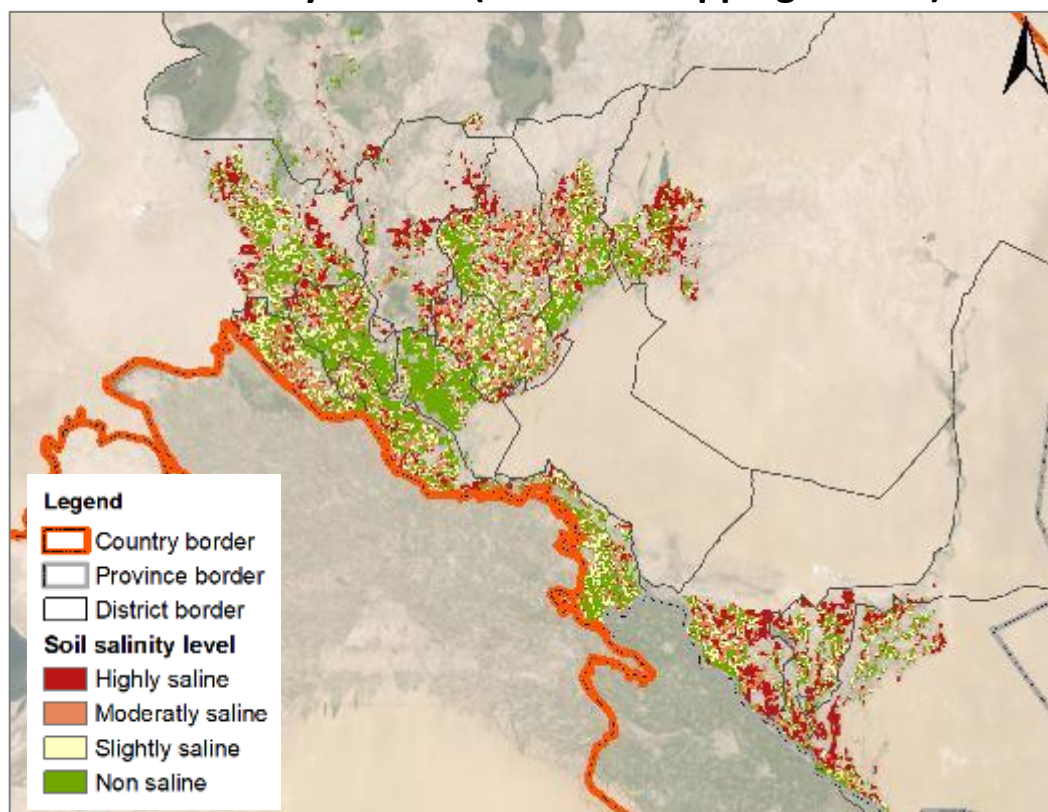
Soil salinity in 2005 (summer crop season)



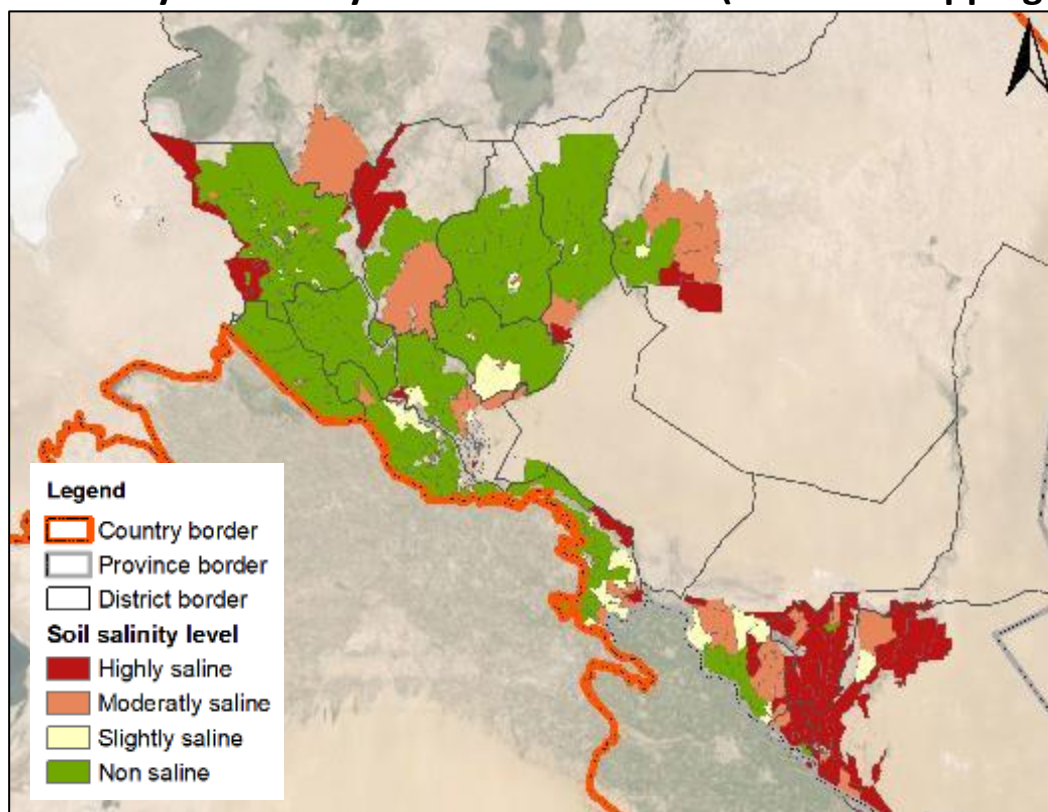
Soil salinity in 2005 by district boundaries (summer crop season)



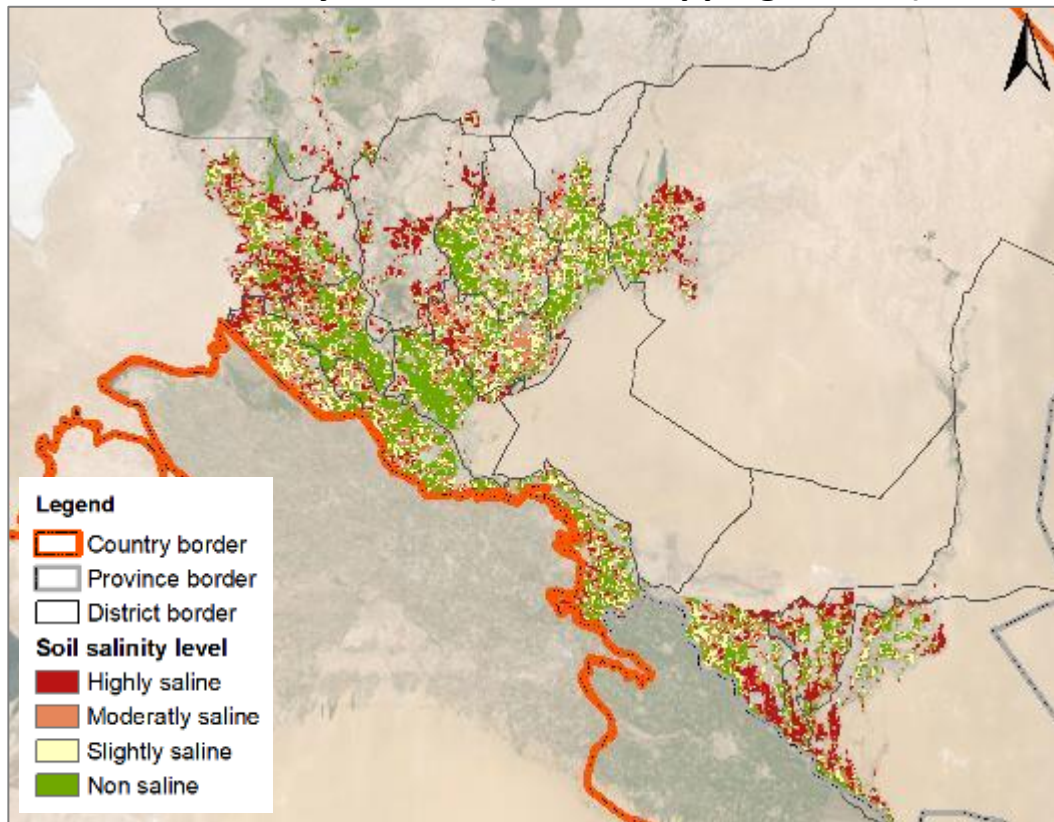
Soil salinity in 2010 (summer cropping season)



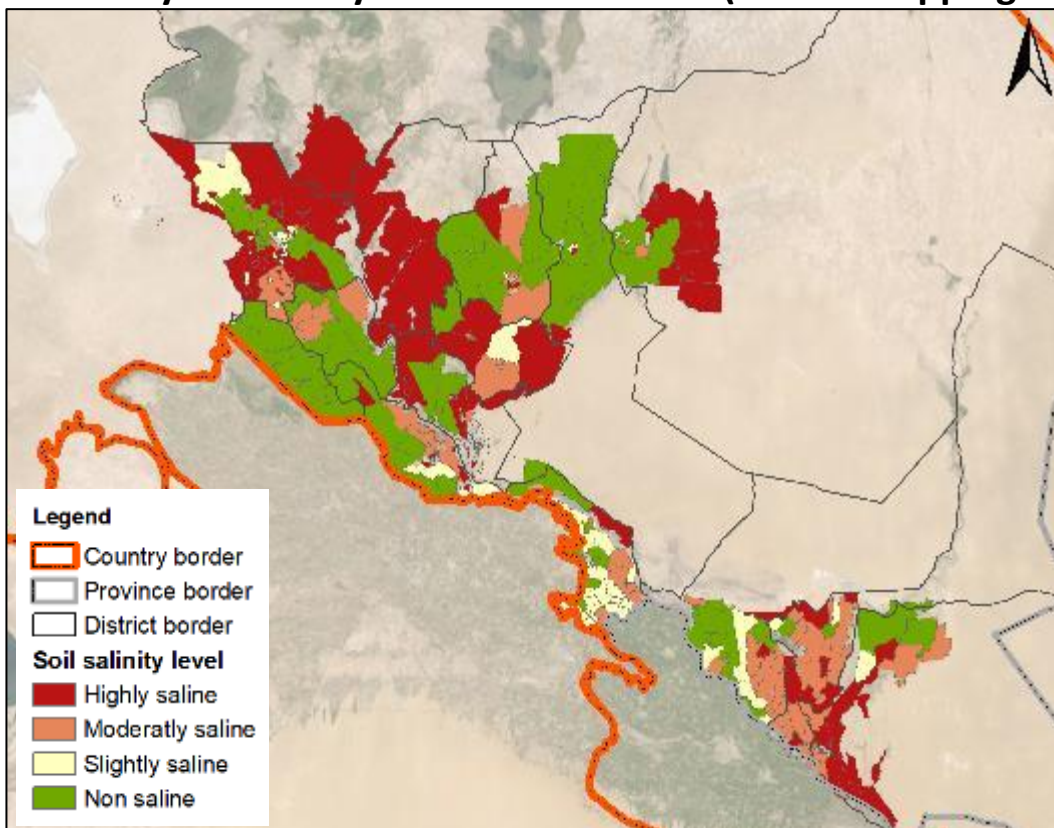
Soil salinity in 2010 by district boundaries (summer cropping season)



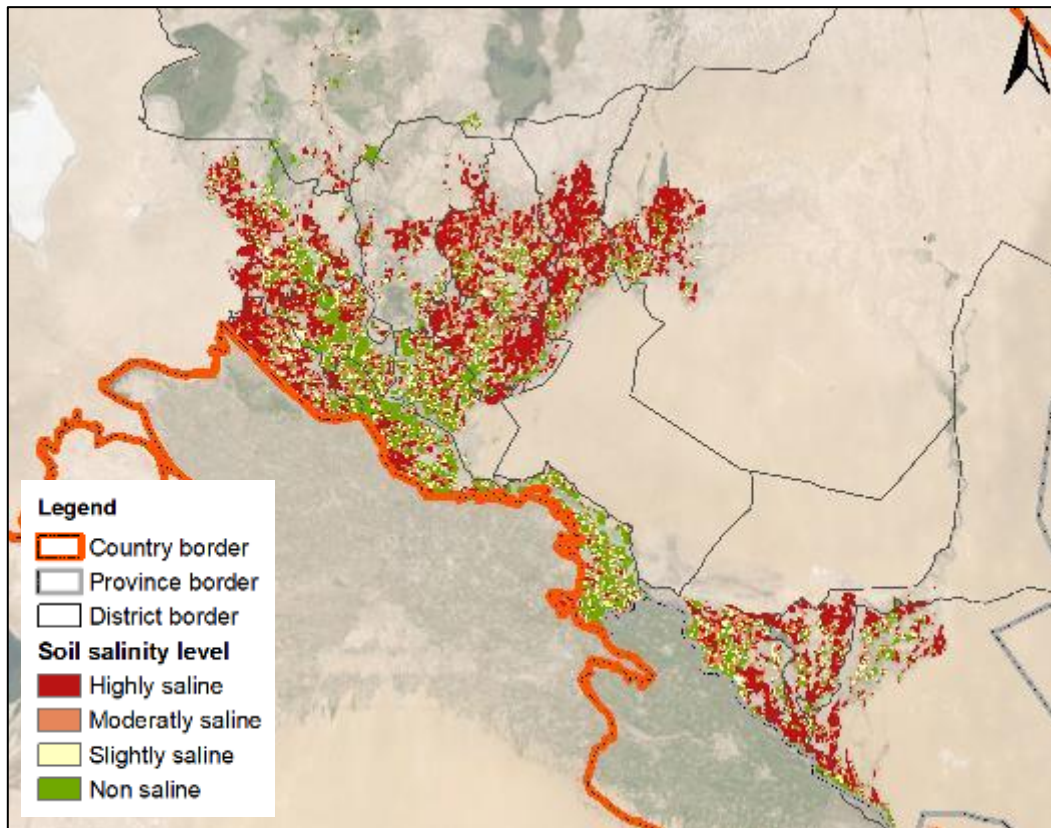
Soil salinity in 2015 (winter cropping season)



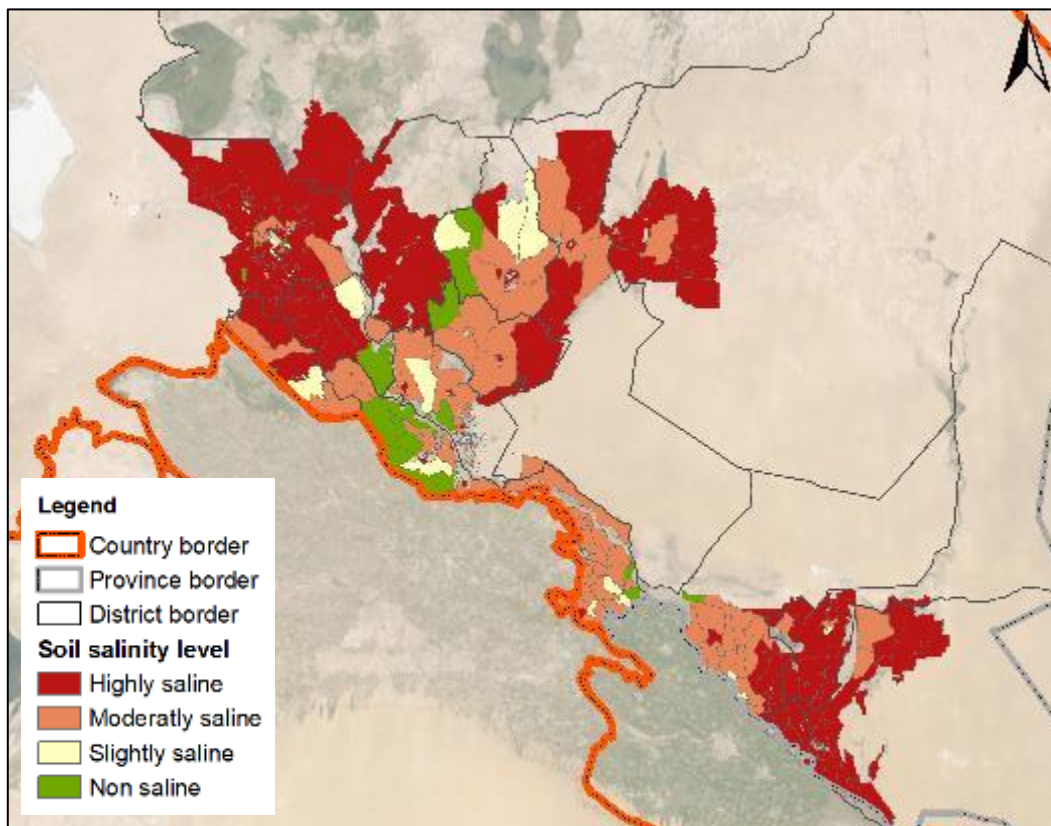
Soil salinity in 2015 by district boundaries (winter cropping season)



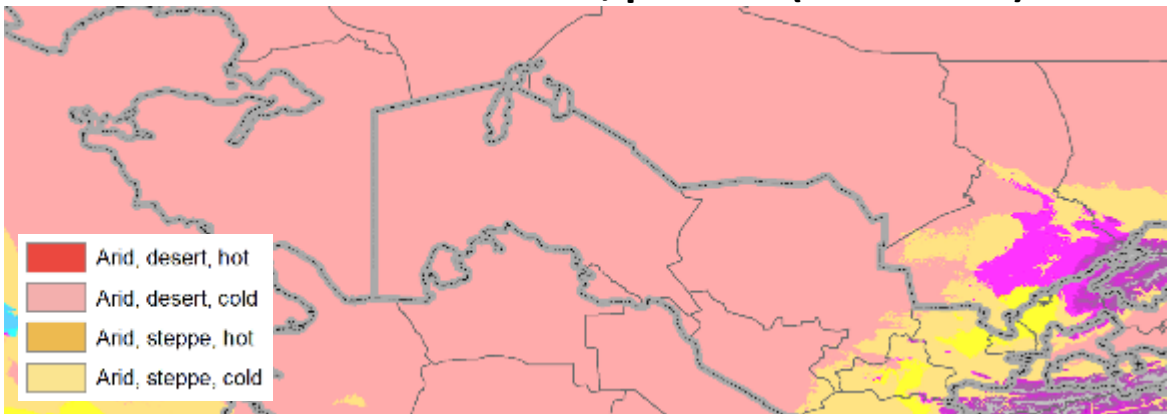
Soil salinity in 2020 (summer cropping season)



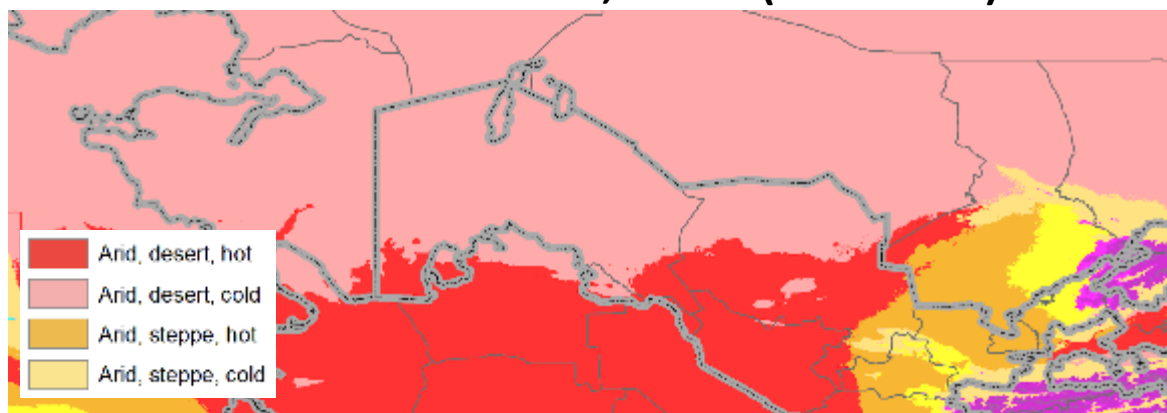
Soil salinity in 2020 by district boundaries (summer cropping season)



Climate classification, present (1980-2016)



Climate classification, future (2070-2100)

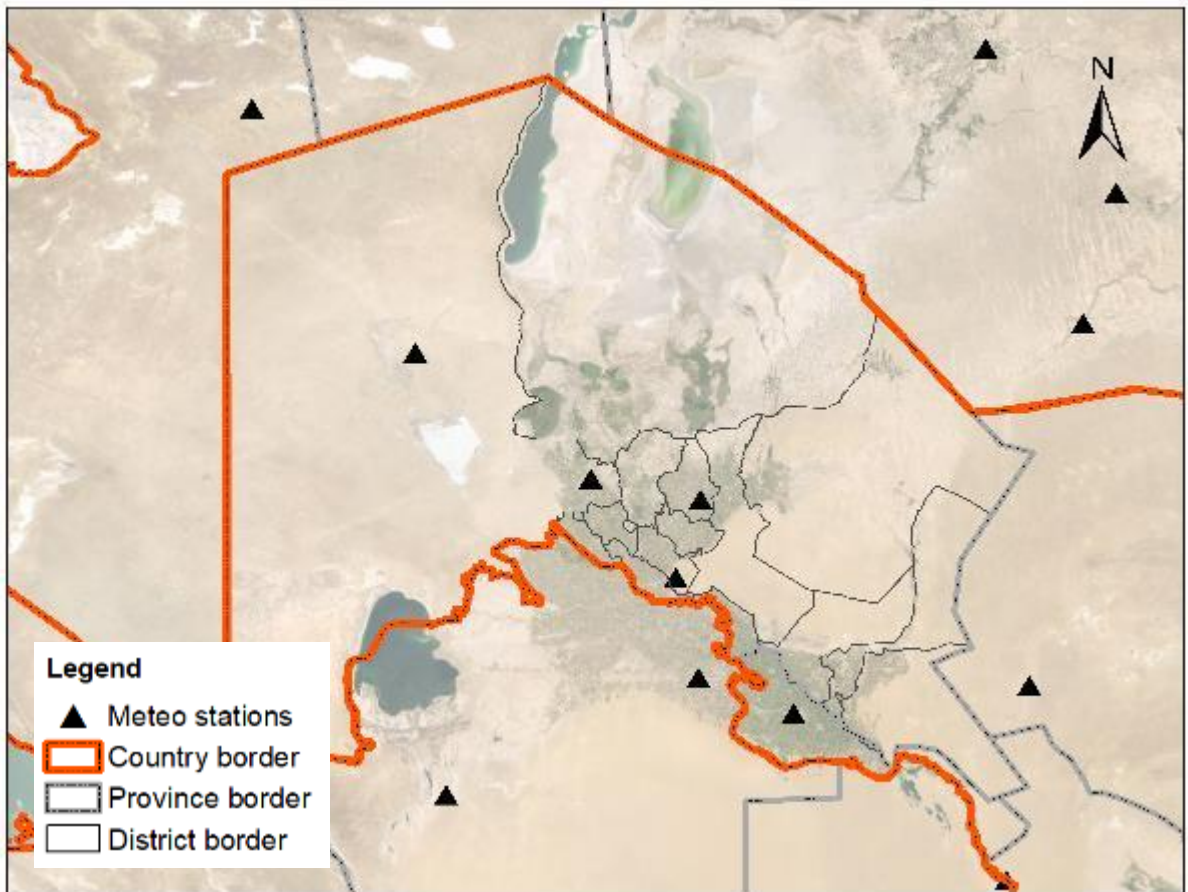


Source: Present and future Köppen-Geiger climate classification maps (Beck et al. 2018).

The climate in the study area is continental and arid, with an annual rainfall of about 120 mm. The climate of Karakalpakstan falls into the BWwk Köppen-Geiger climate class (Peel et al. 2007). According to the ICARDA map of Agroclimatic Zones (Celis et al. 2007) the site belongs to zone 310 which is arid climates with cool or cold winters and warm or very warm summers. The area is characterized by sharply continental and dry climate (with hot summers and cold winters) with strong fluctuations of temperatures both daily and seasonally, with an annual rainfall of about 120 mm. Desert winds are common. Following the cold winter, spring is notoriously short and immediately followed by hot, dry and long summers (Glazirin et al. 1999). The maximum temperature in the region is in July-August with an average of between +24.6 and +27.4° C and with a minimum of – 9.6° C in January. The mean annual precipitation in the form of snow and rain varies from 60 up to 180 mm. Precipitation occurs predominantly during the cold period with roughly 28% of the annual precipitation falling as snow in winter and about 61% in spring and autumn as rain. The number of frost days varies from 90 to 110.

The Köppen-Geiger system classifies climate into five main classes and 30 sub- types. The classification is based on threshold values and seasonality of monthly air temperature and precipitation. Considering vegetation as “crystallized, visible climate”, this classification empirically maps biome distributions around the world: different regions in a similar class share common vegetation characteristics (Beck et al. 2018).

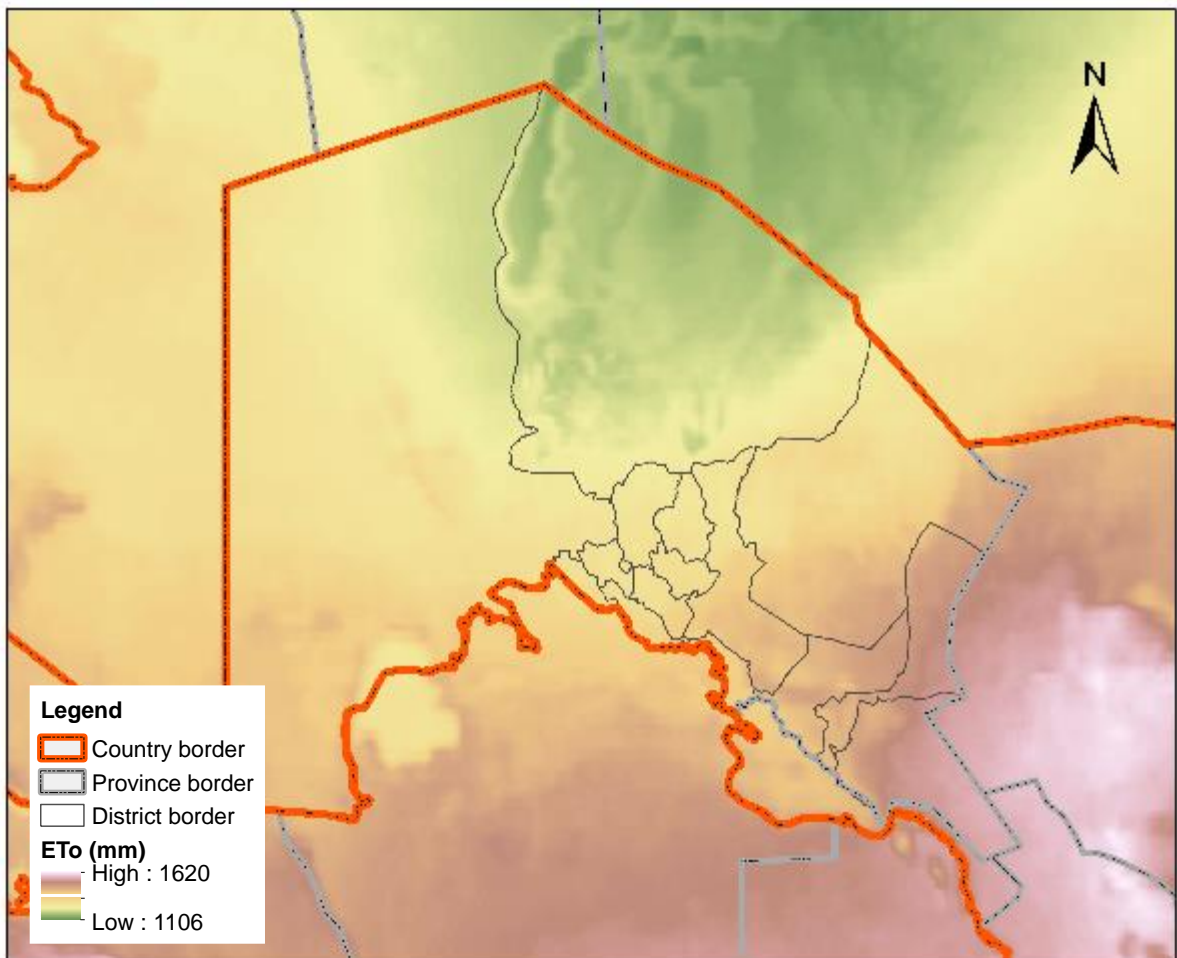
Meteorologic stations



The Centre for Hydro-Meteorological Services (Uzhydromet 2022) is a specialized governmental agency vested with tasks, matters, and concerns in the field of hydrometeorology in the Republic of Uzbekistan.

Uzhydromet performs hydro-meteorological and agro-meteorological observations on the entire territory of the Republic of Uzbekistan. The responsibility of Uzhydromet also extends over the stations for long-term observations. The main objectives and tasks of hydrometeorological monitoring are to generate and provide the users with hydrometeorological data, forecasts and analytical information. In our study area we use meteorological data (i.e., precipitation, temperature, solar radiation, relative humidity, wind speed) from 4 weather stations (Chimbai, Jaslyk, Kungrad and Nukus). A wide range of data is necessary to adequately monitor the status of climate and water supply (i.e., precipitation, temperature, stream flow, ground water and reservoir levels, soil moisture, snow pack). These data are often not available at the density required for accurate assessments. Given climate change, seasonal forecasts and warning systems should be also linked with water user and farmer groups as well as extension services for the warnings to be effectively and timely delivered (World Bank 2015).

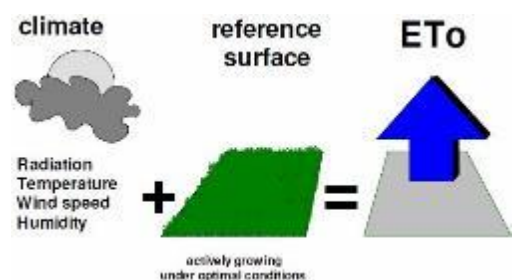
Average annual reference evapotranspiration (ET_o) (1991-2020)



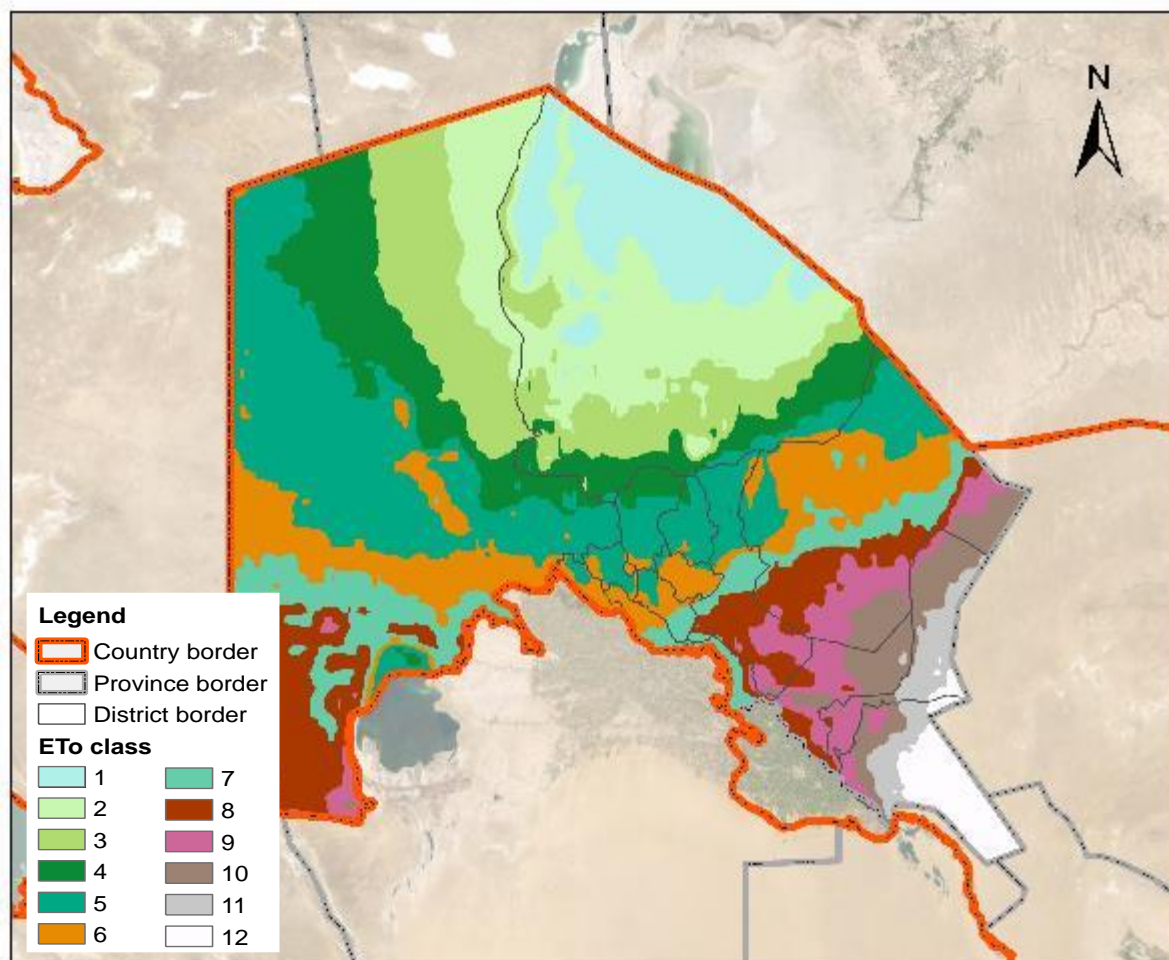
Source: TerraClimate (Abatzoglou et al. 2018).

Reference evapotranspiration (ET_o) is the evapotranspiration rate from a clearly defined reference surface. The concept was introduced to allow the estimation of the evaporative demand of the atmosphere independently of crop type, crop development or management practices. ET_o corresponds to the evapotranspiration from a hypothetical extensive well-watered field covered with 12 cm height green grass having an albedo of 0.23 under the given down-welling short-wave radiation.

TerraClimate is a dataset of monthly climate and climatic water balance for global terrestrial surfaces. It uses climatically aided interpolation, combining high-spatial resolution climatological normals from the WorldClim dataset, with coarser spatial resolution, but time-varying data from CRU Ts4.0 and the Japanese 55-year Reanalysis (JRA55) (Abatzoglou et al. 2018).



Reference evapotranspiration (ET_o) zones (1991-2020)



Monthly Average Reference Evapotranspiration by ETo Zone (mm/month)

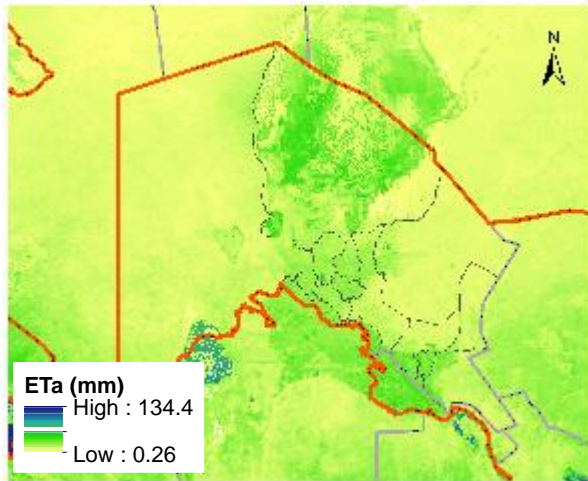
Zone	Area (%)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Sum
1	8%	1	0	22	106	171	209	221	201	133	78	20	3	1166
2	12%	1	1	31	109	174	213	225	205	136	80	18	2	1196
3	11%	1	1	37	114	181	221	230	207	136	79	16	2	1223
4	10%	1	2	45	119	184	225	234	209	137	79	17	1	1253
5	19%	1	4	55	123	186	229	237	210	140	80	19	2	1285
6	10%	2	6	63	125	188	231	238	212	142	82	22	3	1313
7	7%	2	9	70	127	191	235	243	215	146	84	25	4	1350
8	9%	3	11	74	127	192	237	247	218	149	86	28	5	1377
9	5%	3	12	77	132	198	242	250	221	150	85	28	5	1404
10	4%	3	11	79	135	205	250	258	228	156	85	27	3	1442
11	2%	3	14	84	139	208	254	265	234	161	88	29	4	1484
12	2%	5	20	89	140	209	256	271	238	166	92	35	7	1526

Source: TerraClimate (Abatzoglou et al. 2018).

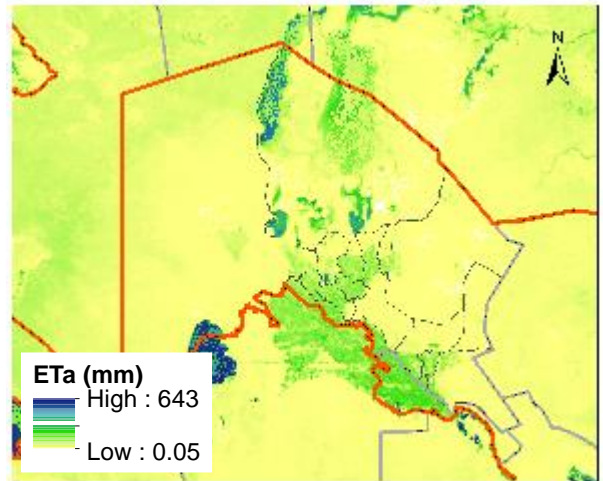
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Average annual actual evapotranspiration (1991-2020)

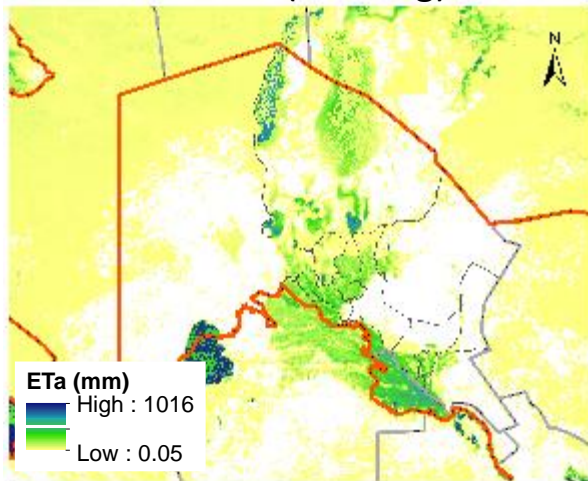
Winter (Dec-Feb)



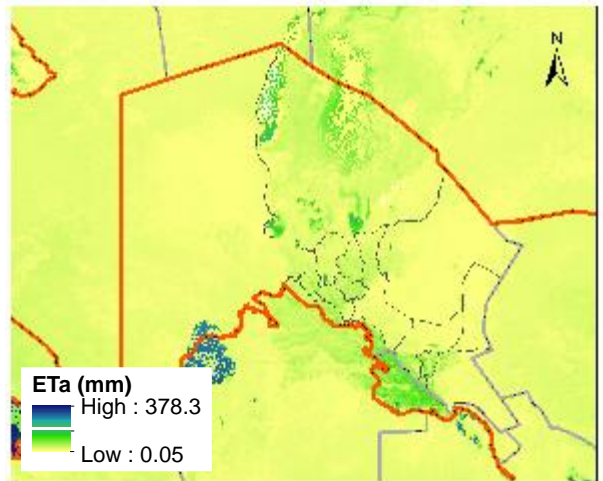
Spring (Mar-May)



Summer (Jun-Aug)



Fall (Sep-Nov)



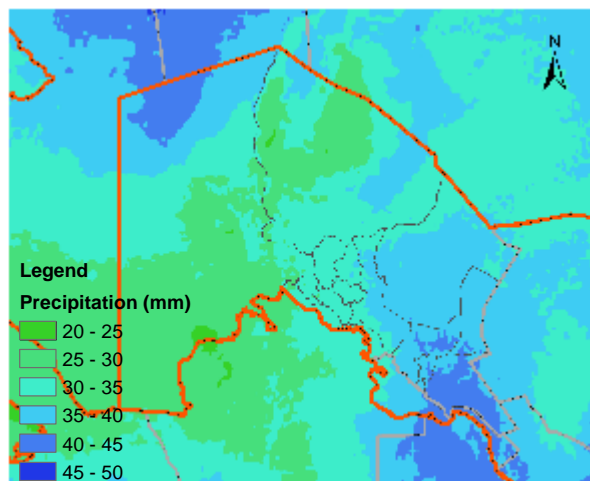
Source: Senay et al. 2020.

Evapotranspiration (ET), for the most part, is the combination of transpiration from vegetation and evaporation from soil surfaces.

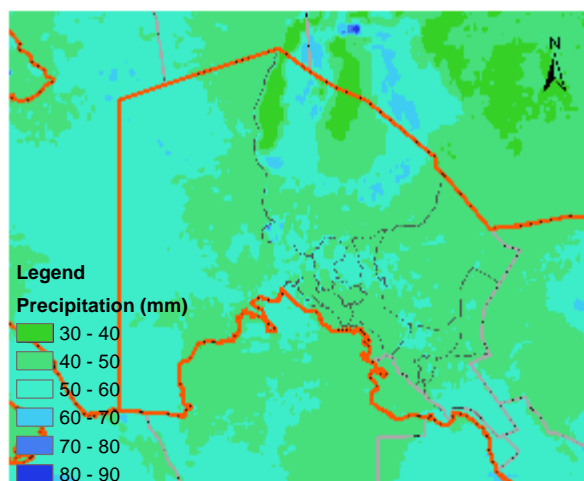
Actual ET (ETa) is produced using the Operational Simplified Surface Energy Balance (SSEBop) model for 2003 to present. The SSEBop setup is based on the Simplified Surface Energy Balance (SSEB) approach with unique parameterization for operational applications. It combines ET fractions generated from remotely sensed Moderate Resolution Imaging Spectroradiometer (MODIS) thermal imagery, acquired every 10 days, with reference ET using a thermal index approach. The unique feature of the SSEBop parameterization is that it uses a pre-defined, seasonally and spatially dynamic surface psychrometer parameter to calculate ET fraction as the difference between observed LST (dry-bulb) and a cold/wet boundary condition (wet-bulb) using the principle of satellite psychrometry (Senay et al. 2020).

Average annual precipitation (1991-2020)

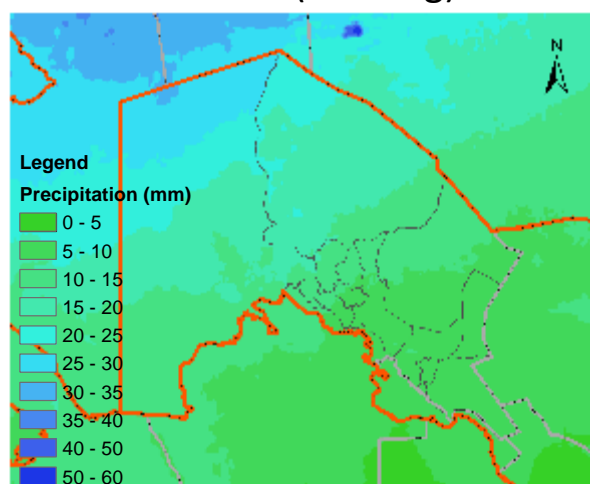
Winter (Dec-Feb)



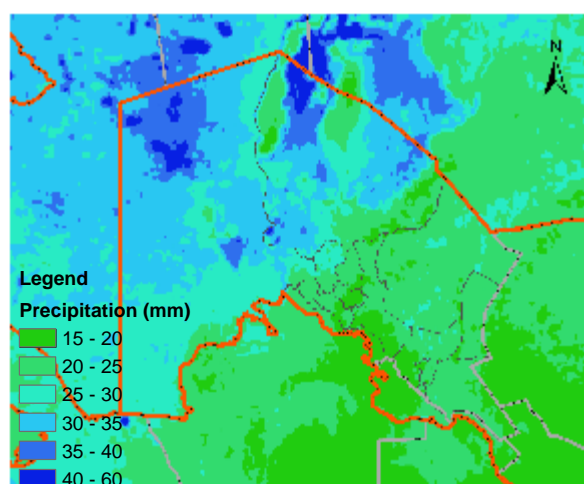
Spring (Mar-May)



Summer (Jun-Aug)



Fall (Sep-Nov)

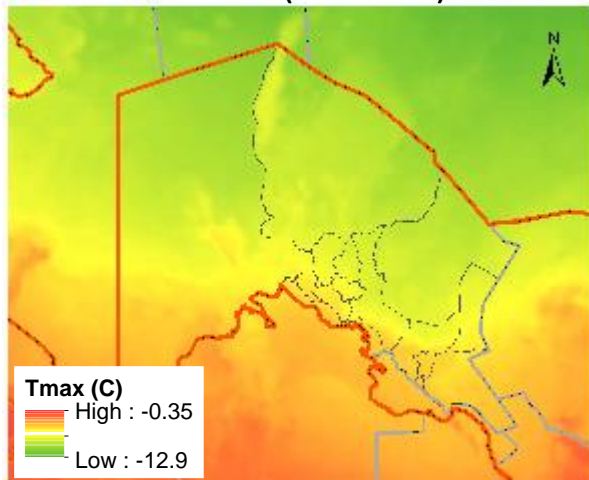


Source: TerraClimate (Abatzoglou et al. 2018).

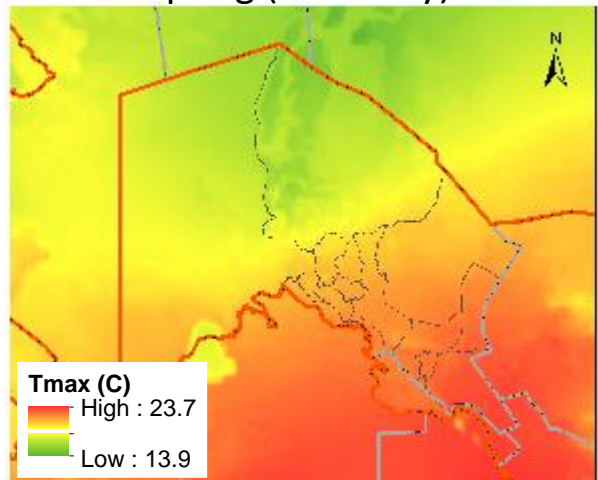
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Average seasonal maximum temperature (1991-2020)

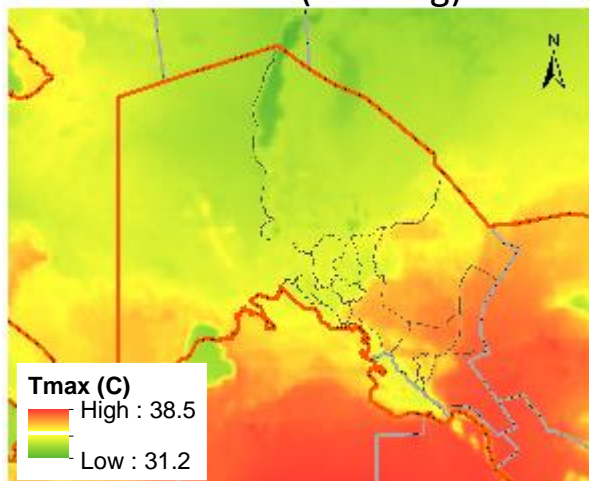
Winter (Dec-Feb)



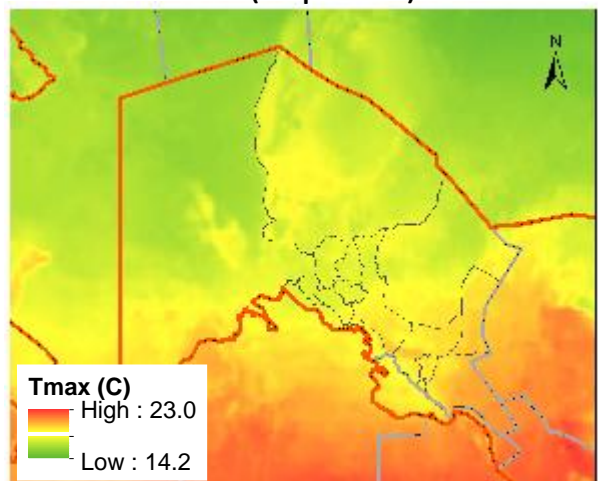
Spring (Mar-May)



Summer (Jun-Aug)



Fall (Sep-Nov)

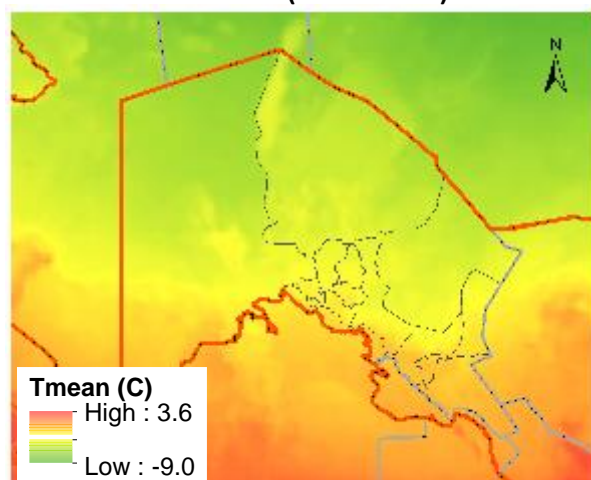


Source: TerraClimate (Abatzoglou et al. 2018).

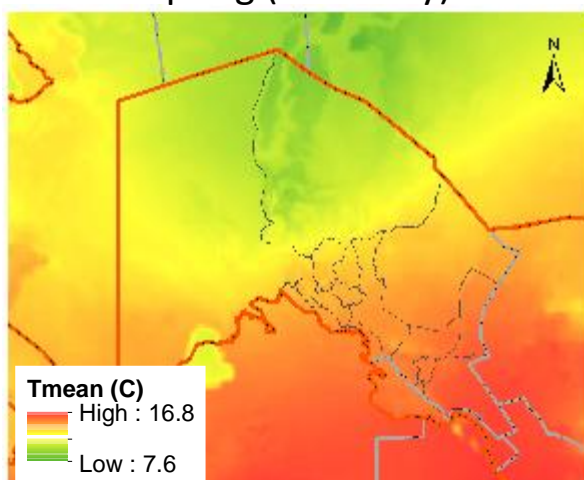
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Average seasonal mean temperature (1991-2020)

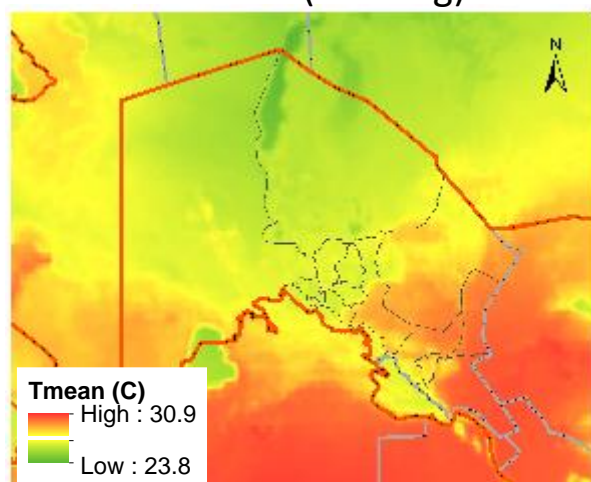
Winter (Dec-Feb)



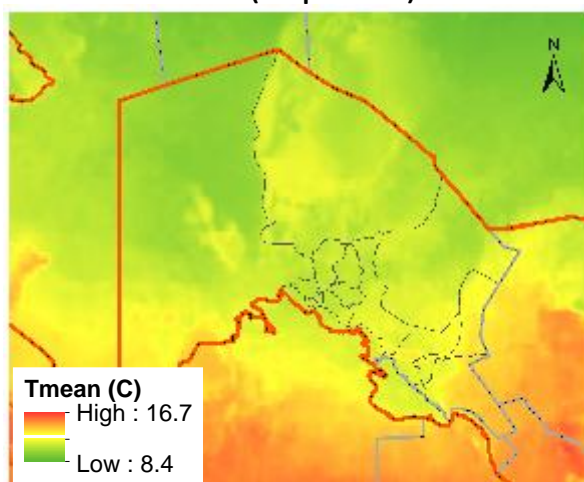
Spring (Mar-May)



Summer (Jun-Aug)



Fall (Sep-Nov)

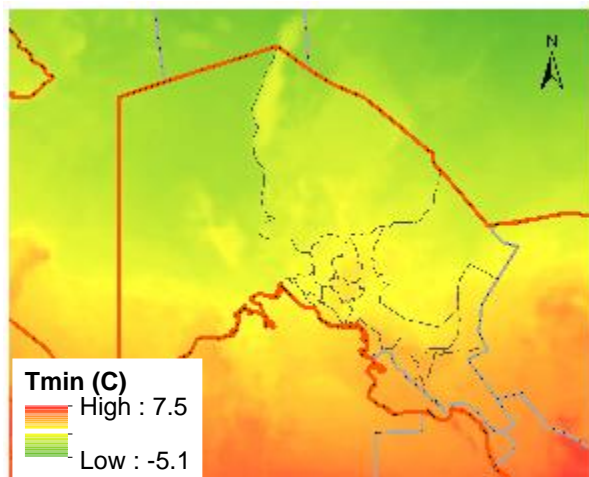


Source: TerraClimate (Abatzoglou et al. 2018).

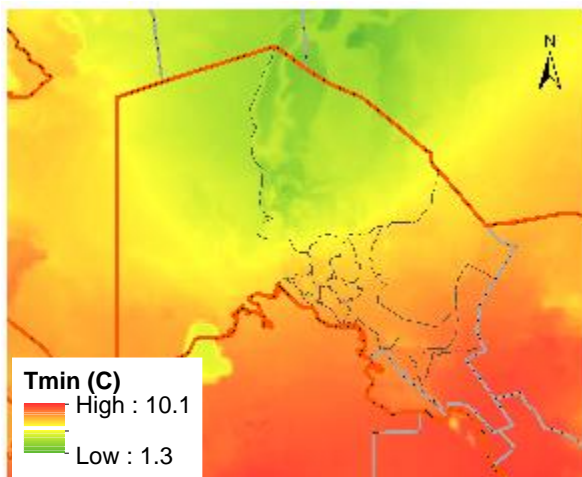
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Average seasonal min temperature (1991-2020)

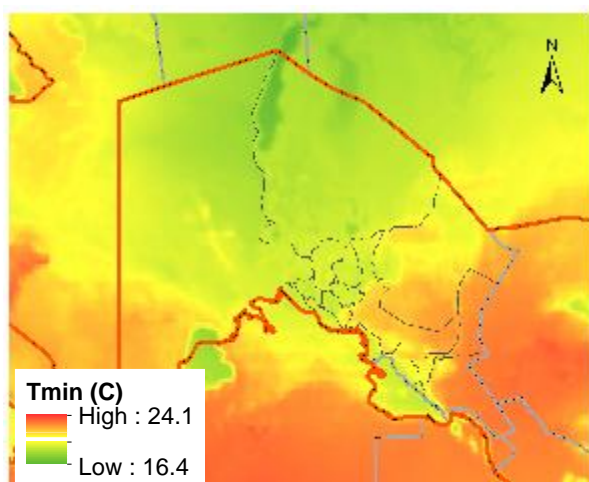
Winter (Dec-Feb)



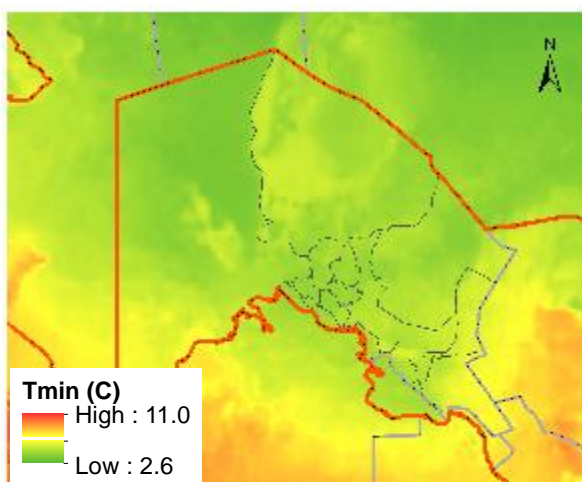
Spring (Mar-May)



Summer (Jun-Aug)



Fall (Sep-Nov)

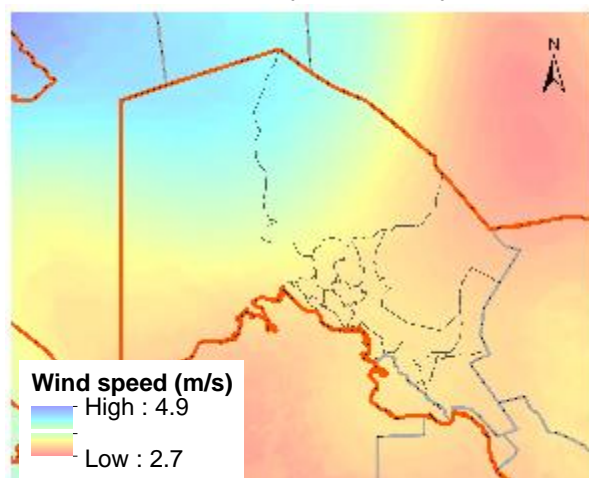


Source: TerraClimate (Abatzoglou et al. 2018).

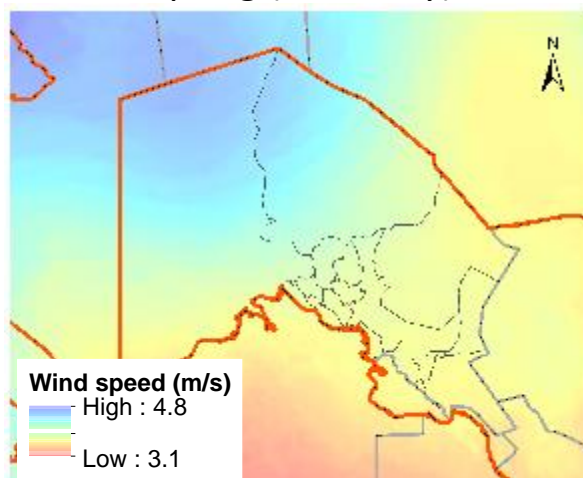
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Average seasonal wind (1991-2020)

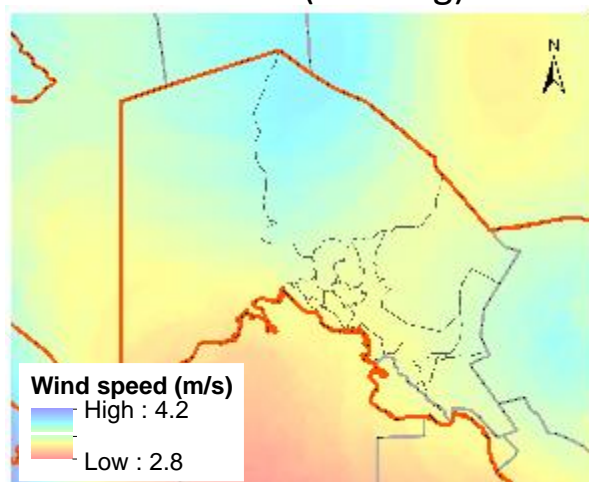
Winter (Dec-Feb)



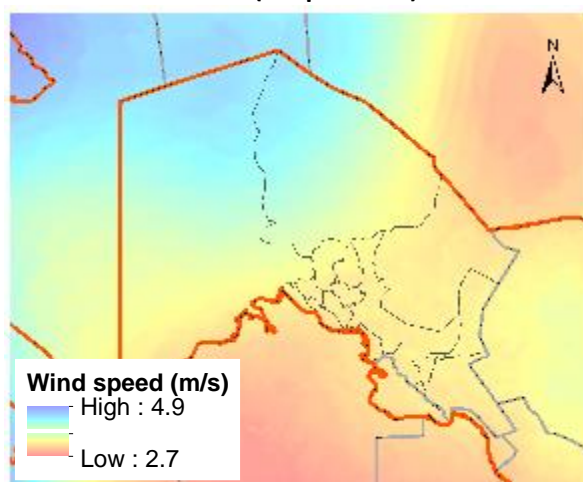
Spring (Mar-May)



Summer (Jun-Aug)



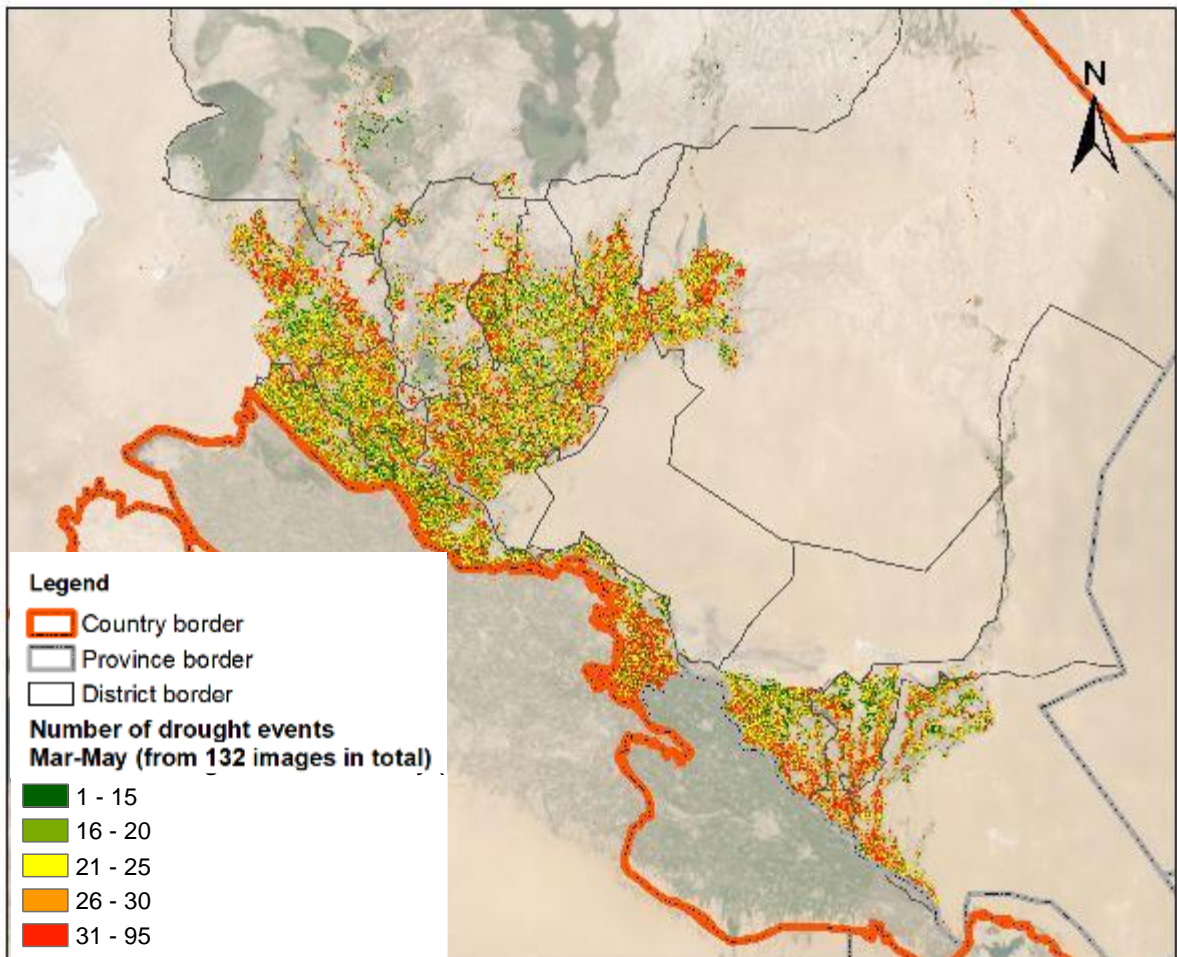
Fall (Sep-Nov)



Source: TerraClimate (Abatzoglou et al. 2018).

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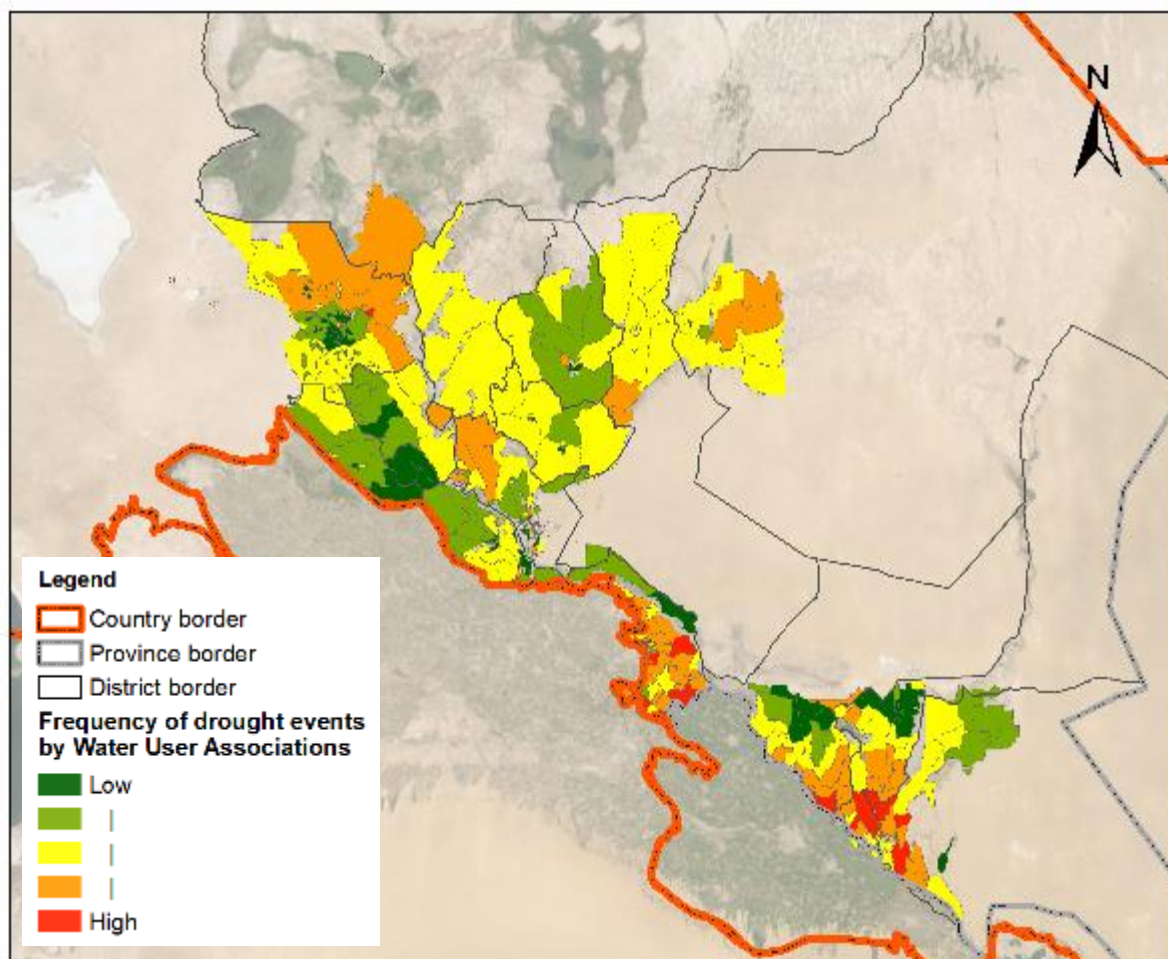
Location of champion farms Winter crops (March-May, 2000-2020)



Drought is a recurring phenomenon that can lead to significant losses to societies affecting different aspects of human life such as agriculture, food security, and the environment. Traditional methods of drought assessment and monitoring rely on rainfall data. However, this approach has two main disadvantages: rainfall data are limited to the region, and they are often inaccurate and difficult to obtain in near-real time. In contrast, satellite-sensor data is continuously available and can be used to detect the onset of a drought, its duration and magnitude. Availability, simplicity, free of charge data, good research literature and citation, minimum requirements of inputs are main criteria, which have been considered to define the methodology.

Kogan (1990) proposed a Vegetation Condition Index (VCI) based on the relative Normalized Difference Vegetation Index (NDVI) change with respect to minimum historical NDVI value. The VCI, therefore compares the current Vegetation Index (VI) such as NDVI or Enhanced Vegetation Index (EVI) to the values observed in the same period in previous years **within a specific pixel**.

Districts with champion farms: Winter crops (March-May, 2000-2020)



The VCI is calculated as shown here,

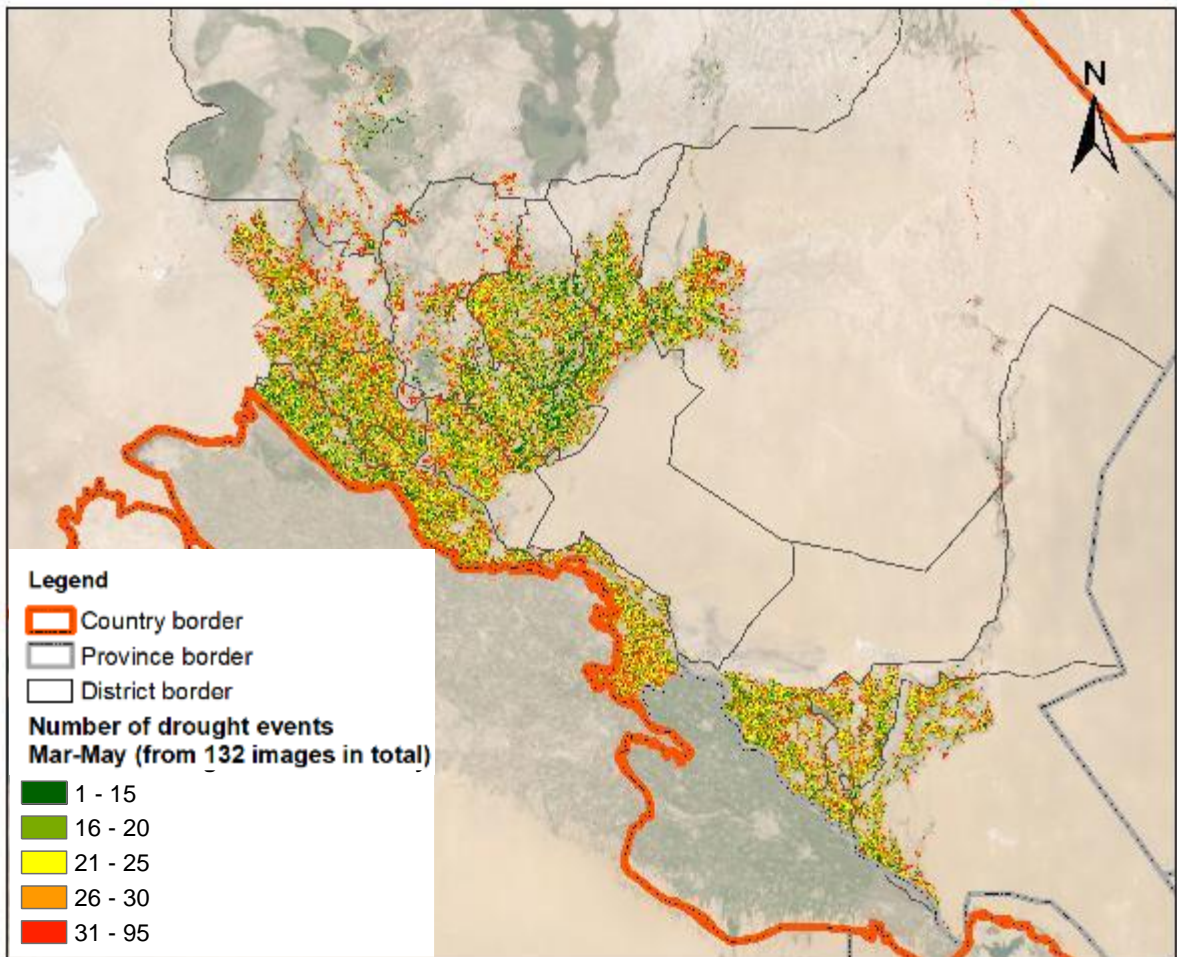
$$VCI_{ijk} = \frac{VI_{ijk} - VI_{i,min}}{VI_{i,max} - VI_{i,min}} * 100$$

where VCI_{ijk} is the VCI value for the pixel i during week/month/DOY j for year k , VI_{ijk} is the weekly/monthly/DOYs VI value for pixel i in week/month/DOY j for year k whereby both the NDVI or EVI can be utilized as VI, $VI_{i,min}$ and $VI_{i,max}$ are the multiyear minimum and maximum VI, respectively, for pixel i .

Consequently, the frequency of Severe Drought cases will be calculated for each pixel in the study area that assist us define the most stable, climate resilient and less vulnerable agricultural lands.

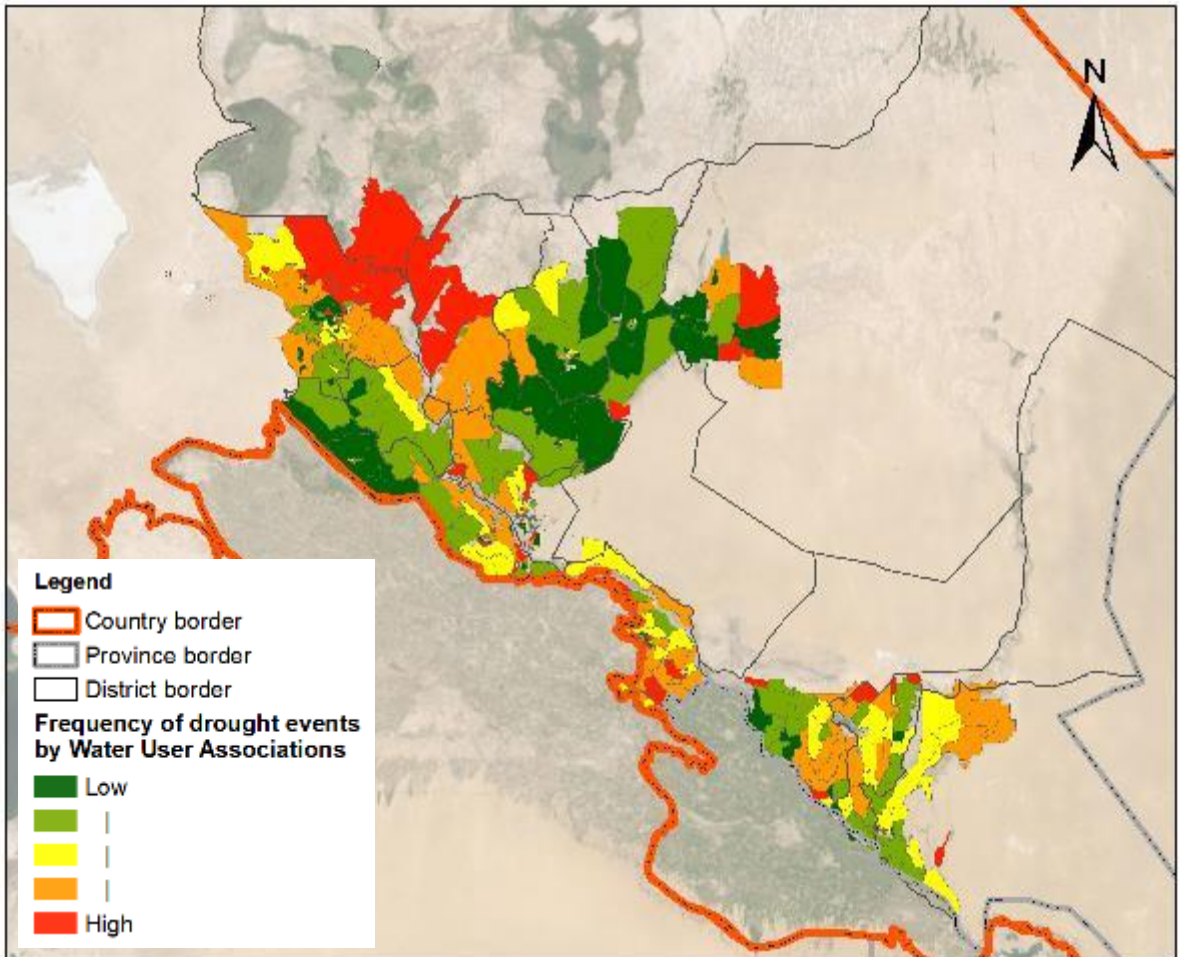
Value	Category
90 - 100 %	No Drought
80 - 90 %	No Drought
70 - 80 %	No Drought
60 - 70 %	No Drought
50 - 60 %	No Drought
40 - 50 %	No Drought
30 - 40 %	Light Drought
20 - 30 %	Moderate Drought
10 - 20 %	Severe Drought
0 - 10 %	Extreme Drought

Location of champion farms Summer crops (June-August, 2000-2020)



Drought is a recurring phenomenon that can lead to significant losses to societies affecting different aspects of human life such as agriculture, food security, and the environment. Traditional methods of drought assessment and monitoring rely on rainfall data. However, this approach has two main disadvantages: rainfall data are limited to the region, and they are often inaccurate and difficult to obtain in near-real time. In contrast, satellite-sensor data is continuously available and can be used to detect the onset of a drought, its duration and magnitude. Availability, simplicity, free of charge data, good research literature and citation, minimum requirements of inputs are main criteria, which have been considered to define the methodology.

Districts with champion farms: Summer crops (June-August, 2000-2020)



The VCI is calculated as shown here,

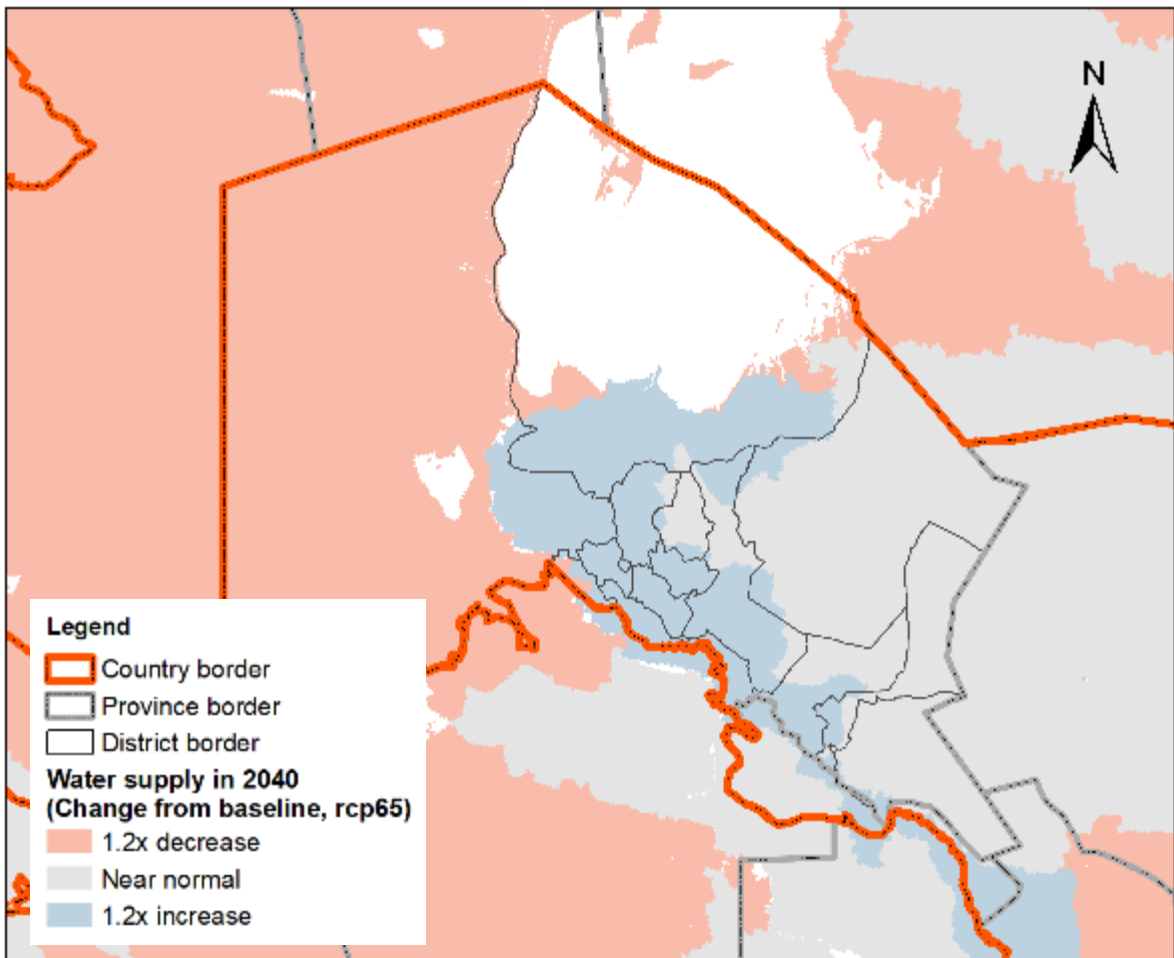
$$VCI_{ijk} = \frac{VI_{ijk} - VI_{i,min}}{VI_{i,max} - VI_{i,min}} * 100$$

where VCI_{ijk} is the VCI value for the pixel i during week/month/DOY j for year k , VI_{ijk} is the weekly/monthly/DOYs VI value for pixel i in week/month/DOY j for year k whereby both the NDVI or EVI can be utilized as VI, $VI_{i,min}$ and $VI_{i,max}$ are the multiyear minimum and maximum VI, respectively, for pixel i .

Consequently, the frequency of Severe Drought cases will be calculated for each pixel in the study area that assist us define the most stable, climate resilient and less vulnerable agricultural lands.

Value	Category
90 - 100 %	No Drought
80 - 90 %	No Drought
70 - 80 %	No Drought
60 - 70 %	No Drought
50 - 60 %	No Drought
40 - 50 %	No Drought
30 - 40 %	Light Drought
20 - 30 %	Moderate Drought
10 - 20 %	Severe Drought
0 - 10 %	Extreme Drought

Water supply in 2040, rcp65

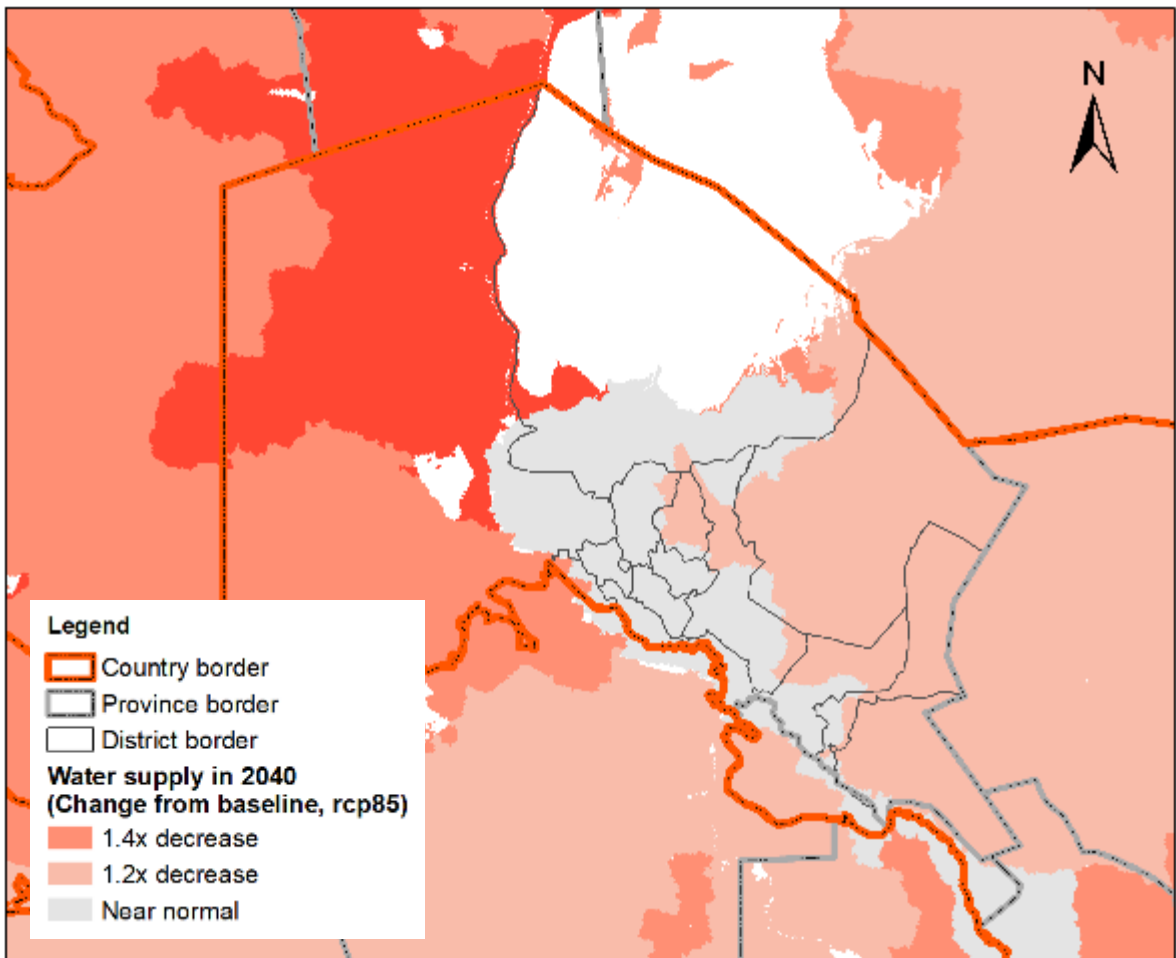


Source: *Aqueduct's tools* (Luck et al. 2015).

Total blue water (renewable surface water) was our indicator of water supply. Projected change in total blue water is equal to the 21-year mean around the target year divided by the baseline period of 1950–2010.

Aqueduct's tools map water risks such as floods, droughts, and stress, using open-source, peer reviewed data. Beyond the tools, the Aqueduct team works one-on-one with companies, governments, and research partners to help advance best practices in water resources management and enable sustainable growth in a water-constrained world (Luck et al. 2015).

Water supply in 2040, rcp85

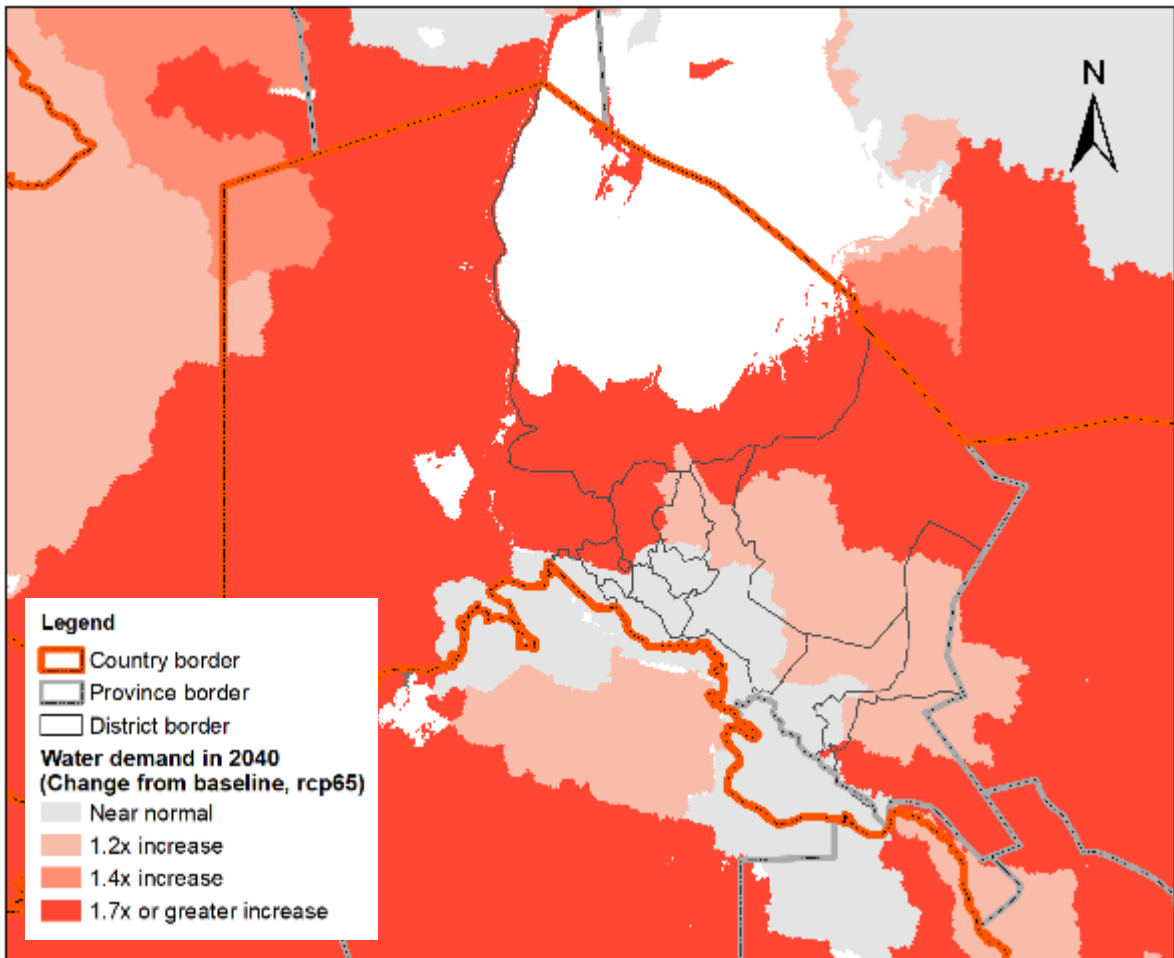


Source: Aqueduct's tools (Luck et al. 2015).

Total blue water (renewable surface water) was our indicator of water supply. Projected change in total blue water is equal to the 21-year mean around the target year divided by the baseline period of 1950–2010.

Aqueduct's tools map water risks such as floods, droughts, and stress, using open-source, peer reviewed data. Beyond the tools, the Aqueduct team works one-on-one with companies, governments, and research partners to help advance best practices in water resources management and enable sustainable growth in a water-constrained world (Luck et al. 2015).

Water demand in 2040, rcp65

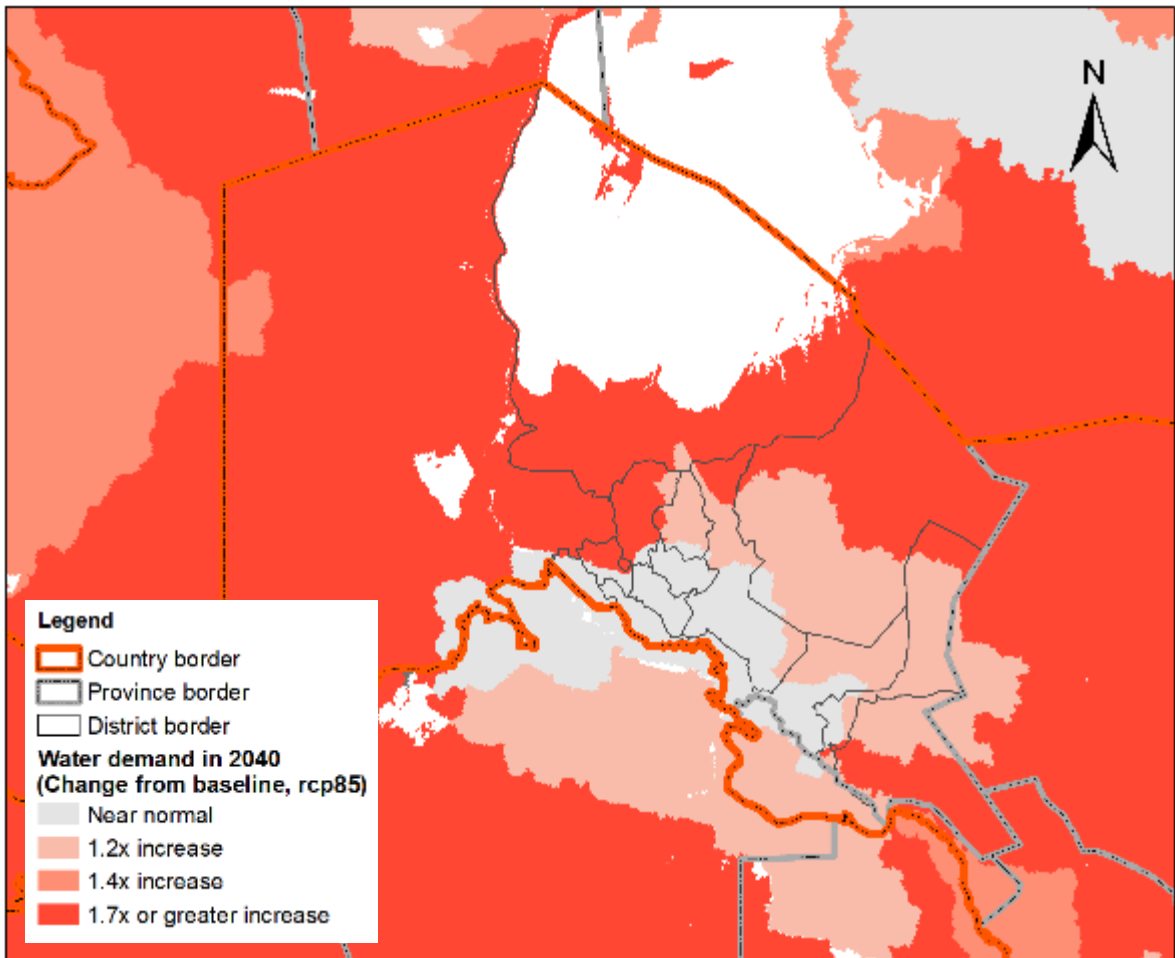


Source: *Aqueduct's tools* (Luck et al. 2015).

Water demand was measured as water withdrawals. Projected change in water withdrawals is equal to the summarized withdrawals for the target year, divided by the baseline year, 2010. Since irrigation consumptive use varies based on climate, we generated unique estimates of consumptive and non-consumptive agricultural withdrawal for each year. Estimates for consumptive and non-consumptive agricultural withdrawal for each ensemble member, scenario, and target year are the mean of the 21-year window around the target year.

Aqueduct's tools map water risks such as floods, droughts, and stress, using open-source, peer reviewed data. Beyond the tools, the Aqueduct team works one-on-one with companies, governments, and research partners to help advance best practices in water resources management and enable sustainable growth in a water-constrained world (Luck et al. 2015).

Water demand in 2040, rcp85



Source: Aqueduct's tools (Luck et al. 2015).

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Aqueduct's tools map water risks such as floods, droughts, and stress, using open-source, peer reviewed data. Beyond the tools, the Aqueduct team works one-on-one with companies, governments, and research partners to help advance best practices in water resources management and enable sustainable growth in a water-constrained world (Luck et al. 2015).

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