3. Ecosystem services

3.1. Regulating ES

3.1.A. Water-related regulating ES

3.1.A1. Methodology of assessment of water-related ES

General modeling framework

Four of the six regulating services assessed are closely linked to the water cycle via evapotranspiration and indicators of surface runoff and baseflow. They were assessed using the InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) integrated tool:

- Seasonal water flow regulation and baseflow provision (InVEST Seasonal Water Yield);
- Prevention of soil water erosion and sediment export in waterbodies (InVEST Sediment Delivery Ratio);
- Flood risk mitigation (InVEST Urban Flood Risk Mitigation);
- Cooling effect of terrestrial ecosystems (InVEST Urban Cooling).

The modeling framework simulated current (2023) and past (2017) conditions, as well as alternative land-cover scenarios, to evaluate ecosystem services (ES) provided by terrestrial ecosystems and to detect changes in these services (Figure 31A1-1). To calculate ES values across the different EAAs, we used the administrative boundary map from the Forest Atlas of Armenia and the vegetation map developed under the project (Section 2.3). A comparison of the modeling results with ARMSTAT water-use data was conducted to assess the supply–use balance, thereby demonstrating the relevance of ES accounting data for evidence-based decision-making on water use and territorial development.

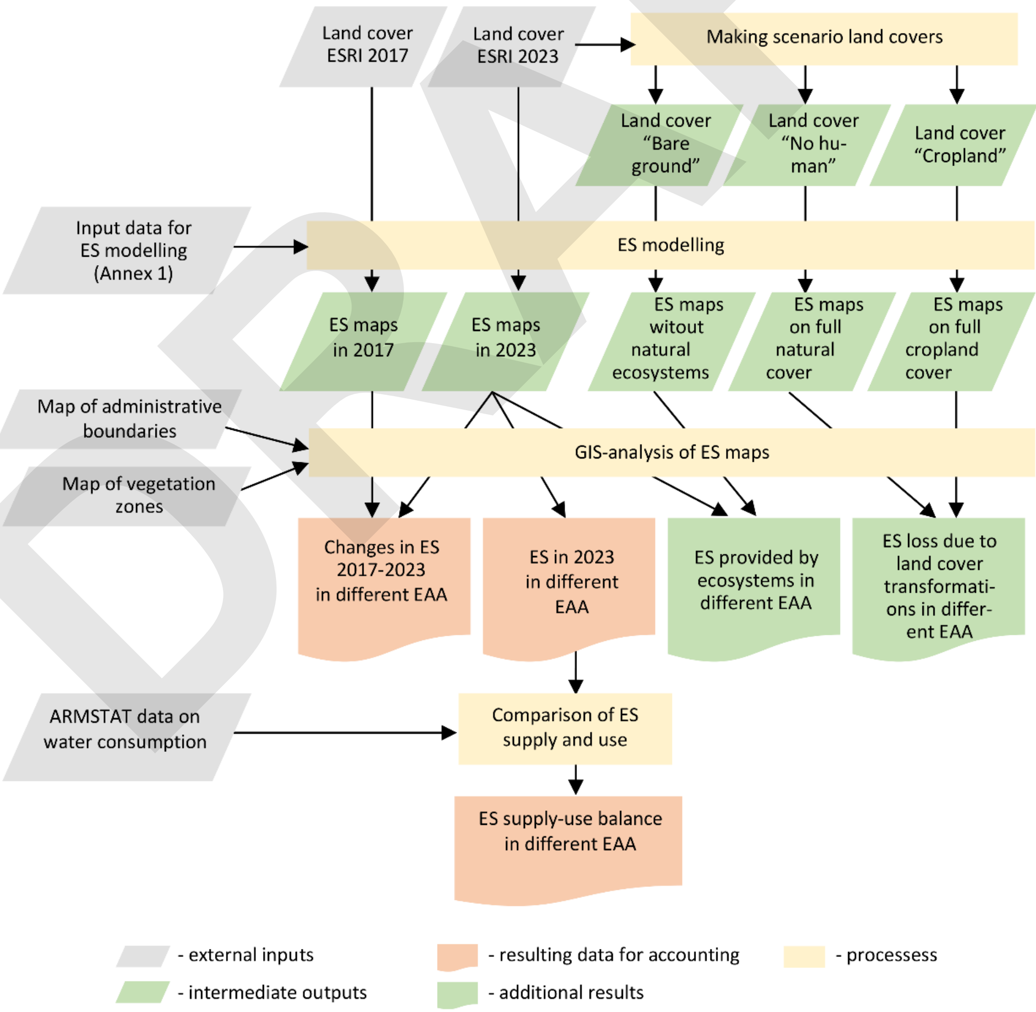


Figure 31A1-1. Flow-chart of ES assessment.

The InVEST models used

The ES of s easonal water flow regulation and baseflow provision was estimated and mapped with InVEST Seasonal Water Yield (SWY) model which estimates the impact of terrestrial ecosystems on the total amount of water flow and its seasonal redistribution. Based on monthly precipitation, reference evapotranspiration, soil permeability, topography, and the land use/land cover (LULC), the model calculates two key indicators: quick flow and baseflow. Quick flow represents the portion of precipitation that runs off during or shortly after a rain event (within hours to days). Baseflow is the portion of precipitation that gradually enters streams through subsurface flow with watershed residence times ranging from months to years. Baseflow plays a crucial role in maintaining water flow during dry periods and mitigating the impacts of drought.

The ES of prevention of soil water erosion and sediment export in waterbodies was estimated and mapped with InVEST Sediment Delivery Ratio (SDR) model which estimates the impact of terrestrial ecosystems on soil water erosion and sediment export into streams. The model relies on the widely used Universal Soil Loss Equation (USLE) and Sediment Delivery Ratio that estimates the ratio between the amount of sediment eroded from each land pixel, the amount of sediment that is trapped along the flow path downslope from this pixel, and the amount of sediment that reaches a stream. Based on rainfall erosivity, soil erodibility, topographic, and LULC data, the model calculates potential and avoided erosion and sediment export into streams. Thus, the model evaluates and maps two ecosystem services simultaneously: prevention of soil water erosion and ensuring water flow quality.

The ES of flood risk mitigation was estimated and mapped with InVEST Urban Flood Risk Mitigation (UFRM) model which calculates two main indicators: (1) the runoff retention, i.e., the amount of runoff retained by soil and vegetation when modeling rainfall; (2) the runoff (Q), mm, which is a potentially hazardous factor that can cause flooding. These calculations were based on LULC, soil hydrologic groups, watersheds and climate data.

Cooling effect of terrestrial ecosystems was estimated and mapped with InVEST Urban Cooling (UC) model which is primarily aimed at assessing the cooling effect of green spaces within urban areas. However, it also allows for evaluating this effect over large areas outside of cities. Since the assessment of urban ES is not a goal of our project, we focused on the ES of areas outside settlements. We used the Cooling Capacity Calculation Method, which estimates *cooling capacity* based on evapotranspiration, albedo, shade (the proportion of area that is covered by tree canopy), air temperature in a rural reference area, and the Urban Heat Index (UHI), i.e., the difference between the rural reference temperature and the maximum temperature observed in the city. We modeled this ES for the hottest season in Armenia—July and August.

Detailed descriptions of the models can be found in the above-mentioned sections of the InVEST website and in the InVEST User Guide [42].

Model inputs

Table 31A1-1. Model inputs.

Data Type	Models	Sources	Resolution	Notes
LULC	SWY, SDR, UFRM, UC	ESRI land cover data	10 m	Data for 2017 and 2023
Soil hydrologic groups	SWY, SDR, UFRM	Soil map of Armenia from [38]	Vector map	The hydrological soil groups were defined in accordance with USDA recommendations [44]: A—slightly and moderately stony sand; very stony sandy loam; B—slightly and moderately stony sandy loam; very stony loam; C—slightly and moderately stony loam; very stony clay; D—slightly and moderately stony clay. The obtained map of soil hydrologic groups is presented on the project's webGIS [45]
Soil erodibility (K-factor)	SDR	Soil map of Armenia from [38]	Vector map	A soil erodibility map was obtained on the basis of soil textures using the following coefficients from the InVEST User Guide [42]: 0.0290 for clay, 0.0395 for loam, 0.0171 for sandy loam, 0.0026 for sand.
Digital elevation model	SWY, SDR	[46]	30 m	-
Watershed boundaries	SWY, SDR, UFRM	[39]	Vector map	The analysis was made for parts of watersheds that are located on the territory of Armenia: Aghstev, Akhuryan, Arpa, Debed, Hrazdan, Metsamor, and Vorotan (Figure 1b)
Climate data (annually and monthly precipitation and temperature)	SWY, UFRM< UC	[47]	30 arc seconds *	The amount of liquid precipitation has been adjusted to take into account the snow period (see below)
Rain events table	SWY, UFRM	[48]		The number of rainy days for each climatic zone was calculated as the average for several cities located within that zone. In the moderate-cool climate zone, where there are no cities, the average data for this zone is based on three cities situated near its border [49]
Climate zones of Armenia	SWY, SDR, UC, UFRM	The map of climate zones	Vector map	The digital vector map of climate zones of Armenia was generalized to the four climate zones: (1) Arid; (2) Moderate dry; (3) Moderate cool; (4) Moderate humid. For details, see the project's webGIS [45]

		of Armenia from [38]		
Monthly reference evapotranspiration (ET0)	SWY, UC	[50]	30 arc seconds *	-
Crop coefficients Kc	SWY, UC	[51,52]		Kc were determined for the four climate zones. The used Kc are presented at the project website [49]
Crop vegetation periods	SWY, UC	[53]		Vegetation periods were determined for the four climate zones
Leaf Area Index	SWY, UC	[54]		The LAI values for dates in the middle of the months were used
Curve numbers (CN)	SWY, UFRM	[55–57]		Coefficients for medium hydrological conditions and vegetation states were used. For croplands and rangelands, differences in climatic zones were taken into account [48]
C-factor for crops	SDR	[58]		C-factor was defined as average values for Europe: 0.3 for crops and sparse vegetation, 0.05 for rangelands (average between pastures and low productive grasslands), and 0.0014 for forests (average value for Southern European countries). C-factor was considered equal to zero for water, flooded vegetation, built areas, and snow/ice on the InVEST recommendations.
P-factor	SDR	-		P-factor was considered equal to 1 because we did not take into account special anti-erosion measures
Rainfall erosivity	SDR	[59]	30 arc seconds *	
Albedo	UC	[58]		The following albedo values were used for land cover classes: water and flooded vegetation 0,6; trees 0.15; rangeland 0.2; crops 0.2; built-up area 0.17; bare ground 0.25; snow/ice 0.9
Shade	UC	-		The following shade values were used for land cover classes: built-up – 0.2; forests – 1.0; croplands, taking into account the share of orchard area, in the arid climate zone – 0.35, in the moderate-dry and moderate-cool zones – 0.03, in the moderate-humid zone – 0.34, other land cover classes – 0.
UHI effect	UC	[59]		The UHI value was set to zero

* At latitude 40°, 30 arc seconds correspond to an area of approximately 709 by 390 m.

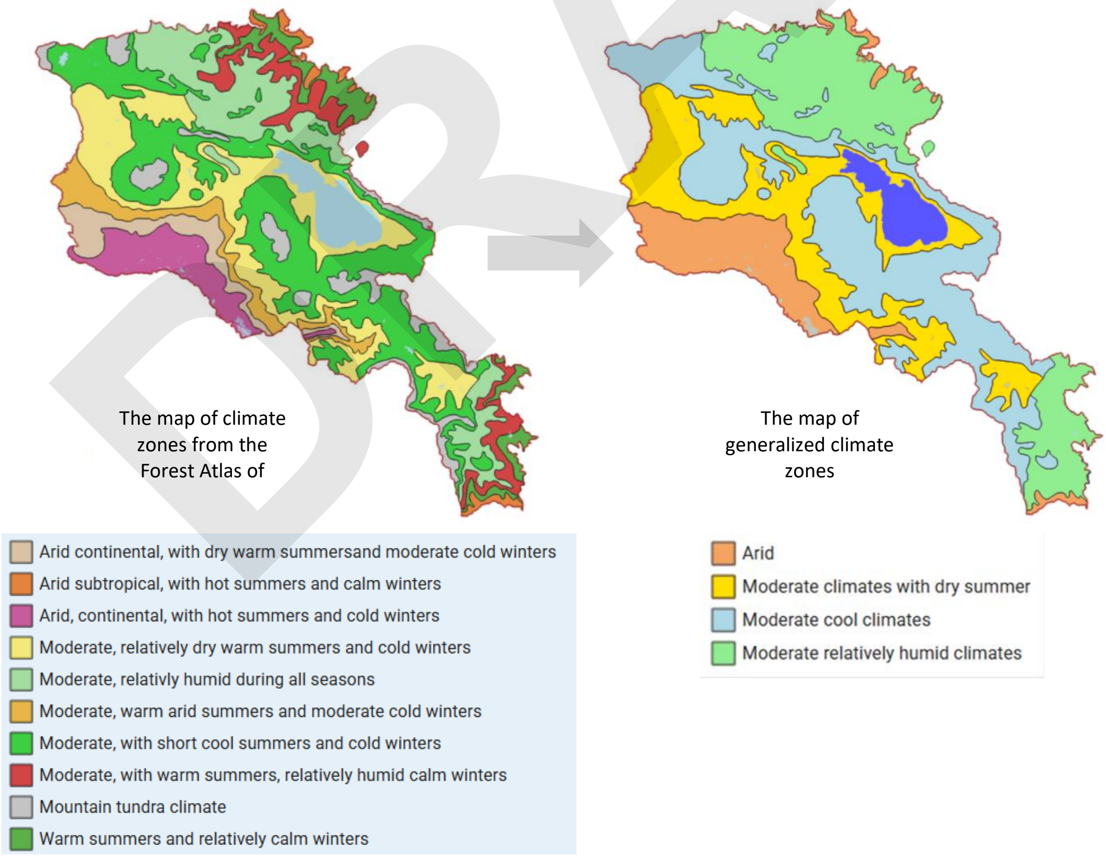


Figure 31A1-3. Generalization of climate zones for ES modeling

Crop coefficients (Kc) were defined as average values for the main groups of agricultural crops, based on FAO data [51,52]. Areas of various agricultural crops such as grains and legumes, vegetables, potatoes, melons, fruits and berries, and grapes in the provinces of Armenia in 2023 were obtained from the Statistical Committee of the Republic of Armenia [41]. To calculate Kc for croplands, we averaged the area shares of different crops for four climatic zones based on data from provinces predominantly located in one or another zone. Average Kc values were then calculated for croplands in each climatic zone, taking into account the share of the area of different agricultural crops within it. Kc values for bare soil were determined based on [60] as the average values for different soil types. For natural vegetation (rangeland and trees), in accordance with the recommendations of InVEST [42], Kc values were set as Kc = 1 if LAI > 3 and Kc = LAI/3 if LAI ≤ 3. According to InVEST and FAO [52] recommendations, Kc = 1 was used for water and flooded vegetation, Kc = 0.35—for built-up areas (assuming that impervious surfaces account for 50%), and Kc = 0.4—for permanent snow. The values of other coefficients were taken from the InVEST User Guide recommendations [42].

UHI effect is incorporated into UC model as a single value. Calculations based on a single UHI value for all of Armenia are impractical due to the significant variation in conditions across different cities. The global UHI effect map [59] shows that in Armenia, it has varying values with opposite signs in different settlements—some settlements are warmer than their surroundings, while others are colder, which makes the use of this factor biased [62]. Therefore, we decided not to account for this factor and set the UHI value to 0.

The values of other coefficients were taken from the InVEST User Guide recommendations [42].

Regional ArmStat statistics on water consumption in 2023 were used to estimate the consumption of ESs.

Scenarios used for ES modeling and assessment the ES provided by ecosystems

To estimate the role of natural ecosystems in ES provisioning, we used three hypothetical LULC scenarios:

- Bare ground scenario: all vegetation, including forests and grasslands, was replaced with bare ground;
- Cropland scenario: all areas, except for urban territories and water bodies, were converted to cropland;
- No-human scenario: urban areas and croplands were replaced with grasslands, simulating a landscape without human activity.

One of the tested models—SDR—directly calculates ES values provided by ecosystems, i.e., indicators of avoided erosion and avoided sediment export. The other models calculate ES indicators for a given LULC but do not determine what portion of these values is attributable to ecosystems rather than to physical processes. In the SWY and UFRM models, we estimated the volume of ES provided by ecosystems as the difference between ES values for the current land cover and the bare ground scenario. Thus, negative indicator values (for the ecosystem effect) mean that ecosystems decrease the indicator, while positive values mean that ecosystems increase it.

The cropland scenario was used in the SWY model to compare ES loss resulting from the replacement of natural vegetation with bare ground and croplands. The no-human scenario was used in the UFRM model to estimate possible ES loss in historical time due to anthropogenic land transformation.

We tested the flood mitigation ES model (UFRM model) for average and extreme spring rainfall scenarios. The highest precipitation in Armenia falls in May and June. While precipitation levels vary significantly across different climatic zones, for the initial model testing, we considered it reasonable to use countrywide average values. During these months, an average rainfall event delivers 12 mm of precipitation. For the extreme

Incorporating snow dynamics in the SWY model

Since the SWY model does not account for the snow period, we assumed zero liquid precipitation during the winter months when the average temperature is below zero, and added this amount to the precipitation of the spring months, when the average temperature rises above zero. The estimation was made without taking into account the sublimation of snow at subzero air temperatures. Digital monthly maps of liquid precipitation are presented on project web GIS [45].

To calculate monthly liquid precipitation, we used a combination of mean monthly air temperature and mean monthly precipitation data. These datasets were provided as raster coverages in GeoTIFF format and unified in terms of spatial extent and resolution.

A Python script was used to iterate through the rasters based on the following logic:

- If the mean monthly air temperature in a pixel was below zero, precipitation in that pixel for that month was set to 0, and its value was carried over to the same pixel in the next month's precipitation raster;
- If the mean monthly temperature remained negative in the following month, the accumulated total was carried forward again until the temperature became positive. At that point, all accumulated snow melted, generating a cumulative water flow.

Data preprocessing and assimilation

To ensure the correct use of data in InVEST models, preprocessing was performed using the QGIS 3.40 application [62] and custom Python 3.10.4 scripts.

Land cover data plays a critical role in all InVEST models. The source data were provided as raster files in GeoTIFF format, which we cropped based on Armenia's national borders. Distinct versions of land cover rasters were created for different modeling scenarios using custom Python scripts—bare ground, cropland, and grassland—by modifying pixel values according to each scenario. For example, in the bare ground scenario, all pixels with values 2 (forest) and 11 (rangeland) were converted to 8 (bare land).

We then juxtaposed land cover rasters for different scenarios with the climate zones dataset using a raster calculator, which allowed a transition from basic categories such as "forest" and "cropland" to enriched classifications like "forest in an arid zone" and "cropland in a moderately humid zone". The climate zone data were originally provided as a vector layer in GeoPackage format. It was rasterized in QGIS to ensure that the resulting raster matched the land cover raster in extent, resolution, and spatial reference system, with climate zones assigned numerical values from 1 to 4.

Then, we combined land cover and climate zone rasters in a two-step process:

1 - The pixel values of the land cover raster were multiplied by 100;

2 - These adjusted values were added to the corresponding pixel values of the climate zone raster, resulting in a unified dataset.

For example, a final pixel value of 204 indicates that the pixel represents land cover type 2 (e.g., trees) and climate zone 4 (e.g., moderate humid zone).

Data preparation for InVEST and statistic calculation

For compatibility with InVEST, all raster datasets were resampled to match the spatial domain of the land cover dataset, ensuring uniform spatial extent, resolution, and coordinate reference system for accurate model execution. These tasks were carried out using standard QGIS 3.40 tools [62], including raster alignment and raster calculator. All raster files were prepared in GeoTIFF format, which is supported by both QGIS and InVEST.

Vector zones required for InVEST models were stored in GeoPackage format 1.3.1 and projected into the same coordinate reference system as the raster datasets.

The results of InVEST model computations, represented as raster coverages, were aggregated based on the boundaries of three vector layers: Armenia's provinces, major river basins, and vegetation zones. Two standard QGIS tools were used for aggregation, zonal statistics for calculating pixel-based sums and averages within the zones, and zonal histogram for counting the number of pixels of different values within each zone.

Watersheds

For the SWY, SDR, and UFRM models, we used those portions of HydroSHEDS level-6 watersheds that lie within Armenia. These parts of the watersheds are further named after their largest rivers (Figure31A1-3a):

– Aghstev (involves Getik and Voskepar tributaries)
– Akhuryan
– Arpa (involves the Arpa River, the Azat River and the Vedi River)
– Debed (involves Pambak and Dzoraget tributaries)
– Hrazdan (involves two parts – Lake Sevan drainage basin and its outlet River Hrazdan)
– Metsamor (involves Kasagh tributary)
– Vorotan (involves Vorotan River, the Voghji River, and the Meghri River).

Note that these are not the basins of the named rivers themselves, but the portions of larger basins, named after the largest river present in each portion.

For comparing ES supply and use, it is important that the watershed boundaries largely coincide with marz boundaries (Figure 31A1-3b).

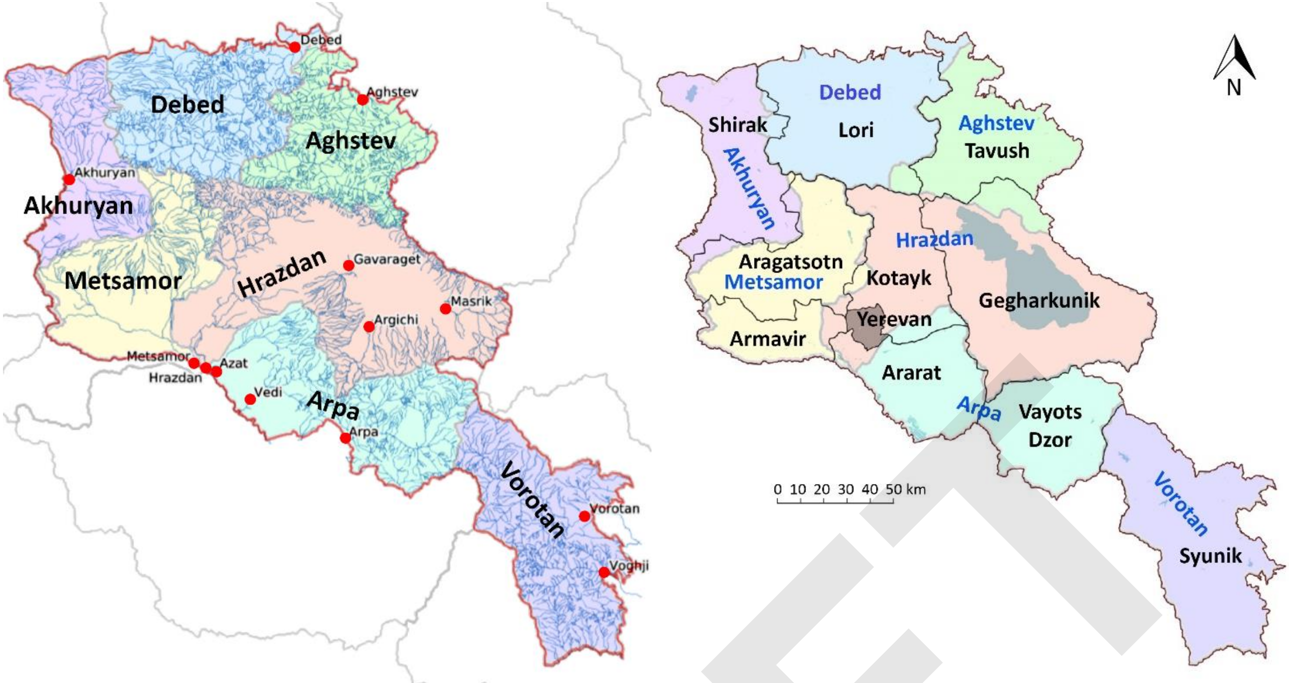


Figure 31A1-3. Watersheds used for ES modeling: a) Watersheds and points of cumulative baseflow values in the lower reaches of rivers; b) Boundaries of marzes and watersheds, the boundaries and names of the marzes are shown in black; the watersheds are shown in different colors with blue labels.

3.1.A2. Seasonal water flow regulation and baseflow provision (InVEST Seasonal Water Yield)

The ES of seasonal flow redistribution and baseflow provision is extremely important for Armenia, which has a seasonal climate with dry summers over a significant part of the territory. The ES was estimated and mapped using InVEST Seasonal Water Yield model. The model takes into account the monthly amount of precipitation, soil permeability, and the water balance of each pixel, including moisture that comes into it from the overlying pixels. The main resulting indicators for assessing the ecosystem service are quick flow (QF), that is, the generation of streamflow with watershed residence times of hours to days; and baseflow (B), that is the generation of streamflow with watershed residence times of months to years. Values of cumulative baseflow (Bsum) show the flow through a pixel, contributed by all upslope pixels (Figure 31A2-1). Baseflow ensures runoff maintaining during the dry season and possible droughts.

The coefficients used for the modeling can be found here https://biodiversity-armenia.am/en/seea-ea/ongoing-projects/preliminary-results-on-ea/%d1%81oefficients-used-for-modeling/

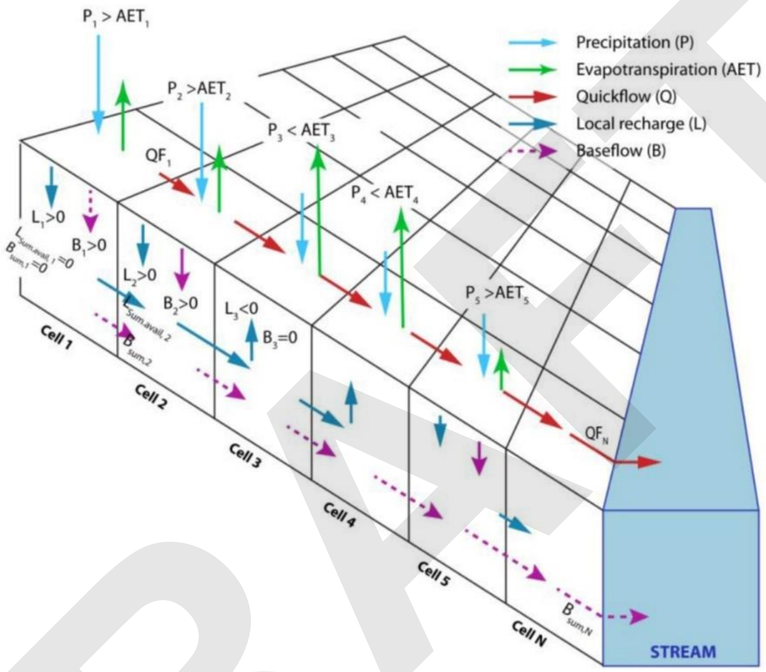


Figure 31A2-1. The InVEST Seasonal Water Yield model diagram (from Hamel et al., 2020)

ES provided by terrestrial ecosystems

The baseflow values (B) for the actual land cover (ESRI 2023) are much higher, while the quick flow (QF) values, on the contrary, are lower compared to hypothetical cases where all natural ecosystems are replaced with bare ground or croplands (Table 31A2-1). The difference between runoff values for the actual land cover and bare ground can be interpreted as the ES provided by terrestrial vegetation: B = 47.8 mm in average, and QF = -22.2 mm in average. Thus, ecosystems provide 93% of baseflow and reduce quickflow by 22%.

ES maps show that under the bare ground and cropland scenarios, baseflow is almost absent (Figure 31A2-2), meaning that the existing baseflow is almost entirely provided by terrestrial ecosystems.

Table 31A2-1. Mean ES indicator values for Armenia under different scenarios

Scenario	Baseflow, mm (B)	Quick flow, mm (QF)	(B+QF)	Share of B in total flow, %
Land cover 2017	51.97	97.01	148.97	34.88
Land cover 2023	51.28	98.04	149.32	34.34
Bare ground scenario	3.43	120.22	123.65	2.78
Cropland scenario	3.58	124.96	128.54	2.78

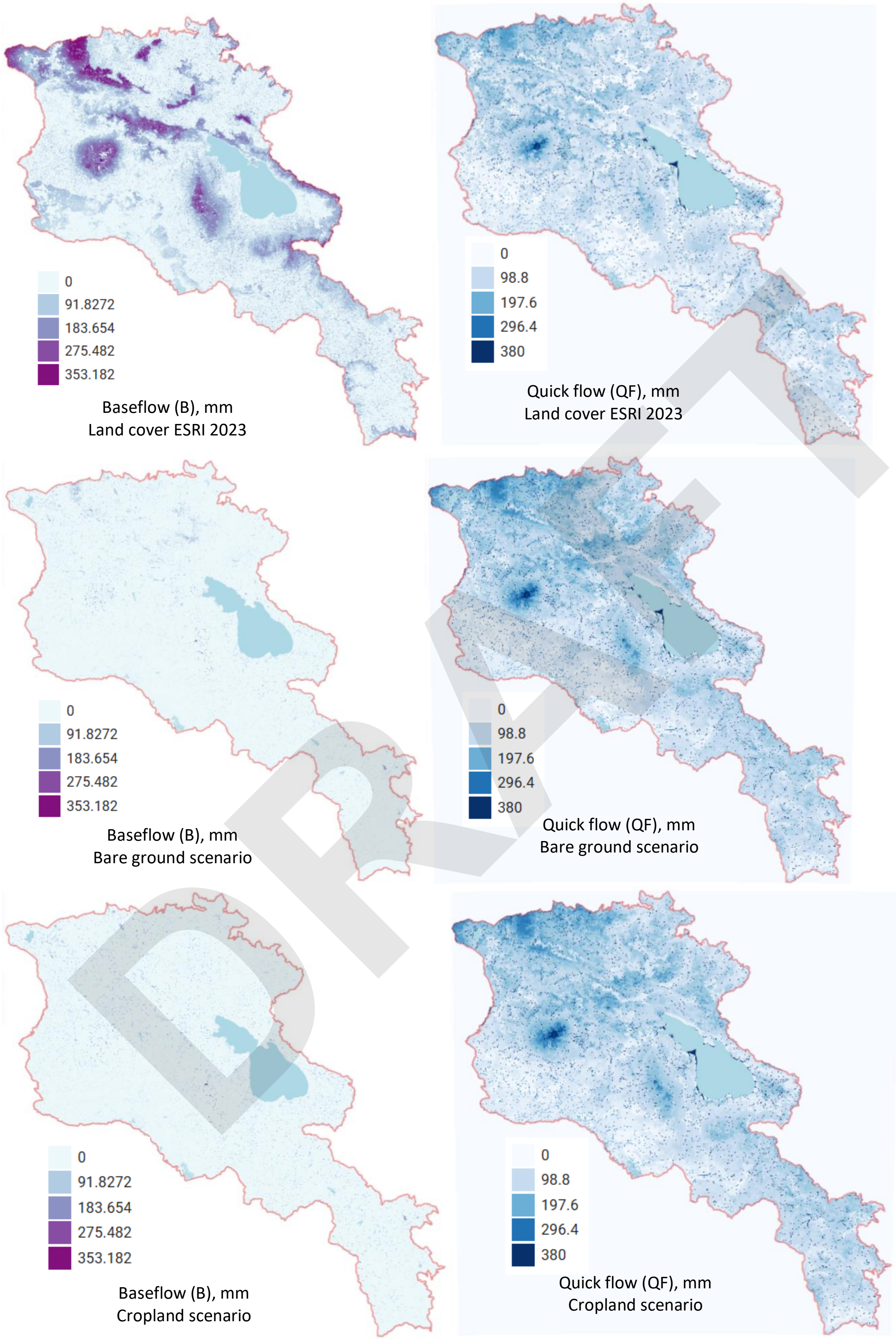


Figure 31A2-2. Maps of ES indicators for different scenarios. For detailed maps see section "Seasonal Water Yield" in the project WebGIS

With the current landcover, the baseflow is on average 35% of the total flow (from 28 to 40% in different watersheds). With the bare ground scenario, the baseflow is only 3% (from 2 to 4%) (Table 31A2-2; Figure 31A2-3). The values of these indicators across the marzes largely mirrors them for the corresponding watersheds (Figure 31A2-4).

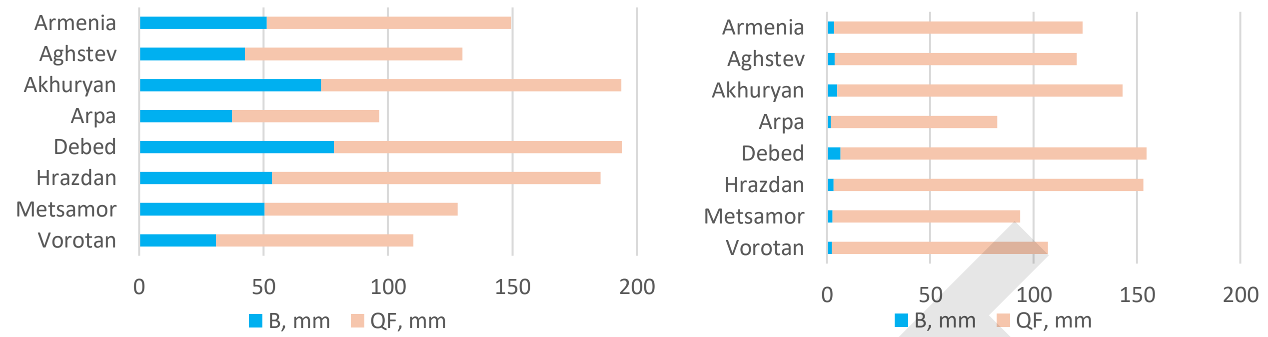


Figure 31A2-3. Baseflow and quick flow under the current land cover and the bare ground scenario across watersheds

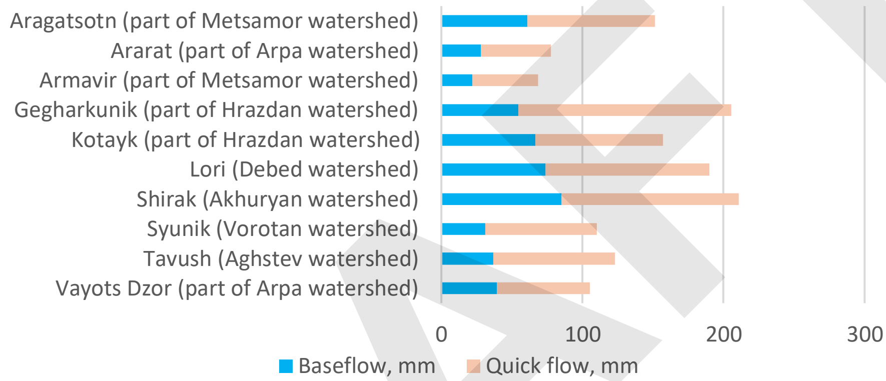


Figure 31A2-4. Baseflow and quick flow under the current land cover across marzes

We estimated ES volume provided by terrestrial vegetation as difference between ES indicator values for the current land cover in 2023 and the bare ground scenario where all grasslands and trees were replaced by bare ground. Across watersheds, ecosystems provide 92%–95% of baseflow (Table 31A2-2; Figure 31A2-5) and reduce quick runoff by 13%–36% (Table 31A2-2; Figure 31A2-6).

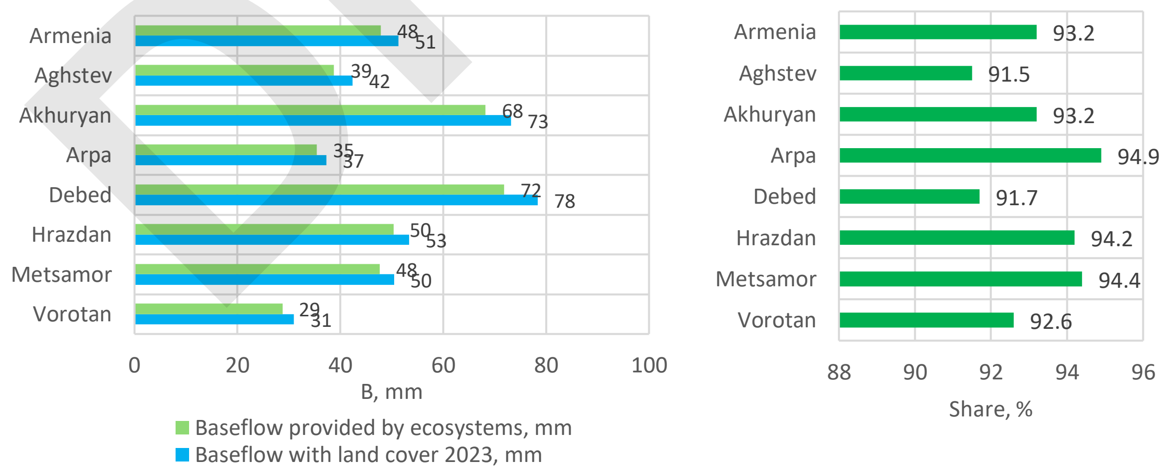


Figure 31A2-5. Ecosystem effects on baseflow: (a) baseflow under current land cover and the component provided by ecosystems; (b) share of baseflow provided by ecosystems (%).

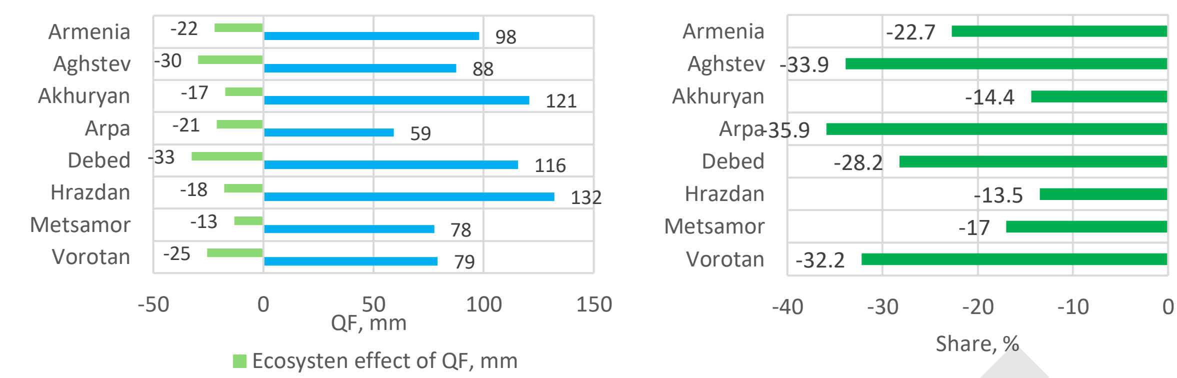


Figure 31A2-6. Ecosystem effects on quick flow: (a) quick flow under current land cover and its part reduced by ecosystems; (b) share of quick flow reduced by ecosystems (%).

Table 31A2-2. ES indicators under the current land cover and the bare ground scenario across watersheds

	Indicators	*Vorotan*	*Metsamor*	*Hrazdan*	*Debed*	*Arpa*	*Akhuryan*	*Aghstev*	*Armenia*
Land cover ESRI 2023	Baseflow, mm, B_{2023}	31.0	50.4	53.4	78.3	37.3	73.2	42.4	51.3
	Quick flow, mm, QF_{2023}	79.2	77.5	132.0	115.6	59.3	120.7	87.6	98.0
	Share of B in total flow, %	28.2	39.4	28.8	40.4	38.6	37.7	32.6	34.3
Bare ground scenario	Baseflow, mm, B_{bg}	2.3	2.8	3.1	6.5	1.9	4.9	3.6	3.4
	Quick flow, mm, QF_{bg}	104.6	90.7	149.9	148.2	80.6	138.1	117.3	120.2
	Share of B in total flow, %	2.1	3.0	2.0	4.2	2.3	3.5	3.0	2.8
Ecosystem effects	Baseflow provided by ecosystems, mm $B_{eco}=B_{2023}-B_{bg}$	28.7	47.6	50.3	71.8	35.4	68.2	38.8	47.8
	Share of baseflow provided by ecosystems, % $B_{eco}*100/B_{2023}$	92.6	94.4	94.2	91.7	94.9	93.2	91.5	93.2
	Reduction of quickflow by ecosystems, mm $QF_{eco}=QF_{2023}-QF_{bg}$	-25.5	-13.2	-17.8	-32.6	-21.3	-17.4	-29.7	-22.2
	Share of quick flow reduced by ecosystems, % $QF_{eco}*100/QF_{2023}$	-32.2	-17.0	-13.5	-28.2	-35.9	-14.4	-33.9	-22.7

Analysis of ES indicators across vegetation zones shows that the highest average baseflow values occur in alpine and subalpine zones, while woody vegetation exhibits levels similar to those of various grassland types. The range of values within individual polygons of certain vegetation zones is quite large — in alpine, subalpine, meadow-steppe, forest zones, and juniper woodlands (Figure 31A2-7a). Proportion of current baseflow contributed by ecosystems is lowest in forest, steppe, and marsh zones (88–89%), and highest (98%) in the desert zone due to the specific characteristics of the only small area where it is currently found in Armenia. In other vegetation zones, this indicator ranges from 93% to 96% (Figure 31A2-7b).

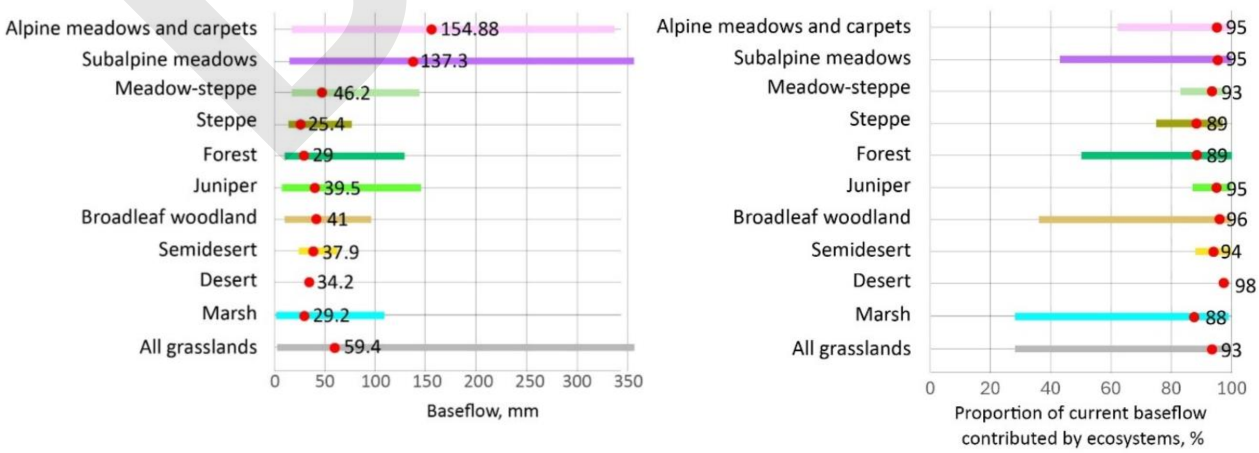


Figure 31A2-7. Baseflow indicators across vegetation zones. Red dots indicate average values, while colored bars represent the range of values within individual polygon

The highest baseflow values (155 and 137 mm) are calculated for alpine and subalpine grasslands, while the forest zone showed a minimal baseflow of 29 mm, similar to that of the steppes (25 mm); both are lower than those in the semidesert and desert zones. The proportion of baseflow contributed by ecosystems is also minimal in the forest and steppe zones (89%). This counterintuitive result, in our view, is explained by the combined effects of multiple factors that determine baseflow—precipitation, terrain slope, and soil permeability. Very high absolute baseflow values in mountain grasslands result from the high precipitation in the mountains. The low baseflow values in the forest zone are most likely the result of forests occurring predominantly on the steep slopes of gorges and mountains. According to our assessment, the highest mean slope among the vegetation zones occurs in the forest and juniper zones —about 20°, whereas mountain grasslands and steppes occupy gentler slopes from 10° to 17°, and the semideserts and the single desert patch lie on plains with an average slope of about 6° (Figure 31A2-8). The moderate baseflow of 38 mm and the high proportion of it contributed by ecosystems (94%) in the semidesert zone are most likely due to its location in areas with the gentlest relief and a high proportion of highly permeable soils. The only small desert patch remaining in Armenia exhibits moderate baseflow of 34 mm an extremely high proportion of baseflow provided by ecosystems (98%), probably because it is entirely located on soils with the highest permeability.

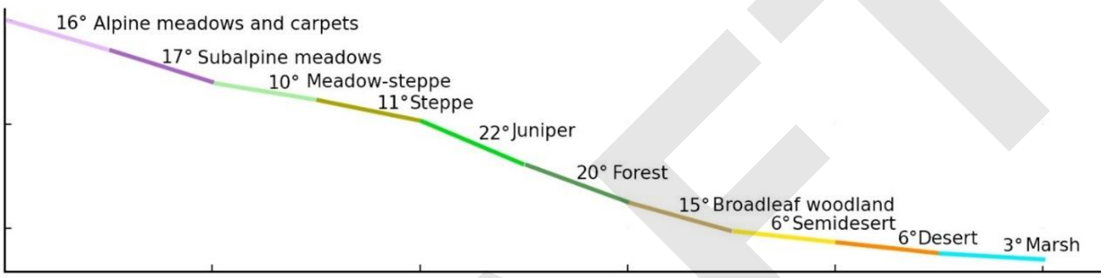
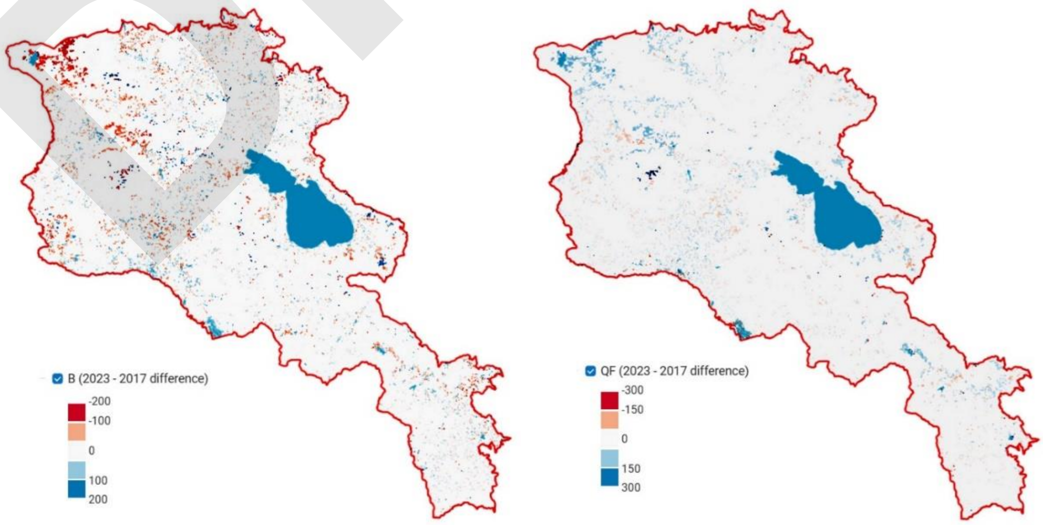


Figure 31A2-8. Average slope for vegetation zones (the zones are arranged by elevation for illustration only; in reality, the elevation distribution may differ).

ES changes from 2017 to 2023

All changes identified are determined only by changes in the landcover (Section 2.2.B). Weather and climate changes are not taken into account. The maps show that the changes are sporadic and oppositely directed (Figure 31A2-9). Nevertheless, overall, they can be characterized as negative. In cases where ES indicators changed significantly, baseflow (B) decreased while quick flow (QF) increased. This means that the ability of terrestrial ecosystems to sustain baseflow during dry periods is declining. The only exception is the Arpa basin, where B has increased. The most significant negative changes occurred in the Shirak province and the Akhuryan watershed corresponding to land cover changes in the Shirak province. The reason is the expansion of the croplands at the expense of the grasslands in the Shirak province [(see here)](#).



a b

Figure 31A2-9. Changes in baseflow (a) and quickflow (b) from 2017 to 2023, mm. For detailed maps see sections "Seasonal Water Yield - Dynamics" in the project Web GIS

The most notable changes across watersheds and marzes are a decrease in baseflow and an increase in quickflow. These negative changes are most pronounced in the Akhuryan and Metsamor watersheds and in the marzes Shirak and Aragatsotn. A slight increase in baseflow is observed in the Arpa and Aghstev watersheds and in Ararat marz (Table 31A2-3; Figures 31A2-10 and 31A2-11).

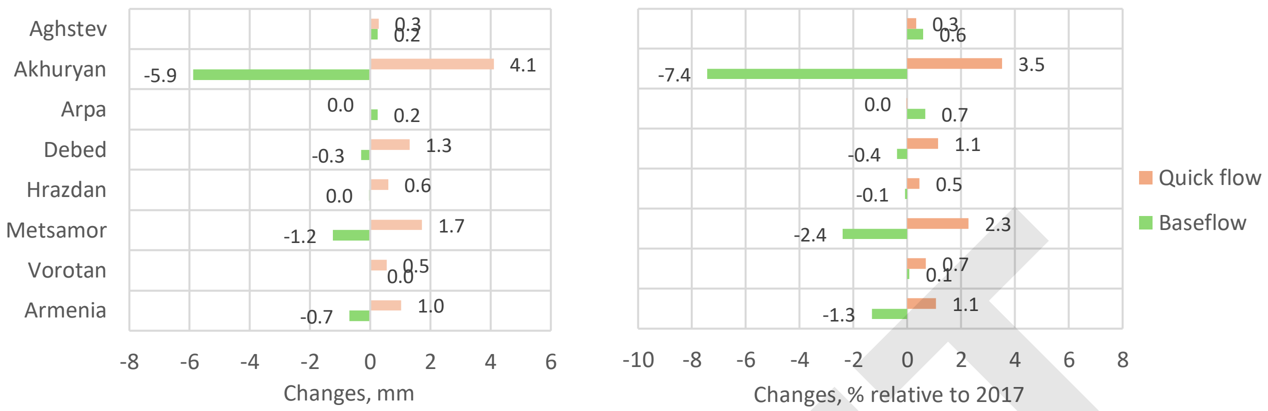


Figure 31A2-10. Changes in baseflow and quickflow from 2017 to 2023 in absolute (a) and relative (b) indicators across watersheds

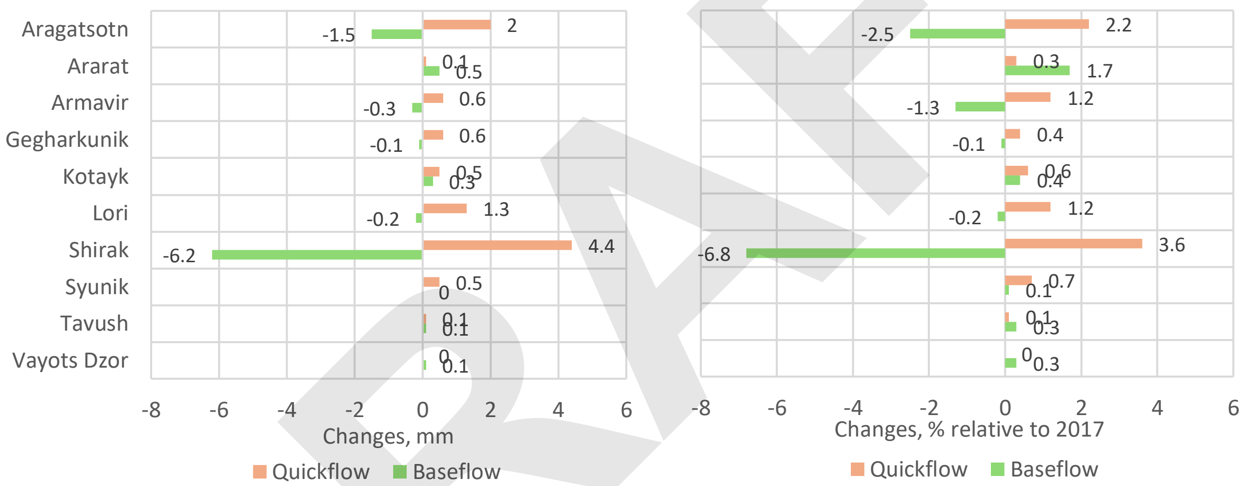


Figure 31A2-11. Changes in baseflow and quickflow from 2017 to 2023 in absolute (a) and relative (b) indicators across marzes

Table 31A2-3. Changes in baseflow and quick flow from 2017 to 2023 across watersheds and marzes

EAA		Baseflow, mean				Quick flow, mean			
		B 2017, mm	B 2023, mm	Change in B, mm	Change in B, % relative to 2017	QF 2017, mm	QF 2023, mm	Change in QF, mm	Change in QF, % relative to 2017
Watersheds	Aghstev	42.1	42.4	0.2	0.6	87.3	87.6	0.3	0.3
	Akhuryan	79.0	73.2	-5.9	-7.4	116.6	120.7	4.1	3.5
	Arpa	37.0	37.3	0.2	0.7	59.3	59.3	0.0	0.0
	Debed	78.6	78.3	-0.3	-0.4	114.3	115.6	1.3	1.1
	Hrazdan	53.5	53.4	0.0	-0.1	131.4	132.0	0.6	0.5
	Metsamor	51.7	50.4	-1.2	-2.4	75.8	77.5	1.7	2.3
	Vorotan	31.0	31.0	0.0	0.1	78.6	79.2	0.5	0.7
Provinces	Aragatsotn	62.5	61.0	-1.5	-2.5	88.5	90.5	2.0	2.2
	Ararat	27.6	28.1	0.5	1.7	49.5	49.6	0.1	0.3
	Armavir	22.2	21.9	-0.3	-1.3	46.2	46.8	0.6	1.2
	Gegharkunik	54.6	54.5	-0.1	-0.1	150.5	151.1	0.6	0.4
	Kotayk	66.4	66.7	0.3	0.4	89.8	90.3	0.5	0.6
	Lori	74.1	74.0	-0.2	-0.2	114.5	115.8	1.3	1.2
	Shirak	91.3	85.1	-6.2	-6.8	121.3	125.7	4.4	3.6
	Syunik	30.9	30.9	0.0	0.1	78.6	79.1	0.5	0.7
	Tavush	36.7	36.9	0.1	0.3	86.2	86.3	0.1	0.1
	Vayots Dzor	39.3	39.4	0.1	0.3	66.0	66.0	0.0	0.0
Armenia		52.0	51.3	-0.7	-1.3	97.0	98.0	1.0	1.1

Supply-use balance

Since the baseflow and quick flow values computed by the SWY model are, in accordance with the InVEST User Guide, relative measures, the baseflow volume V_B was calculated as follows: $V_B=BFI \cdot V_{tot}$ where V_{tot} is the river discharge according to the data reported by the Government of Armenia and ARMSTAT (Table 31A-4); BFI is baseflow index, BFI = B/(B + QF), where B and QF are baseflow and quick flow values computed by SWY model.

This analysis is approximate, because we used river flow data by watersheds and water-use data by provinces. The boundaries of provinces and watersheds largely coincide (Section 3.1.A.1), which allows such a rough estimate. For watersheds that include two provinces, the data for those provinces were summed. Obviously, the balance should be refined in the future using data from the same EAAs.

Table 31A2-4. Data on river flow

Watershed	*River flow, millions of m_3*	*Data source*	*Details*
Aghstev	260	ArmStat Regional Statistics handbooks 2023 https://armstat.am/en/?nid=651	-
Akhuryan	700.7	Basin management plan https://www.arlis.am/hy/acts/112336	River flow was calculated as the sum of utilizable river flow (506.2) and environmental flow (194.5).
Arpa	1177.0	Basin management plan https://www.arlis.am/hy/acts/112336	The sum of river flows of Azat, Vedi, and Arpa
Debed	960	ArmStat Regional Statistics handbooks 2023 https://armstat.am/en/?nid=651	-
Hrazdan	712.2	Basin management plan https://www.arlis.am/hy/acts/171449	-
Metsamor	1043.3	Basin management plans https://www.arlis.am/hy/acts/171449 https://www.arlis.am/hy/acts/112336	Total river flow was calculated as the sum of Qasagh (265.5) and Metsamor (777.8) rivers. Metsamor river flow wascalculated as the sum of utilizable river flow (1,786.7) and environmental flow (106.0) excluding water available from the reach downstream of the confluence of the Araks and Akhuryan rivers (1,114.9)
Vorotan	1319.6	Basin management plan https://www.arlis.am/hy/acts/106124	The sum of river flows of Southern BMA

The overwhelming majority of water consumption is accounted for by the agriculture, fisheries, and forestry sector, which underscores the importance of assessing the ecosystem service of baseflow provision. In two watersheds — Metsamor and Arpa—agricultural water consumption exceeds the baseflow volume (Figure 31A2-12a). In the Metsamor and Arpa watersheds, baseflow provides 56% and 55% of agricultural water consumption, respectively; in the Hrazdan watershed baseflow slightly exceeds agricultural consumption—by 16%. In the other watersheds baseflow exceeds water consumption by many times (Figure 31A2-12c). The water-use data for Tavush marz used in the analysis pertain to an area larger than the Aghstev River watershed for which river flow data are available. Therefore, in reality the total river flow from the entire area exceeds water consumption even more than indicated by these results.

Table 31A2-5. Supply–use balance of ES

	Water use in agriculture, fish breeding, forestry*, millions of m^3	Total water consum-ption*, millions of m^3	Baseflow, millions of m^3	River flow*, millions of m^3	Difference between baseflow volume and water consumption in agriculture, fishery and forestry, millions of m^3	Share of baseflow in agriculture, fisheries and forestry water consumption (%)
Aghstev (a part of the marz Tavush)	11.10	20.90	84.78	260.00	73.68	763.78
Akhuryan (marz Shirak)	53.00	63.10	264.46	700.70	211.46	498.99
Arpa (marzes Ararat and Vayots Dzor)	820.30	835.90	454.50	1177.00	-365.80	55.41
Debed (marz Lori)	3.00	18.00	387.69	960.00	384.69	12923.03
Hrazdan (marzes Kotayk and Gegharkunik)	176.10	218.60	205.13	712.20	29.03	116.49
Metsamor (marzes Armavir and Aragatsotn)	740.40	769.10	411.06	1043.30	-329.34	55.52
Vorotan (marz Syunik)	6.00	89.50	371.51	1319.60	365.51	6191.75

*Data reported by ARMSTAT and the Government of Armenia

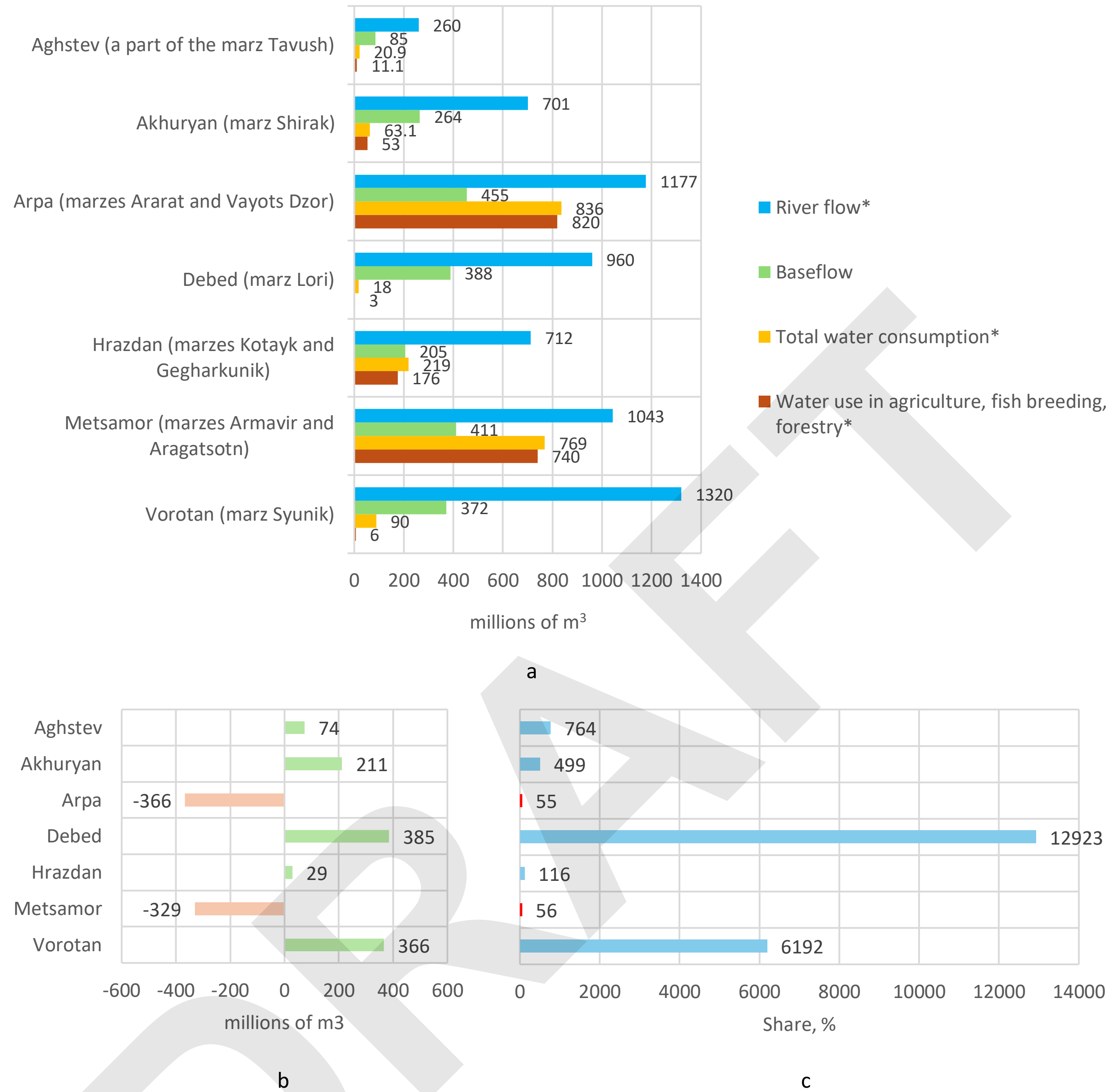


*Figure 31A2-12. Supply–consumption balance of ES: (**a**) river flow, baseflow and water consumption across watersheds (* data reported by ARMSTAT and the Government); (**b**) Difference between baseflow volume and water consumption in agriculture, fishery and forestry; (**c**) Share of baseflow in agriculture, fisheries and forestry water consumption (%).*

3.1.A3. Prevention of soil water erosion and sediment transport to waterbodies (InVEST Sediment Delivery Ratio)

Two ES - 1) prevention of soil water erosion and 2) ensuring water flow quality due to prevention of sediment transport to waterbodies - were estimated and mapped using InVEST Sediment Delivery Ratio (SDR) model. The InVEST SDR model focuses only on overland erosion. Outputs from the model include the sediment load delivered to the stream at an annual time scale, as well as the amount of sediment eroded in the catchment and retained by vegetation and topographic features. The main indicator of the ES of prevention of soil erosion is avoided erosion, and the main indicator of the ES of ensuring water flow quality is avoided sediment export to streams (Figure 31A3-1).

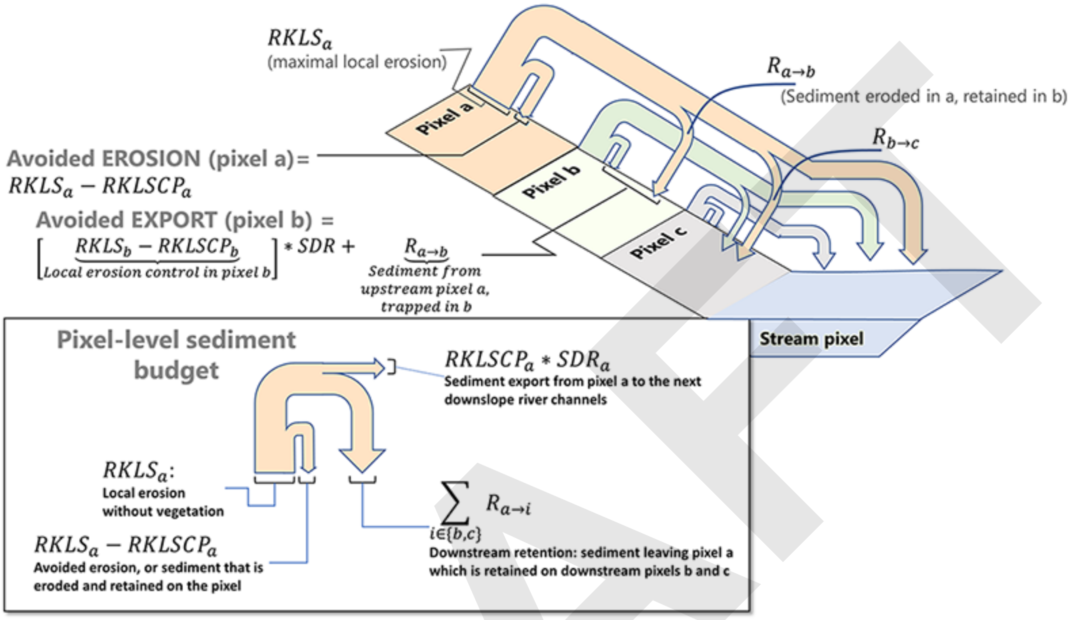


Figure 31A3-1. Schematic of InVEST SDR model (InVEST User Guide [42]).

ES provided by terrestrial ecosystems

In 2023, total avoided erosion was estimated as 140 million tons, and total avoided sediment export to streams was estimated as 13 million tons. ES maps show that current erosion and sediment export are negligible, whereas avoided erosion and sediment export is many times higher (Figure 31A3-2, note that the scale values for current sediment export are one-tenth of those for avoided export). On average, ecosystems prevent about 95% of erosion and 96% of sediment export in Armenia (Table 31A3-1).

Table 31A3-1. ES indicators in Armenia

Indicator	*Land cover 2023*	*Bare ground scenario*	*ES Provided by ecosystems*	*Change in ES due to ecosystem functioning %*
Erosion	2.3 t/ha/year 6.8 Mt/year	48.6 t/ha/year 147.2 Mt/year	Avoided erosion −46.4 t/ha/year −140.4 Mt/year	−95%
Sediment export	0.15 t/ha/year 0.47 Mt/year	4.5 t/ha/year 13.5 Mt/year	Avoided sediment export −4.3 t/ha/year −13.0 Mt/year	−96%

The SDR model estimates that vegetation prevents more than 90% of erosion in all watersheds and provinces (except for the Armavir province with 89%) and more than 95% of sediment export everywhere. The highest rates of avoided erosion were calculated for watersheds Aghstev, Vorotan, and Debed and the corresponding provinces Tavush, Syunik, and Lori. The lowest values were found for watersheds Metsamor and Akhuryan and for the province Armavir. The highest rates of avoided sediment export were calculated for the same watersheds and provinces Syunik, Vayots Dzor, and Lori. The lowest values were found for watersheds Metsamor and Akhuryan and for the province Armavir (Figures (Figure 31A3-3 and 31A3-4). This pattern, in general, is also evident for the total values of avoided erosion and sediment export (Tables 31A3-2 and 31A3-3).

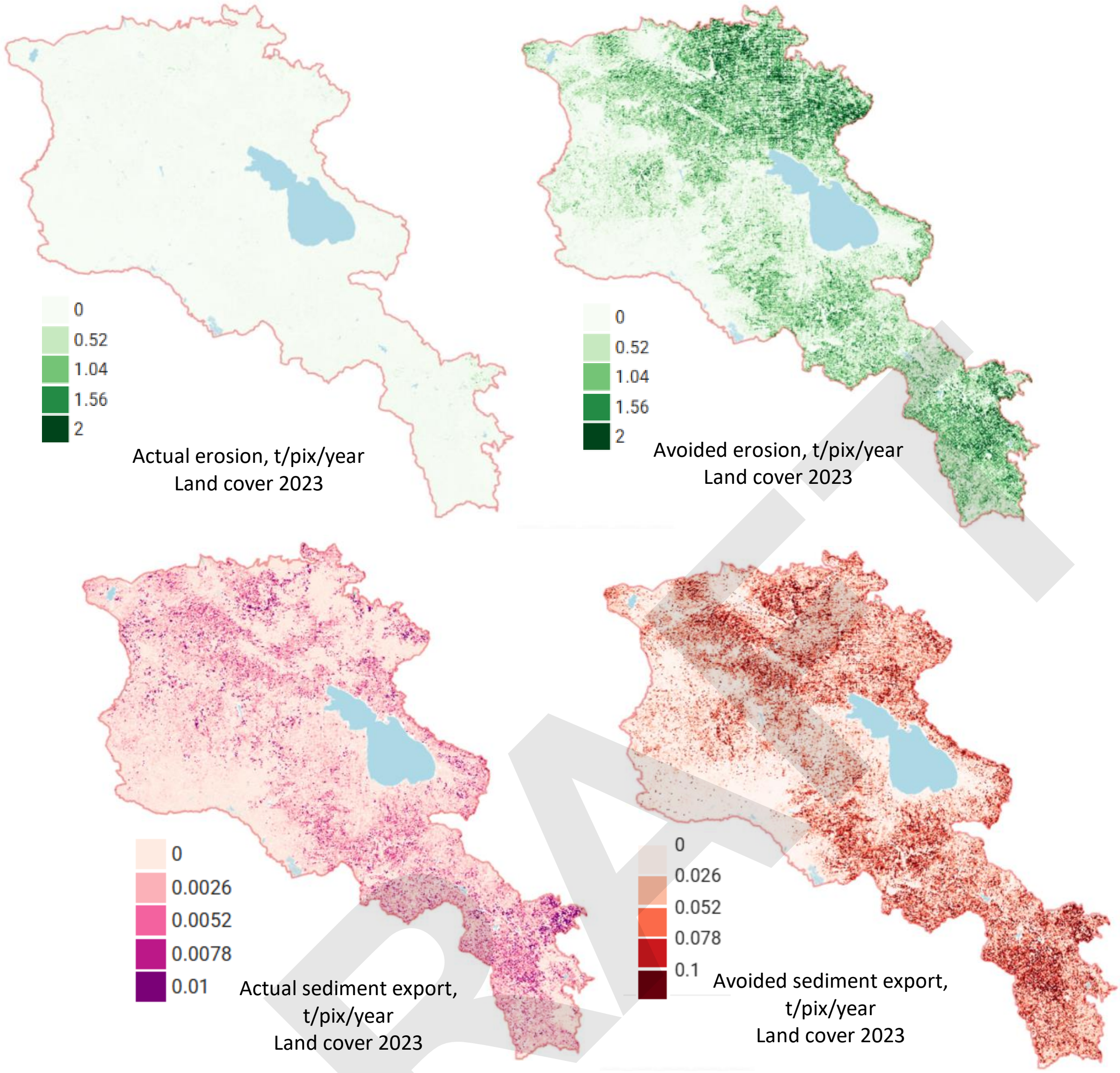


Figure 31A3-2. ES indicators with current land cover, 2023. [For detailed maps see the section "Ecosystem Services - Sediment Delivery Ratio - Basic scenario 2023"] in the project Web GIS

Table 31A3-2. Erosion in watersheds and provinces (Mt - million tons)

		Erosion under bare ground scenario, t/ha/year	*Current erosion in 2023, t/ha/year*	*Avoided erosion, t/ha/year*	*Total erosion under bare ground scenario, Mt/year*	*Total current erosion, Mt/year*	*Total avoided erosion, Mt/year*	*Share of avoided erosion*, %*
Water-sheds	Aghstev	96.0	2.5	93.5	29.7	0.8	28.9	97.4
	Akhuryan	24.7	2.0	23.0	6.6	0.5	6.1	92.0
	Arpa	49.6	2.5	47.0	21.1	1.1	20.1	95.0
	Debed	75.2	2.9	72.4	28.7	1.1	27.6	96.1
	Hrazdan	34.3	1.9	32.3	19.8	1.1	18.6	94.3
	Metsamor	20.3	1.3	19.0	7.1	0.5	6.6	93.6
	Vorotan	78.8	4.0	75.0	34.3	1.7	32.6	94.9
Marzes	Aragatsotn	26.8	1.6	25.2	7.1	0.4	6.6	93.9
	Ararat	33.8	1.7	32.1	6.9	0.3	6.5	94.9
	Armavir	3.9	0.4	3.5	0.5	0.1	0.4	89.1
	Gegharkunik	41.1	2.3	38.8	15.8	0.9	14.9	94.4
	Kotayk	37.7	2.0	35.7	7.7	0.4	7.3	94.6
	Lori	76.5	2.9	73.6	28.0	1.1	26.9	96.2
	Shirak	27.4	2.1	25.3	7.1	0.5	6.6	92.3
	Syunik	78.8	4.0	74.8	34.3	1.7	32.6	94.9
	Tavush	99.2	2.4	96.8	26.4	0.6	25.7	97.6
	Vayots Dzor	60.8	3.1	57.7	13.6	0.7	12.9	95.0

* Share from the sum of current and avoided sediment export

Table 31A3-3. Sediment export in watersheds and provinces, 2023 (Mt - million tons)

		Current sediment export in 2023, t/ha/year	*Avoided sediment export, t/ha/year*	*Total current sediment export 2023, Mt/year*	*Total avoided sediment export 2023, Mt/year*	*Share of avoided sediment export, %**
Water-sheds	Aghstev	0.2	5.5	0.0	1.7	97.3
	Akhuryan	0.1	2.9	0.0	0.8	95.3
	Arpa	0.2	5.2	0.1	2.2	96.7
	Debed	0.2	5.9	0.1	2.2	96.7
	Hrazdan	0.1	3.5	0.1	2.0	96.4
	Metsamor	0.1	2.1	0.0	0.7	96.1
	Vorotan	0.3	7.8	0.1	3.4	96.2
Marzes	Aragatsotn	0.1	2.7	0.0	0.7	96.2
	Ararat	0.1	3.5	0.0	0.7	96.5
	Armavir	0.0	0.5	0.0	0.1	95.1
	Gegharkunik	0.1	4.2	0.1	1.6	96.6
	Kotayk	0.1	3.6	0.0	0.7	96.1
	Lori	0.2	5.9	0.1	2.1	97.0
	Shirak	0.1	3.2	0.0	0.8	96.2
	Syunik	0.3	7.8	0.1	3.4	96.6
	Tavush	0.2	5.4	0.0	1.4	97.2
	Vayots Dzor	0.2	6.4	0.0	1.4	96.6

* Share from the sum of current and avoided sediment export

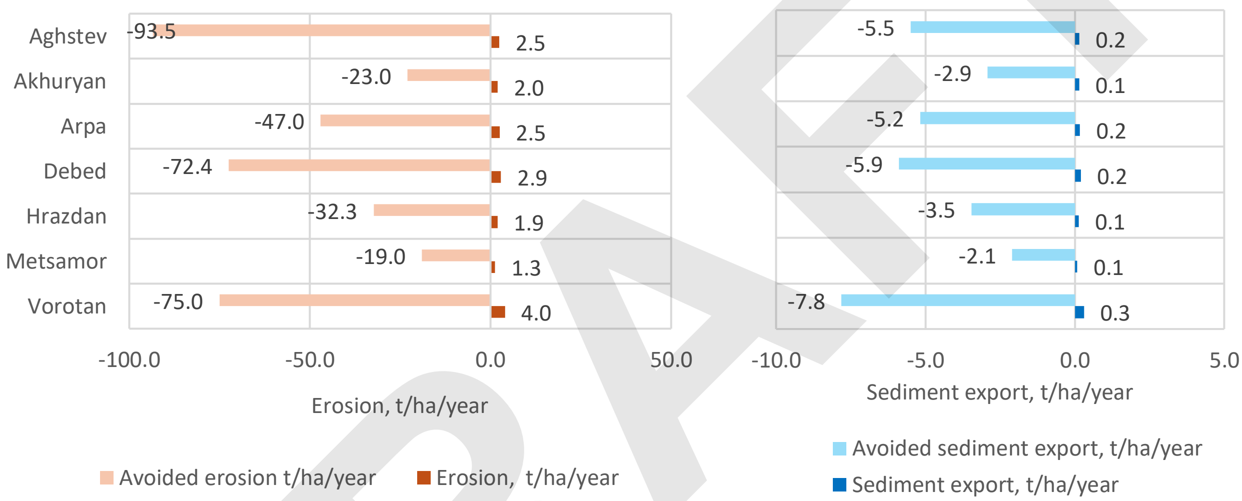


Figure 31A3-3. ES indicators across watersheds

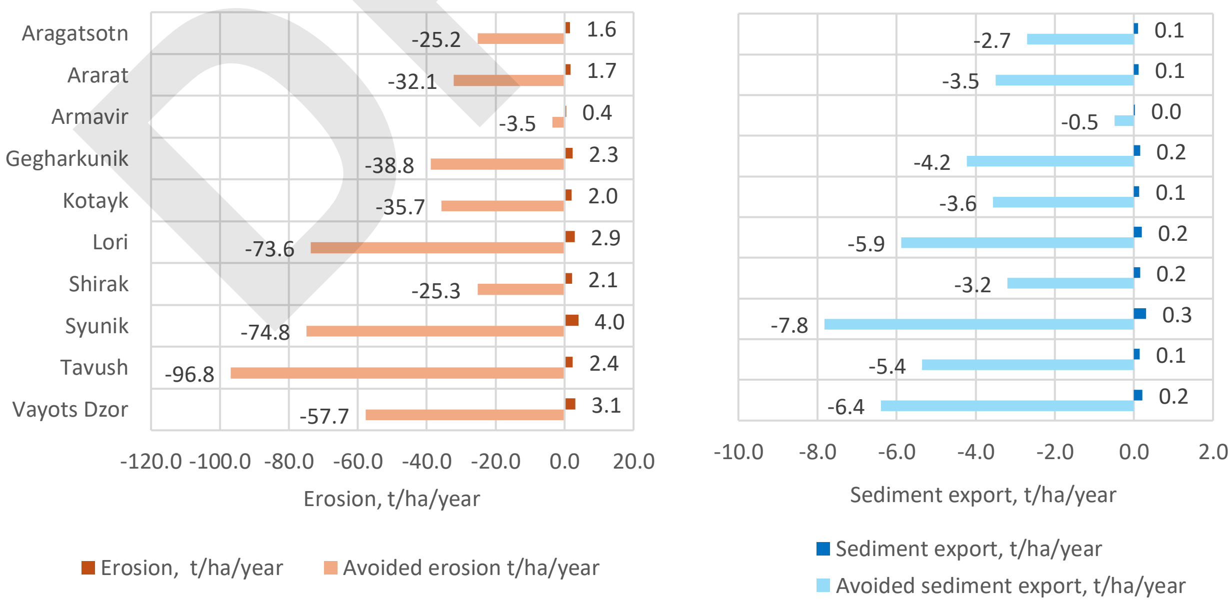


Figure 31A3-4. ES indicators across marzes

Analysis of ES indicators across vegetation zones shows that the average avoided erosion is highest in forest and woodland zones, moderate in alpine and subalpine zones, and lowest in desert, semi-desert, and marshes (Figure 31A3-5 a). The range of values within individual polygons of certain vegetation zones is quite large — in semi-desert, forest, juniper, and broadleaf woodland zones. The ratio of avoided erosion to current erosion is highest in forest and woodland zones (avoided erosion is 96–97 times greater than current erosion), ranging from 93 to 95 in other zones (Figure 31A3-5 b).

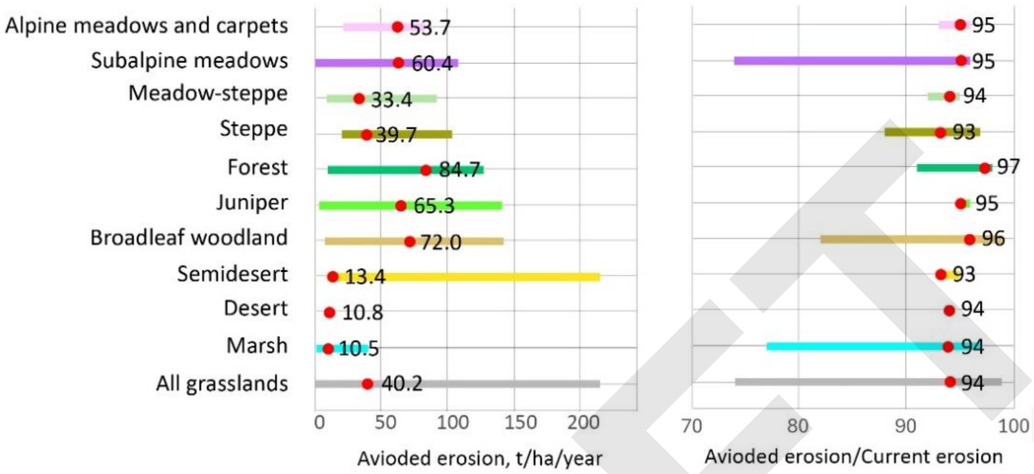


Figure 31A3-5. ES indicators across marzes

ES changes from 2017 to 2023

Changes in the landcover from 2017 to 2023 resulted in changes in avoided erosion and sediment export. The maps show that the changes are sporadic and oppositely directed (Figure 31A3-6). These changes represent only tenths of a percent of total ES volume, but can be important for tracking trends.

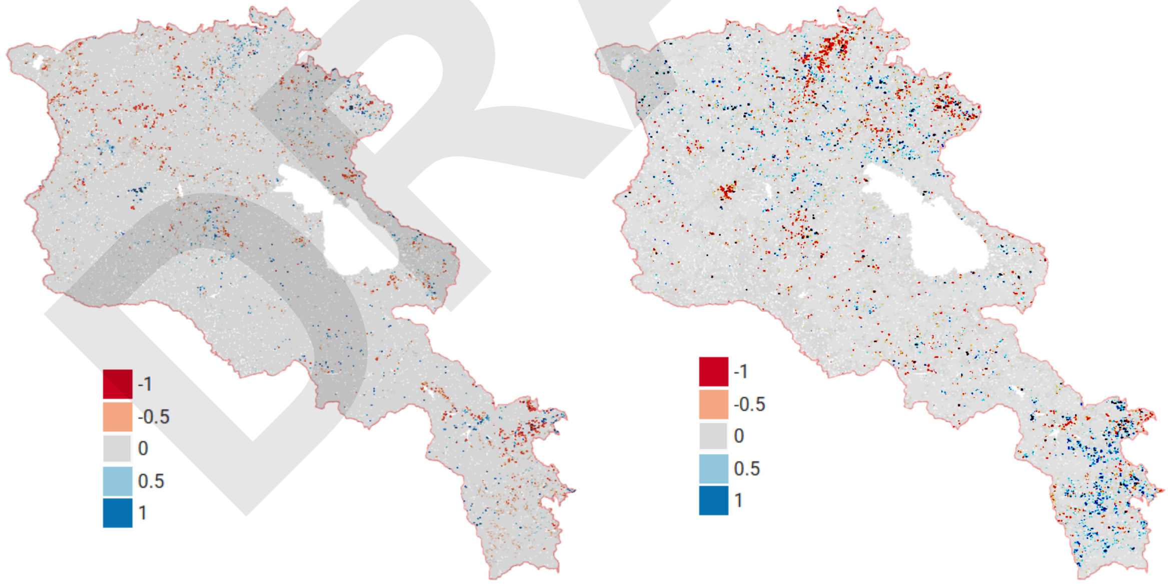


Figure 31A3-6. ES changes from 2017 to 2023: a) Changes in avoided erosion; b) Changes in avoided sediment export. For details see maps in the section "Sediment Delivery Ratio - Dynamics" in the project Web GIS

In absolute terms, the largest negative changes occurred in the Akhuryan and Vorotan watersheds, where erosion increased by 0.23–0.25 t/ha/yr. In the Debed watershed, erosion increased by 0.13 t/ha/yr. Small positive changes were observed in the Arpa watershed, where erosion decreased by 0.08 t/ha/yr. Changes in the other watersheds are negligible. Relative to 2017, erosion and sediment export increased the most in the Akhuryan watershed —by 21% and 13%, respectively. In the Vorotan watershed these indicators rose by 10% and 7%, respectively; in the Debed watershed —by 7% and 5%. In the Arpa watershed they decreased by 5% and 3%, respectively (Figure 31A3-7).

Changes by marz generally mirror those in the corresponding watersheds: Shirak marz — Akhuryan watershed; Syunik marz — Vorotan watershed; Lori marz — Debed watershed; Ararat and Vayots Dzor marzes — Arpa watershed (Figure 31A3-8). An important management-relevant case arises in the marzes of Gegharkunik and Kotayk where opposite changes occurred, which compensated for each other within the Hrazdan watershed, to which these provinces belong. In the marzes of Aragatsotn and Armavir, both within the Metsamor watershed, we also observe changes in opposite directions: the marked deterioration in Armavir relative to 2017 is offset by relatively modest improvements in Aragatsotn, owing to its larger area. Changes in Tavush marz differ from those in the Aghstev basin because the Getik—a major tributary of the Aghstev—lies within Gegharkunik marz.

Table 31A3-4. ES changes from 2017 to 2023 across watersheds and marzes

EAA		Changes in absolute terms, t/ha				Changes in %, relative to 2017			
		Avoided erosion	Current erosion	Avoided sediment export	Current sediment export	Avoided erosion	Current erosion	Avoided sediment export	Current sediment export
Water-sheds	Aghstev	-0.006	0.006	0.018	0.000	-0.01	0.26	0.33	-0.28
	Akhuryan	-0.228	0.228	0.190	0.025	-0.99	12.99	6.94	20.82
	Arpa	0.081	-0.081	-0.066	-0.008	0.17	-3.13	-1.25	-4.53
	Debed	-0.126	0.126	0.055	0.013	-0.17	4.51	0.95	7.18
	Hrazdan	0.012	-0.012	-0.010	-0.001	0.04	-0.62	-0.27	-0.68
	Metsamor	-0.012	0.012	0.005	0.002	-0.06	0.93	0.24	1.98
	Vorotan	-0.248	0.248	0.388	0.028	-0.33	6.64	5.22	10.28
Marzes	Aragatsotn	-0.015	0.015	0.004	0.002	-0.06	0.92	0.16	1.88
	Ararat	0.078	-0.078	-0.064	-0.008	0.24	-4.35	-1.80	-5.97
	Armavir	0.020	-0.020	-0.019	-0.001	0.59	-4.54	-3.73	-5.78
	Gegharkunik	-0.078	0.078	0.076	0.008	-0.20	3.54	1.83	5.43
	Kotayk	0.077	-0.077	-0.053	-0.007	0.22	-3.63	-1.46	-5.09
	Lori	-0.132	0.132	0.071	0.014	-0.18	4.81	1.23	7.58
	Shirak	-0.254	0.254	0.210	0.027	-0.99	13.68	7.03	21.68
	Syunik	-0.247	0.247	0.388	0.028	-0.33	6.62	5.21	10.25
	Tavush	0.070	-0.070	-0.082	-0.008	0.07	-2.86	-1.51	-5.13
	Vayots Dzor	0.079	-0.079	-0.058	-0.009	0.14	-2.51	-0.90	-3.78

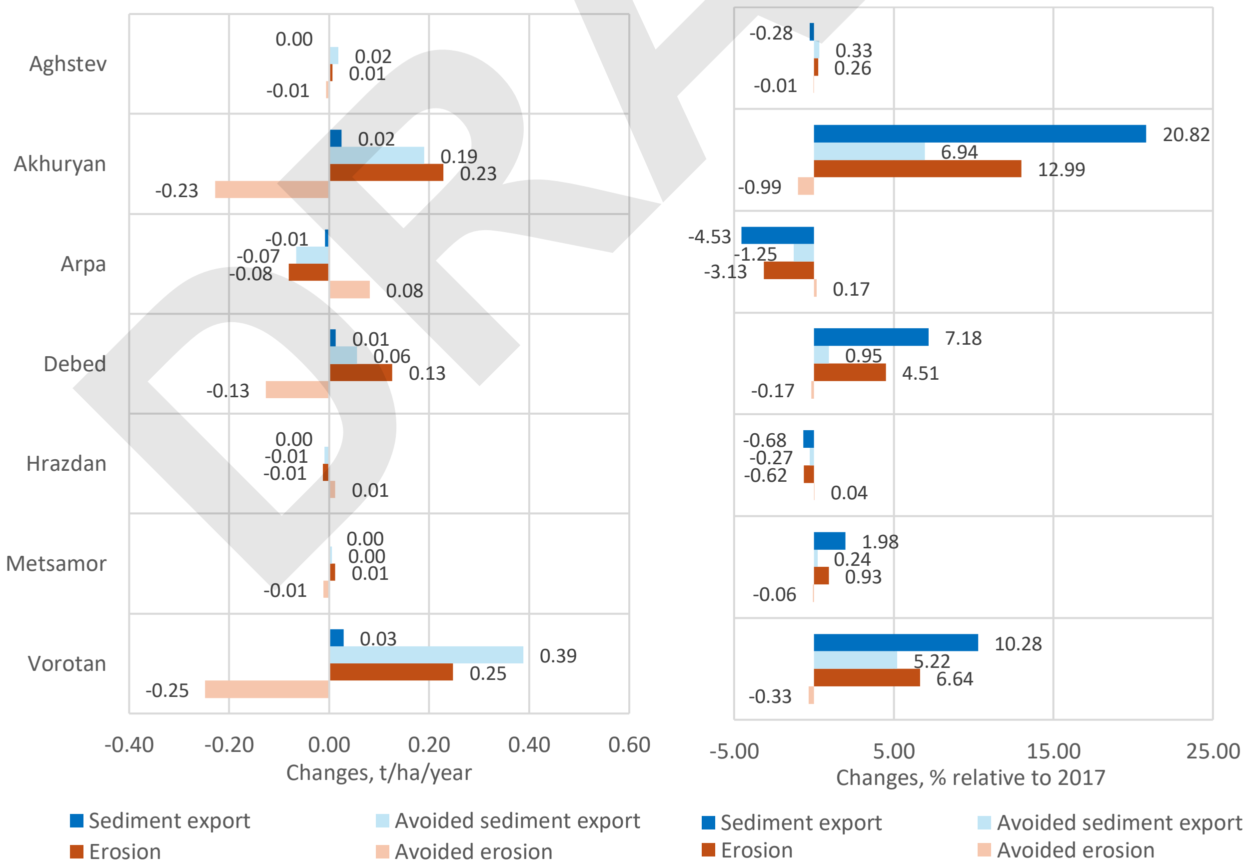


Figure 31A3-7. ES changes from 2017 to 2023 across watersheds

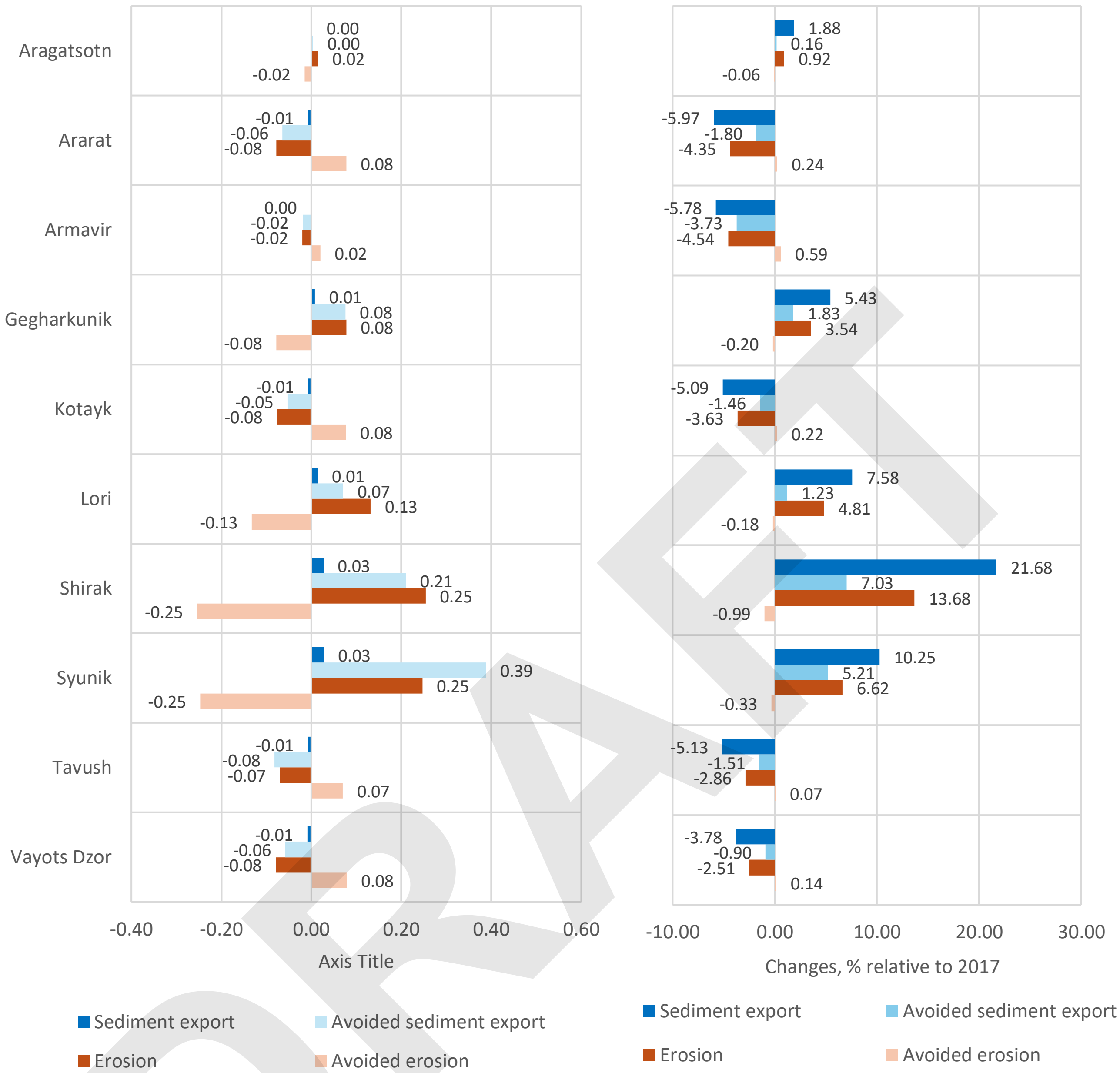


Figure 31A3-8. ES changes from 2017 to 2023 across marzes

Supply - use balance

The supply–use balance was assessed for the ES of preventing sediment export to streams. Terrestrial ecosystems reduce sediment export by 0.7–2.8 kg per cubic meter of river flow (Table 31A3-5; Figure 31A3-9). The value of 6.5 for the Aghstev watershed is not representative, because total amount of sediment export was calculated for an area larger than the actual Aghstev River watershed for which river flow data are available. The true value for that area is clearly lower.

In total, terrestrial ecosystems annually prevent about 3.2 million tonnes of sediment from entering the water that is consumed (Table 31A3-5). This ES is most important in Arpa watershed, where ecosystems annually prevent the export of 1.5 million of tons of sediment to the water used, and lowest in the Debed and Akhuryan watersheds, where this indicator is less than 100 thousands of tons (Table 31A3-5; Figure 31A3-10). However, the share of avoided sediment export in water use everywhere exceeds 95%, which means that the need for this ES is being met.

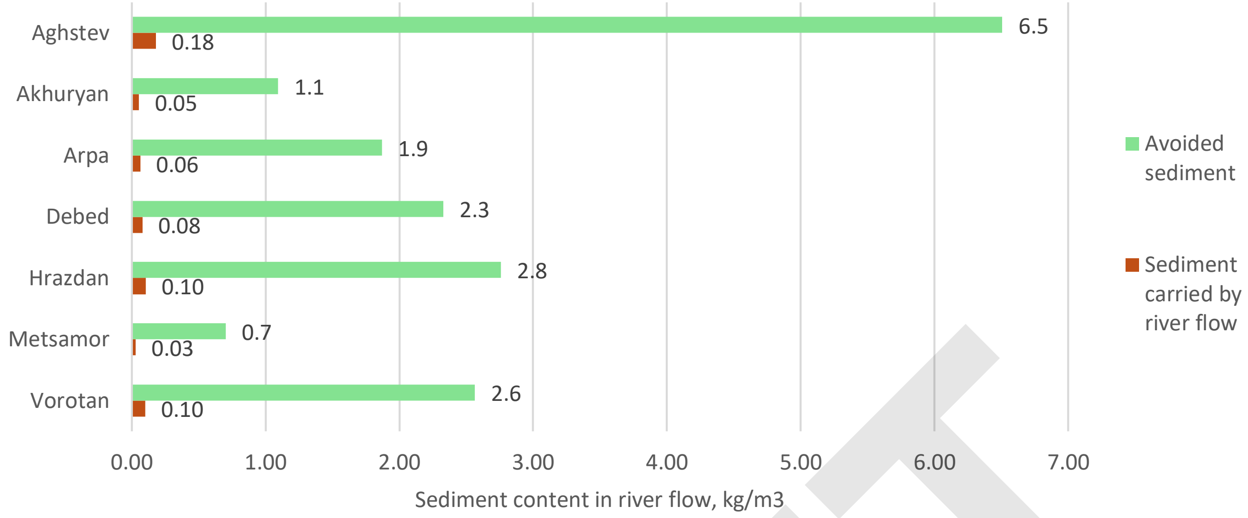


Figure 31A3-9. Sediment carried by river flow and avoided due to terrestrial ecosystems

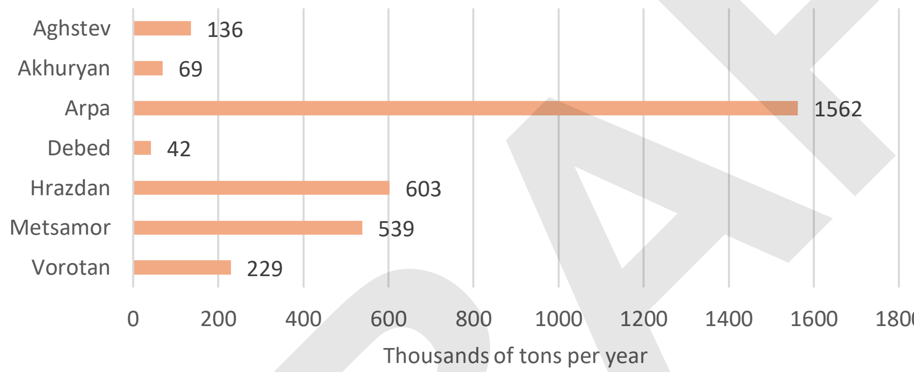


Figure 31A3-10. Total amount of sediment avoided in the volume of water consumed

Table 31A3-5. ES supply-use balance

	Total water consump-tion*, mln m3	River flow* mln m3	Total sediment export, tons/year	Total avoided sediment export, tons/year	Sediment export per 1 m3 of river flow, kg/m3	Avoided sediment export per 1 m3 of river flow, kg/m3	Total amount of sediment avoided in the volume of water consumed, tons/year	The share of avoided sediment per 1 m3 of river flow, %
Aghstev (a part of the marz Tavush)	20.90	260.00	46926.1	1691482.9	0.18	6.5	135969.2	97.3
Akhuryan (marz Shirak)	63.10	700.70	37652.6	766472.4	0.05	1.1	69023.0	95.3
Arpa (marzes Ararat and Vayots Dzor)	835.90	1177.00	74243.8	2199773.9	0.06	1.9	1562269.4	96.7
Debed (marz Lori)	18.00	960.00	75937.3	2235907.1	0.08	2.3	41923.3	96.7
Hrazdan (marzes Kotayk and Gegharkunik)	218.60	712.20	74077.3	1964292.1	0.10	2.8	602912.5	96.4
Metsamor (marzes Armavir and Aragatsotn)	769.10	1043.30	29705.2	731035.0	0.03	0.7	538904.5	96.1
Vorotan (marz Syunik)	89.50	1319.60	131836.5	3383691.3	0.10	2.6	229494.1	96.2
Total	2015.10	6172.80	470378.9	12972654.7	-	-	3180495.8	-

3.1.A4. Flood risk mitigation (InVEST Urban Flood Risk Mitigation)

We tested the model for two scenarios—average and extreme spring rainfall. The highest precipitation in Armenia occurs in May and June. While precipitation levels vary significantly across different climatic zones, for the initial model testing, we considered it reasonable to use countrywide average values. During these months, an average rainfall event delivers 12 mm of precipitation. For the extreme rainfall scenario, we assumed approximately half of the monthly precipitation in either of these months, which is 50 mm (Table 31A4-1).

Table 31A4-1. Precipitation and the number of days with rain in selected cities (http://armenia.pogoda360.ru/[1])

Climate zones	Cities	May			June			
		Days with rain	Precipi-tation, mm	Average rain, mm	Days with rain	Precipi-tation, mm	Average rain, mm	Catastrophic rain, mm (50% of monthly precipitation)
Moderate cool	Sevan	12	140	12	13	157	12	79
	Hrazdan	10	113	11	10	120	12	60
	Stepanavan	11	141	13	10	130	13	65
	Vanadzor	13	177	14	13	189	15	95
	Average	12	143	12	12	149	13	75
Moderate relatively humid	Idjevan	10	127	13	8	97	12	64
	Dilijan	11	133	12	12	133	11	67
	Alaverdi	10	134	13	8	100	13	67
	Goris	9	103	11	5	63	13	52
	Average	10	124	12	8	98	12	62
Arid	Armavir	7	33	5	7	28	4	17
	Ararat	2	39	20	1	20	20	20
	Meghri	6	81	14	3	44	15	41
	Average	5	51	10	4	31	8	26
Moderate with dry summer	Gyumri	6	78	13	5	71	14	39
	Gavar	13	147	11	13	166	13	74
	Vardenis	9	109	12	9	99	11	55
	Sisian	8	112	14	7	84	12	56
	Average	9	112	12	9	105	12	56
Average		9	110	12	8	99	12	48

ES provided by terrestrial ecosystems: the average spring rainfall scenario (12 mm)

ES maps (Figure 31A4-1) show that precipitation is almost entirely retained by vegetation and soil. Quick runoff across most of Armenia is less than 1 mm, slightly exceeding this value in some valleys. Under the bare ground scenario (all natural vegetation is replaced with bare soil), runoff retention (RT) reduces very slightly. Quick runoff (Q) increases slightly in absolute terms, but the relative changes in some watersheds are noticeable.

The ES provided by natural terrestrial ecosystems estimated as the difference in indicators between the ES on current land cover 2023 and on bare ground scenario. The influence of ecosystems on ES indicators is minor, amounting to a decrease in quick runoff by 0.01–0.08 mm and an increase in runoff retention by 1–8 liters per pixel; for the Hrazdan watershed a very small but opposite effect is observed. In relative terms, the effect on runoff retention is extremely small—everywhere under 1% of the 2023 value—and there is a wide spread in the share of quick runoff chnges, ranging from +55% to -3%. (Table 31A4-2; Figures 31A4-2 and 31A4-3).

Table 31A4-2. ES indicators across watersheds under the average rainfall scenaio (12 mm)

	Indicator	Aghstev	Akhu-ryan	Arpa	Debed	Hraz-dan	Metsa-mor	Voro-tan
Current land cover, ESRI 2023	Quick flow, mm, Q_{2023}	0.11	0.40	0.16	0.10	0.24	0.27	0.07
	Runoff retention, m^3/pix, RT_{2023}	1.19	1.16	1.18	1.19	1.18	1.17	1.19
	Total runoff retention, mln of m^3, $RT_{2023Tot}$	37.76	32.07	52.19	46.71	70.43	42.78	53.42
Bare ground scenario	Quick flow, mm, Q_{bare}	0.19	0.41	0.16	0.16	0.26	0.26	0.13
	Runoff retention, m^3/pix, RT_{bg}	1.18	1.16	1.18	1.18	1.17	1.17	1.19
	Total runoff retention, mln of m^3, RT_{bgTot}	37.51	32.04	52.16	46.49	70.30	42.81	53.16
Effect of terrestrial eco-systems	Reduction of quick runoff by ecosystems, mm $Q_{eco} = Q_{2023} - Q_{bg}$	-0.06	-0.08	-0.01	-0.06	0.01	-0.02	-0.01
	Share of Q reduced by ecosystems, % $Q_{eco}*100/Q_{2023}$	-54.88	-19.81	-3.94	-54.91	3.05	-8.13	-13.14
	Runoff retention, provided by ecosystems, m3/pix $RT_{eco} = RT_{2023} - RT_{bg}$	0.01	0.01	0.00	0.01	0.00	0.00	0.00
	Share of RT provided by ecosystems, % $RT_{eco}*100/RT_{2023}$	0.50	0.69	0.05	0.47	-0.06	0.18	0.08
	Total runoff retention, provided by ecosystems, mln of m^3 $RT_{ecoTot} = RT_{2023Tot} - RT_{bgTot}$	0.26	0.25	0.03	0.22	-0.03	0.13	0.03
	Share of total RT, provided by ecosystems $RT_{ecoTot}*100/RT_{2023Tot}$	0.70	0.79	0.05	0.47	-0.04	0.30	0.05

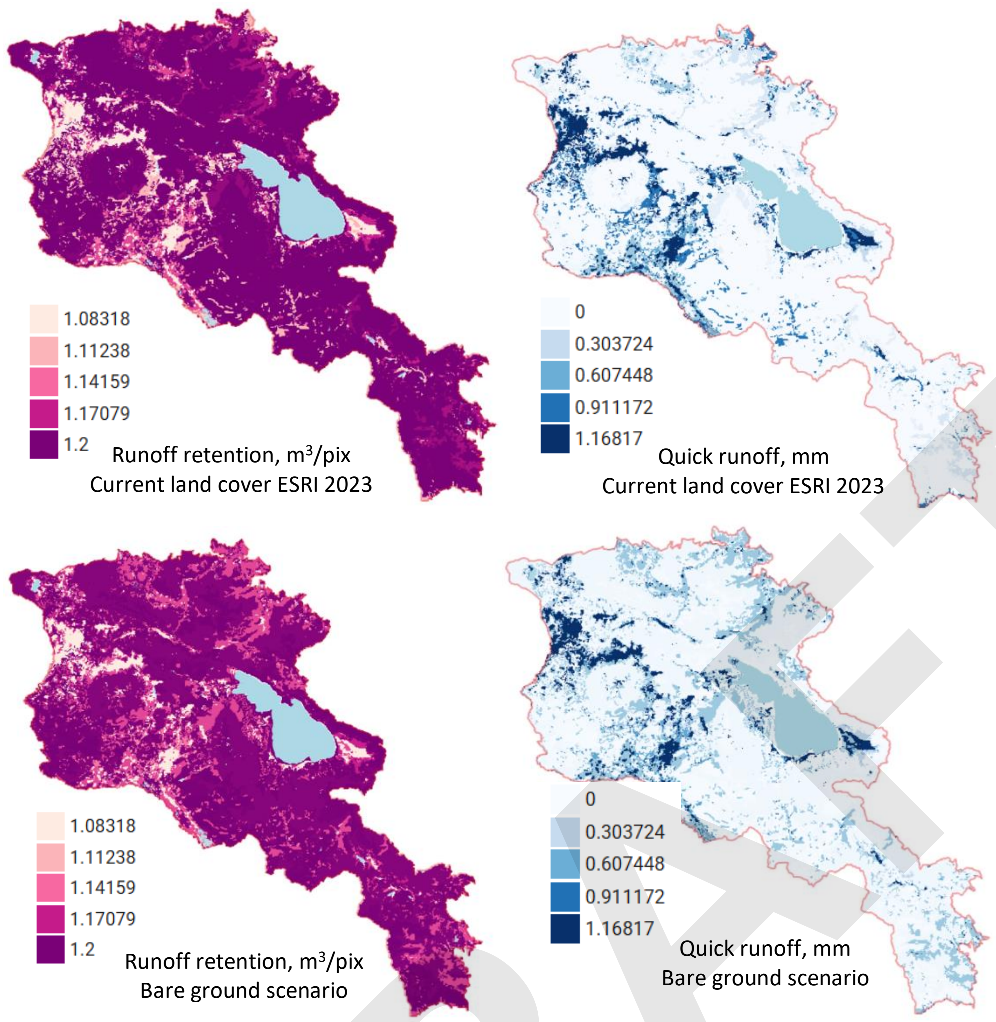


Figure 31A4-1. Maps of ES indicators under the average spring rainfall scenario (12 mm). [For detailed maps see the section "Ecosystem Services - Urban Flood Risk Mitigation – Average rainfall (12 mm)] in the progect WebGIS

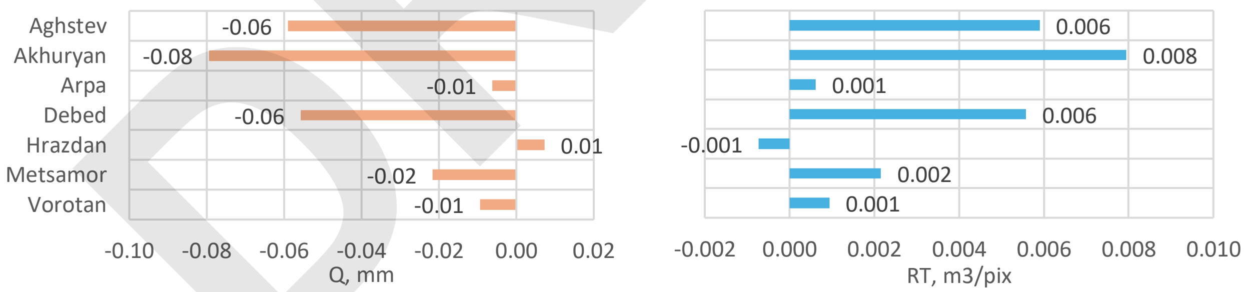


Figure 31A4-2. Ecosystem effect on quick runoff and runoff retention across watersheds under the average spring rainfall scenario (12 mm).

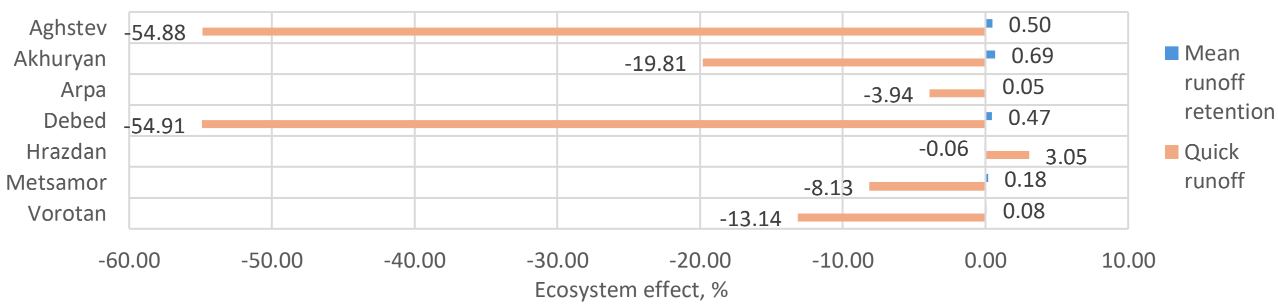


Figure 31A4-3. Ecosystem effect on quick runoff and runoff retention reltive to ES on current land cover (2023), %

ES provided by terrestrial ecosystems: the extreme spring rainfall scenario (50 mm)

Precipitation is fully retained only in a small part of the territory (the darkest areas on the map of runoff retention). As a result, quick runoff exceeds 10 mm across most of the territory and exceeds 20 mm in a significant portion. If all natural vegetation is replaced with bare ground, runoff retention decreases significantly, and quick runoff also increases noticeably. Unlike the average-rain scenario, under an extreme-rain event the ecosystems' influence on the ES indicators is substantial: they reduce quick runoff by an average of 4 mm (−32% relative to the value in 2023) and increase runoff retention by 0.4 m³/pix (+11% relative to the value in 2023). Totally, ecosystems increase runoff retention by 118 millions of m³

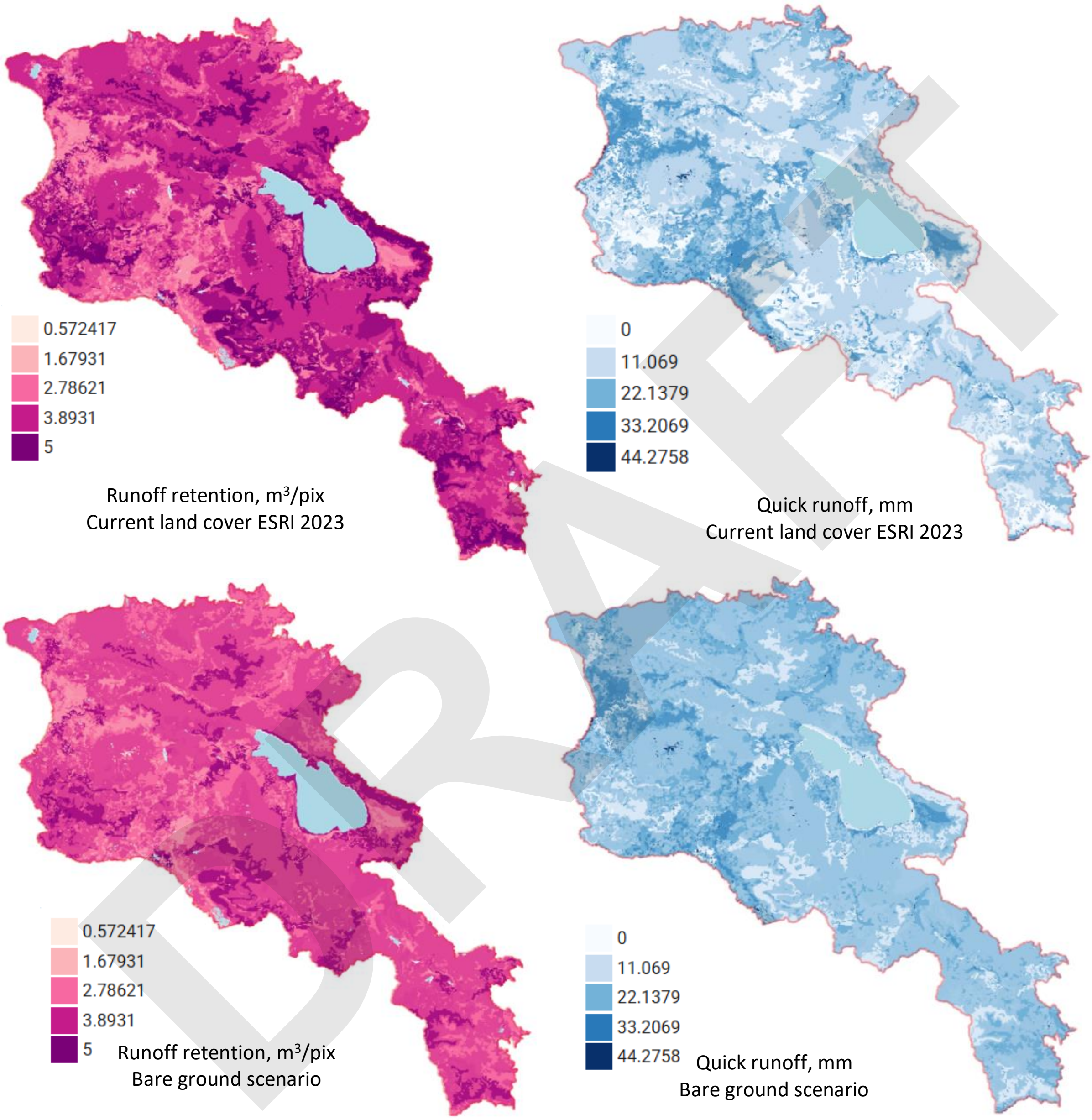


Figure 31A4-4. Maps of ES indicators under the extreme spring rainfall scenario (50 mm). For detailed maps see the section "Ecosystem Services - Urban Flood Risk Mitigation – Extreme rainfall (50 mm) in the progect WebGIS

Ecosystems increase runoff retention across all watersheds by 0.3–0.5 m^3 and reduce quick runoff by 2.9–5.3 mm (Fig. 31A4-5; Table 31A4-3). In relative terms, compared to 2023 values, the ecosystem effect is most pronounced in the Arpa and Vorotan watersheds, where runoff retention increased by 13% and quick runoff decreased by 43–49% (Fig. 31A4-6; Table 31A4-3).

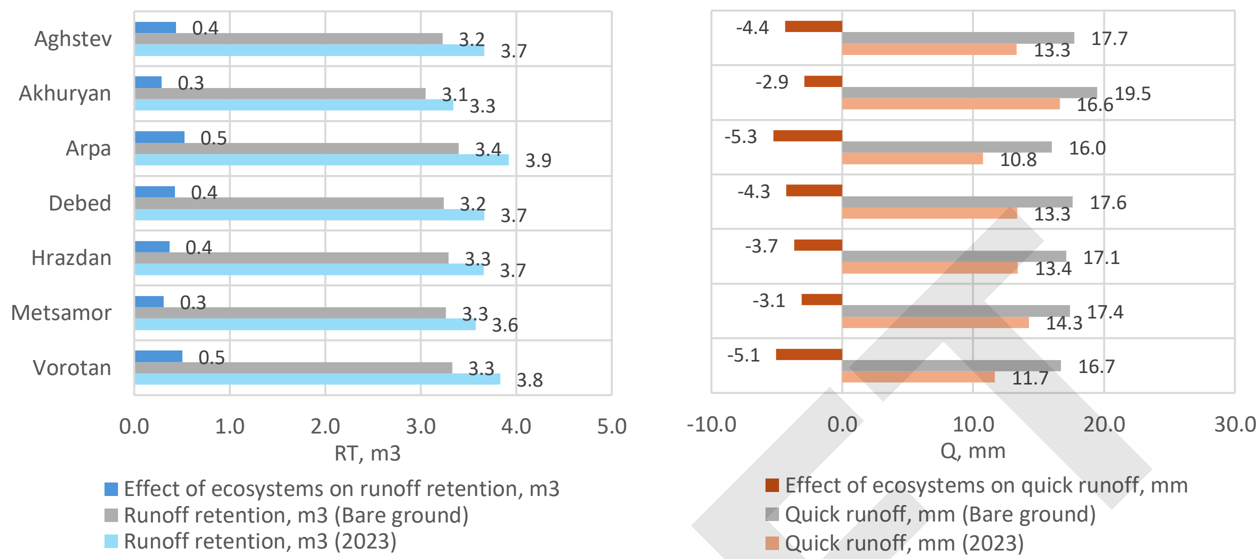


Figure 31A4-5. ES indicators under the extreme spring rainfall scenario (50 mm) across watersheds

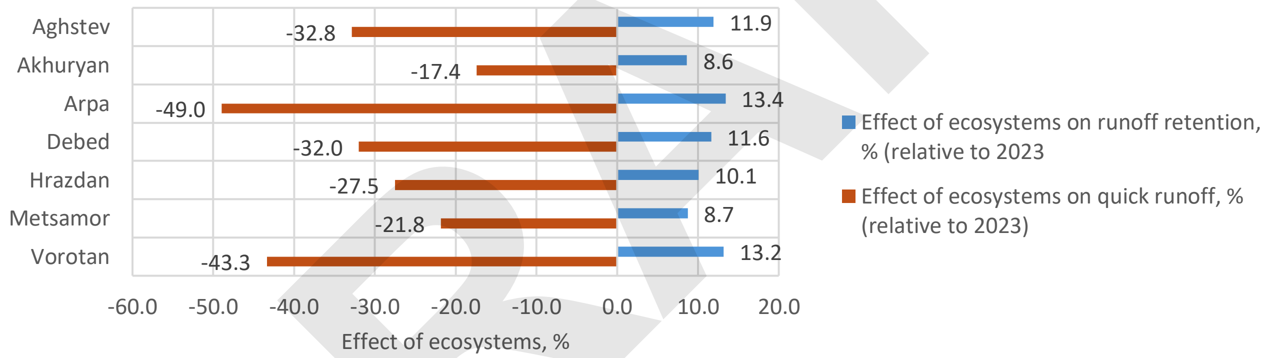


Figure 31A4-6. Ecosystem effect: percentage change in runoff retention (R) and quick runoff (P) relative to 2023, by watershed

Table 31A4-3. ES indicators across watersheds under the extreme rainfall scenaio (50 mm)

	Indicator	*Aghstev*	*Akhu-ryan*	*Arpa*	*Debed*	*Hraz-dan*	*Metsa-mor*	*Voro-tan*
Current land cover, ESRI 2023	Quick flow, mm, Q_{2023}	13.3	16.6	10.8	13.3	13.4	14.3	11.7
	Runoff retention, m^3/pix, RT_{2023}	3.7	3.3	3.9	3.7	3.7	3.6	3.8
	Total runoff retention, mln of m^3, $RT_{2023Tot}$	116	92	173	144	219	130	172
Bare ground scenario	Quick flow, mm, Q_{bare}	17.7	19.5	16.0	17.6	17.1	17.4	16.7
	Runoff retention, m^3/pix, RT_{bg}	3.2	3.1	3.4	3.2	3.3	3.3	3.3
	Total runoff retention, mln of m^3, RT_{bgTot}	103	84	150	127	197	119	149
Effect of terrestrial eco-systems	Reduction of quick runoff by ecosystems, mm $Q_{eco} = Q_{2023} - Q_{bg}$	-4.4	-2.9	-5.3	-4.3	-3.7	-3.1	-5.1
	Share of Q reduced by ecosystems, % $Q_{eco}*100/Q_{2023}$	-32.8	-17.4	-49.0	-32.0	-27.5	-21.8	-43.3
	Runoff retention provided by ecosystems, m^3/pix $RT_{eco} = RT_{2023} - RT_{bg}$	0.4	0.3	0.5	0.4	0.4	0.3	0.5
	Share of RT provided by ecosystems, % $RT_{eco}*100/RT_{2023}$	11.9	8.6	13.4	11.6	10.1	8.7	13.2
	Total runoff retention, provided by ecosystems, mln of m^3 $RT_{ecoTot} = RT_{2023Tot} - RT_{bgTot}$	14	8	23	17	22	11	23
	Share of total RT, provided by ecosystems $RT_{ecoTot}*100/RT_{2023Tot}$	11.9	8.6	13.4	11.6	10.1	8.7	13.2

Changes in ES

Land-cover changes from 2017 to 2023, as captured in ESRI data, resulted in negative changes across all watersheds except Arpa. The most pronounced negative changes are modeled for the Akhuryan watershed, where runoff retention decreased by 1.5% and quick runoff increased by 3.8%. In the other watersheds (except Arpa), runoff retention decreased by 0.1–0.7%, while quick runoff increased by 0.3–1.5% (Figure31A4-7; Table 31A4-4). Changes in ES at the marz level mirror those at the watershed level. The changes are negative everywhere except in Vayots Dzor marz. The most pronounced negative changes are modeled for Shirak marz, which lies within the Akhuryan watershed (Figure 31A4-8; Table 31A4-4).

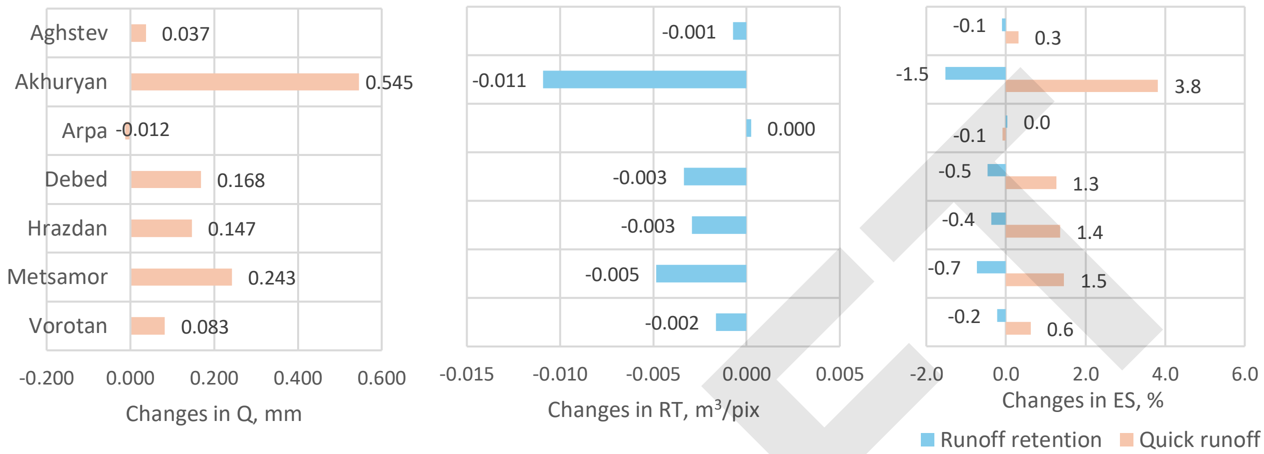


Figure 31A4-7. Changes in ES under the extreme rainfall scenaio (50 mm) from 2017 to 2023 across watersheds

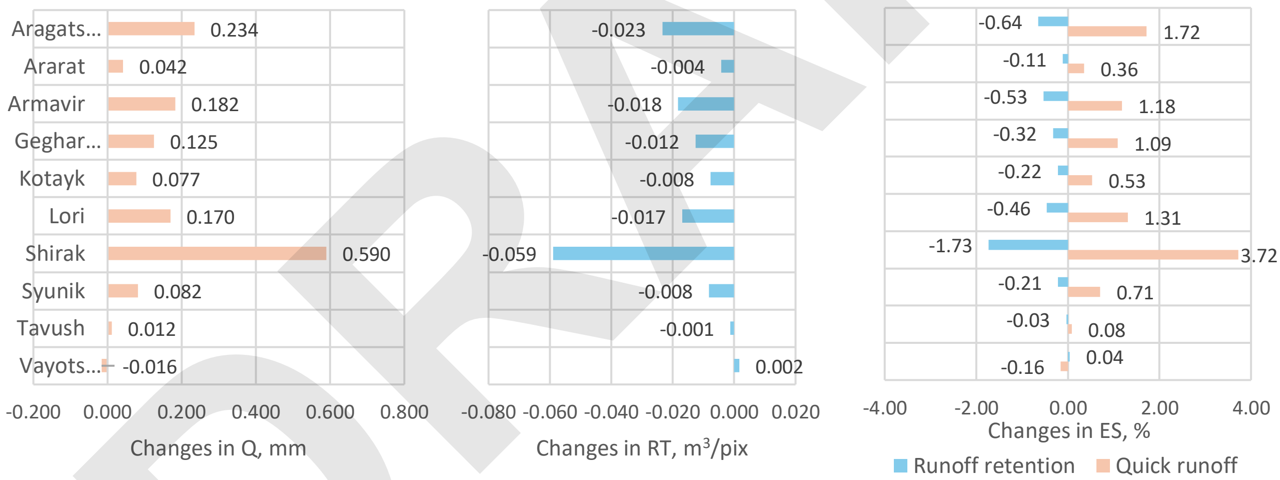


Figure 31A4-8. Changes in ES under the extreme rainfall scenaio (50 mm) from 2017 to 2023 across marzes

Table 31A4-4. Changes in ES under the extreme rainfall scenaio (50 mm) from 2017 to 2023

EAA		*Changes in absolute terms*		*Changes relative to the values in 2017, %*	
		Quick runoff, Q, mm	*Runoff retention, RT, m³/pix*	*Quick runoff, Q*	*Runoff retention, RT*
Watersheds	Aghstev	0.037	-0.001	0.315	-0.096
	Akhuryan	0.545	-0.011	3.822	-1.526
	Arpa	-0.012	0.000	-0.091	0.034
	Debed	0.168	-0.003	1.262	-0.460
	Hrazdan	0.147	-0.003	1.362	-0.373
	Metsamor	0.243	-0.005	1.461	-0.727
	Vorotan	0.083	-0.002	0.619	-0.225
Marzes	Aragatsotn	0.082	-0.008	0.706	-0.213
	Ararat	-0.016	0.002	-0.157	0.041
	Armavir	0.042	-0.004	0.357	-0.110
	Gegharkunik	0.182	-0.018	1.180	-0.527

	Kotayk	0.125	-0.012	1.089	-0.324
	Lori	0.662	-0.066	2.901	-2.438
	Shirak	0.234	-0.023	1.720	-0.643
	Syunik	0.077	-0.008	0.532	-0.217
	Tavush	0.590	-0.059	3.722	-1.728
	Vayots Dzor	0.012	-0.001	0.084	-0.033

Using this ES as a case study, we tested the feasibility of assessing ES loss resulting from the historical conversion of natural grasslands by humans. The loss was assessed as the difference between the ES indicator values for the 2023 land cover and for a fully natural land-cover scenario in which all croplands and built-up areas are replaced by grasslands. ES loss is greatest—both in absolute and relative terms—in the Akhuryan watershed (a 5% decrease in runoff retention and a 10% increase in quick runoff), and smallest in the Arpa watershed (−0.7% and +2.7%, respectively) (Figure 31A4-9). Nonetheless, the results suggest that the ES has been mostly retained.

As expected, the most significant loss of ES occurred in areas that are currently built-up where quick runoff increased the most—by 49%. For croplands, the ES loss is less substantial (Figure 31A4-10).

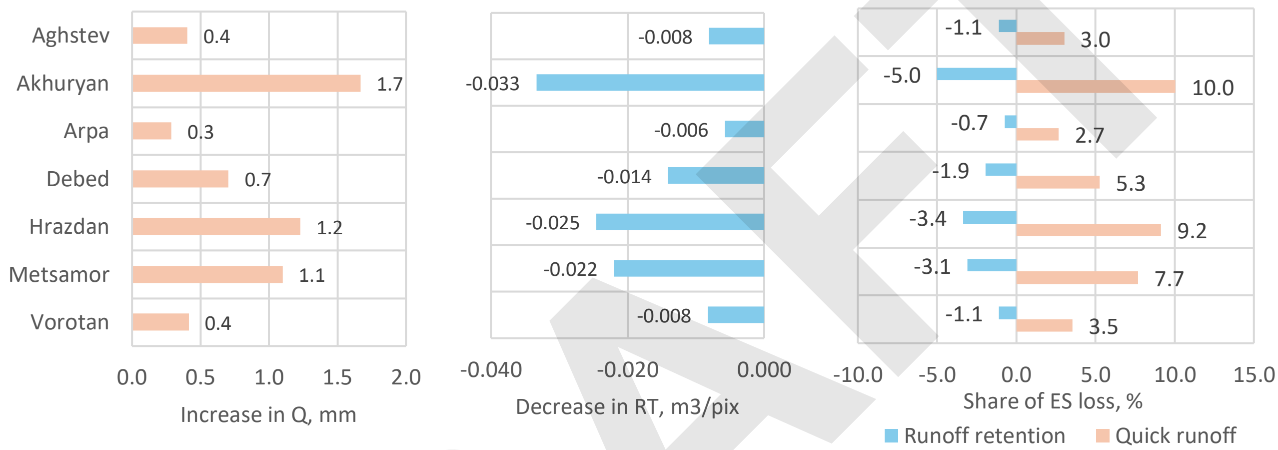


Figure 31A4-9. ES loss resulting from the historical conversion of natural grasslands by humans

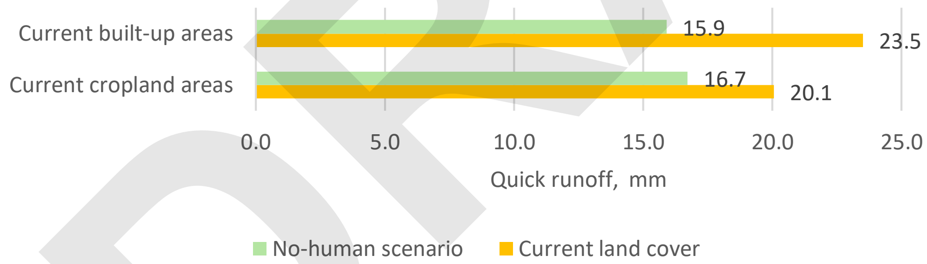


Figure 31A4-10. ES loss loss in built-up areas and in croplands

3.1.A5. Cooling effect of terrestrial ecosystems (InVEST Urban Cooling)

Methodological issues

InVEST model Urban Cooling Effect is primarily aimed at assessing the cooling effect of green spaces within urban areas. However, it also allows for evaluating this effect over large areas outside of cities. Since the assessment of urban ecosystem services is not a goal of our project, we focused primarily on the entire territory of Armenia and its impact on settlements. Green spaces within settlements was not the focus of the assessment. The InVEST Urban Cooling model calculates an index of heat mitigation based on cooling capacity of green spaces and distance from them. The model computes the cooling capacity (CC) index for each pixel based on local shade, evapotranspiration, and albedo. CC is used to estimate a temperature reduction by ecosystems. Heat Mitigation index (HM) estimates the cooling effect of large green spaces (>2 ha) on surrounding urban areas. In our case, it shows the impact of the surrounding area on the settlements. HM is equal to CC if the pixel is unaffected by any large green spaces, but otherwise set to a distance-weighted average of the CC values from the large green spaces and the pixel of interest.

The model calculations are based on indicators of evapotranspiration, albedo, the proportion of area in LULC classes that is covered by tree canopy (shade), air temperature in a rural reference area, and the UHI Effect (Urban Heat Index). The last coefficient shows the difference between the rural reference temperature and the maximum temperature observed in the city. UHI is incorporated into the model as a single value. Calculations based on a single UHI value for all of Armenia are impractical due to the significant variation in conditions across different cities. Thermal images (Landsat 8 Surface temperature data courtesy of the U.S. Geological Survey; Scene ID: LC08_L2SP_170032_20240823_02_T1) show that during the hottest period (August), Yerevan is cooler than the surrounding areas, Gyumri has approximately the same temperature, and Dilijan is warmer (Figures 31A5-1 - 31A5-3). Data from Global Surface UHI Explorer confirm that there is no single UHI coefficient for Armenia. The coefficient varies not only from city to city (Yerevan is cooler, Gyumri is warmer than surrounding area) but also across different parts of the same city (Figures 31A5-4). Therefore, we used UHI=0, meaning we did not account for the influence of this factor.

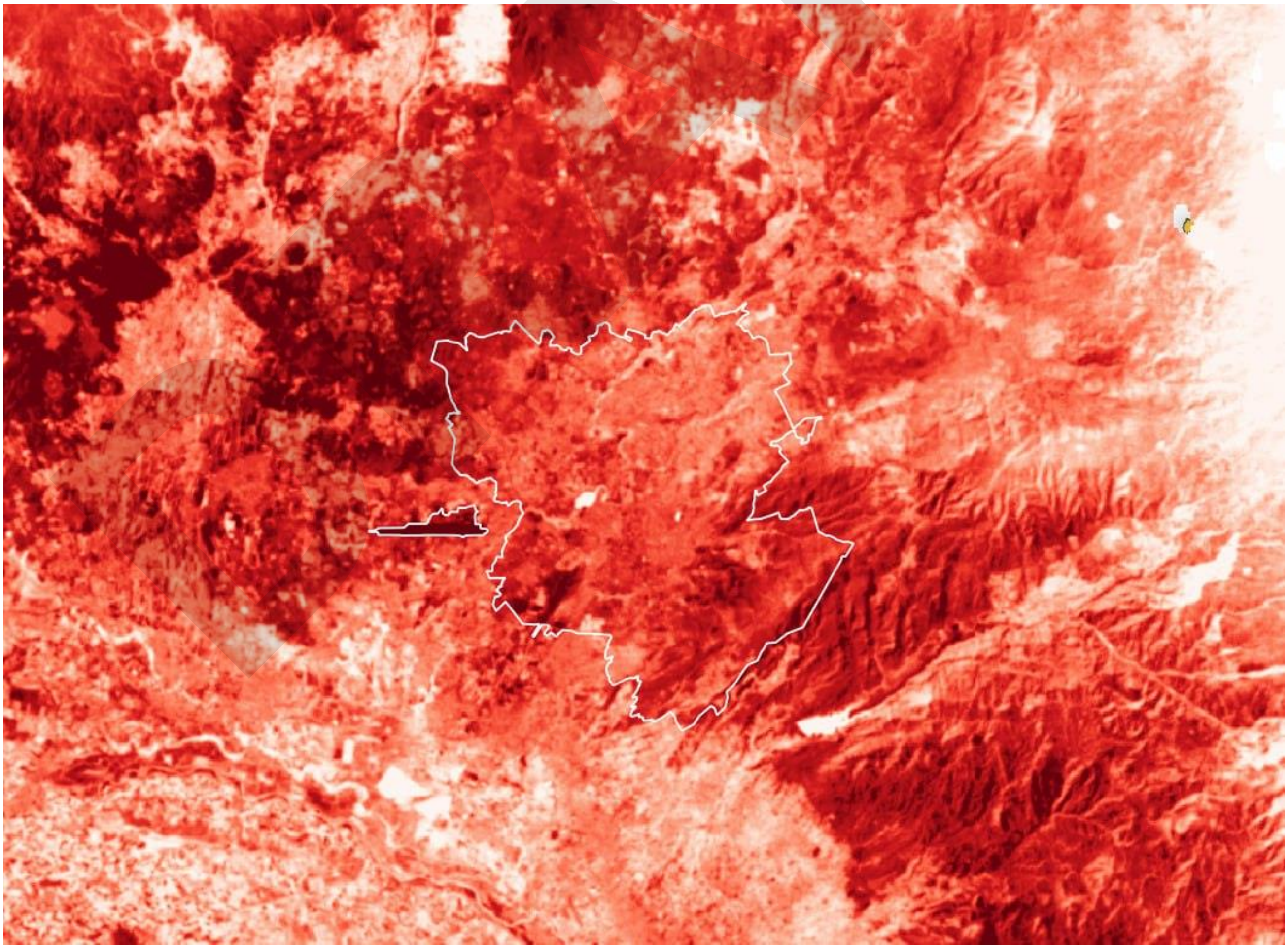


Figure 31A5-1. Thermal image of Yerevan

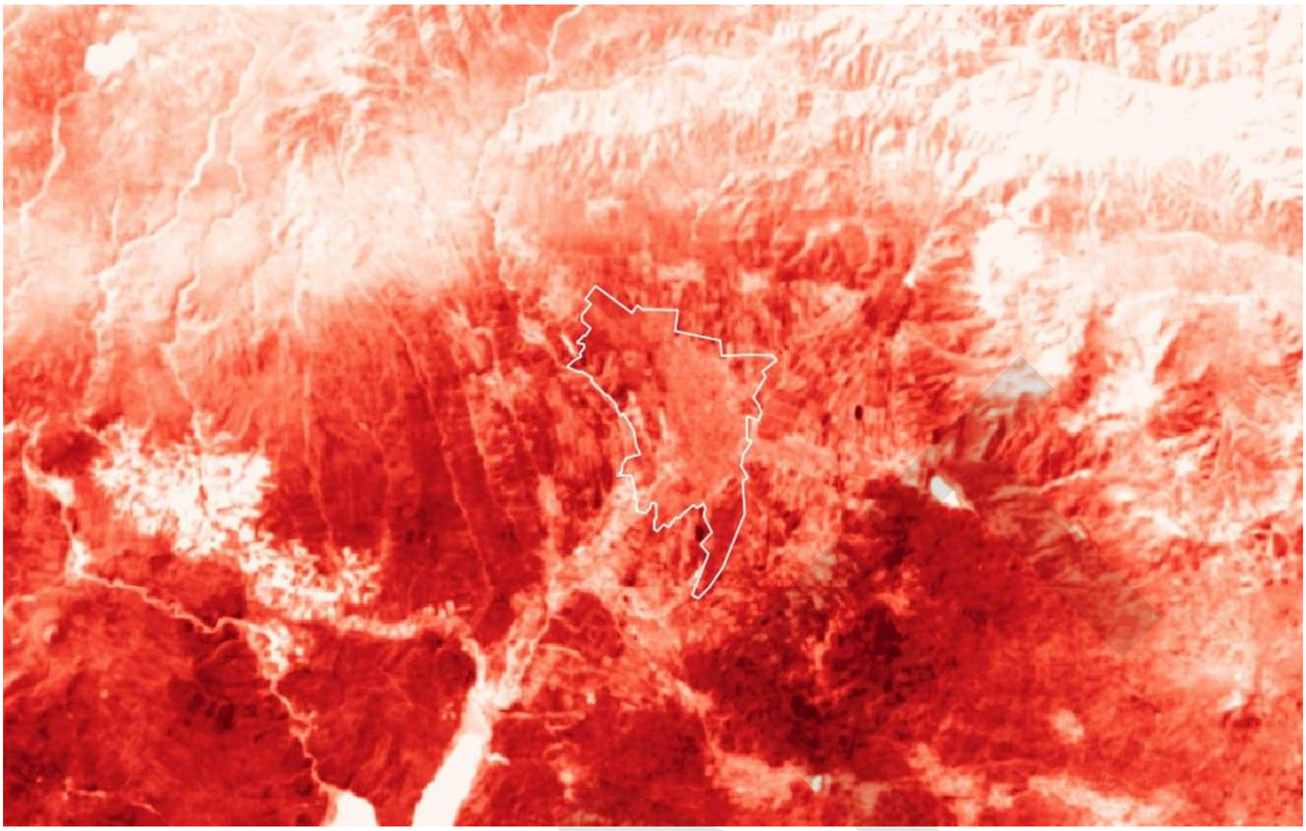


Figure 31A5-2. Thermal image of Gyumri

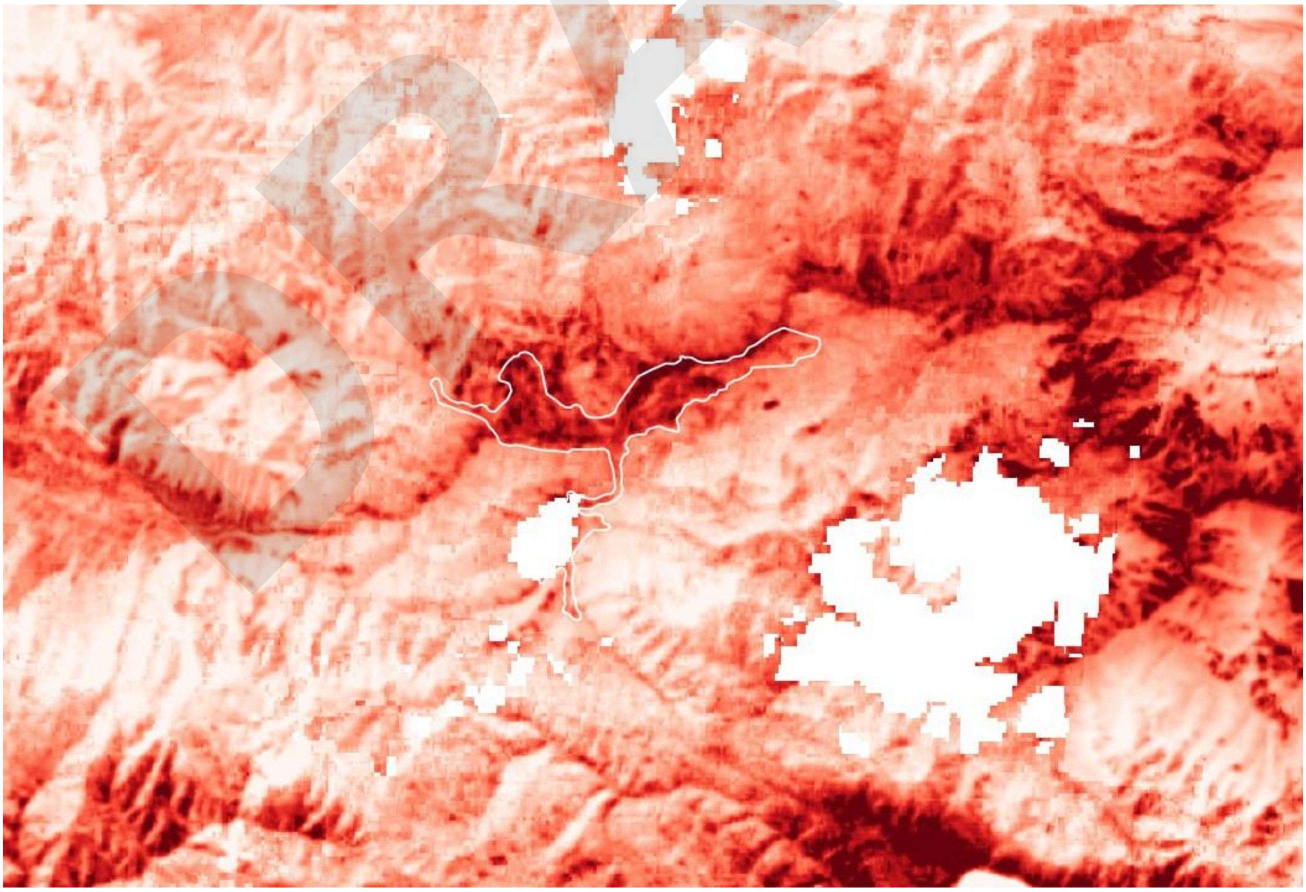


Figure 31A5-3. Thermal image of Dilijan

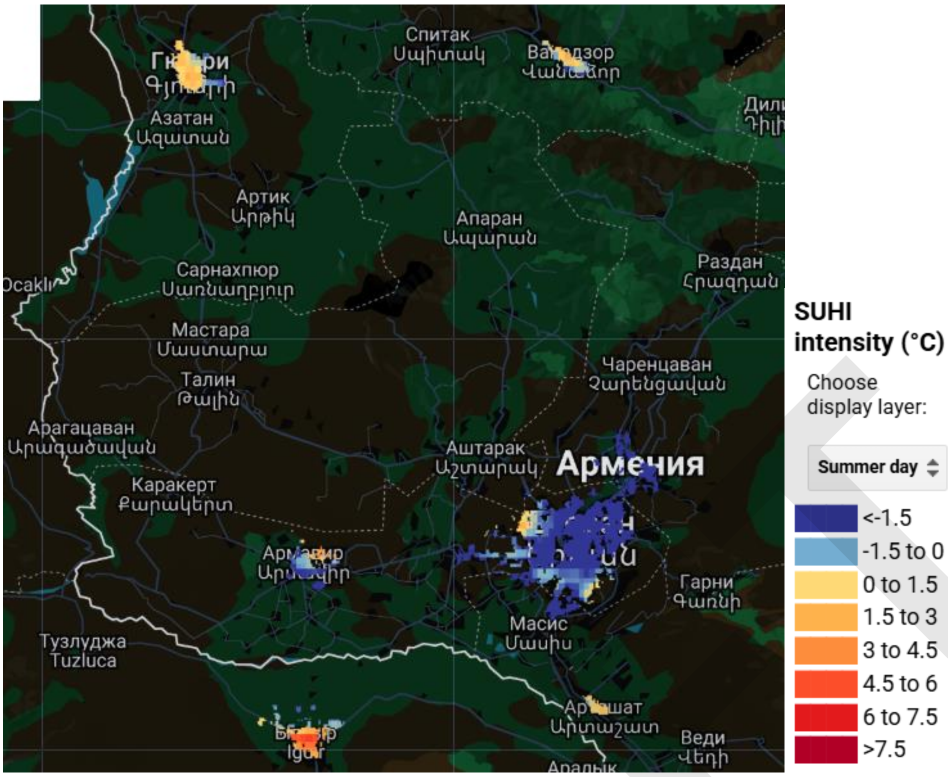


Figure 31A5-4. UHI values in summer (western part of Armeia)

ES provided by terrestrial ecosystems

Estimates of Cooling Capacity (CC) of land cover classes are based on the balance between coefficients of albedo, evapotranspiration cooling, and shade (i.e., the proportion of area covered by tree canopy). The Kc and albedo coefficients, applied in accordance with InVEST recommendations, yielded the following CC values for land-cover classes (Table 31A5-1; Figure 31A5-5):

- The highest CC is associated with forests due to high evapotranspiration cooling.
- The high CC values for croplands in arid and humid climate zones is explained by the large proportion of orchard areas in those regions (according to ArmStat data). CC of croplands in moderate dry and cool climate zones where orchards are scarce, is much lower, approaching the values for bare ground and grasslands.
- The relatively high CC values for built-up areas are due to our assumption that, on average, 20% of the area in settlements is covered by trees (shadow=0.2). Increasing the area of tree cover in settlements will increase CC of built-up areas; decreasing it will reduce CC.
- CC of grasslands is lower than that of bare ground in three of the four climatic zones, and only slightly higher in the humid zone.

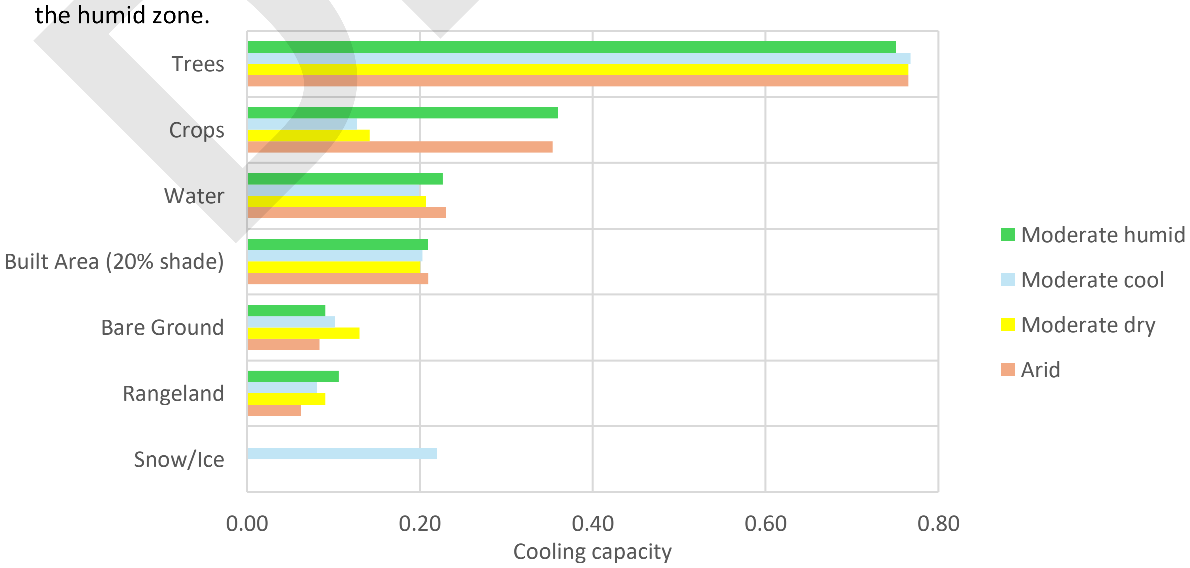


Figure 31A5-5. Cooling capacity of land cover classes in different climate zones

Table 31A5-1. Cooling capacity of land cover classes in different climate zones

	Arid zone	*Moderate dry zone*	*Moderate cool zone*	*Moderate humid zone*
Snow/Ice			0.22	
Rangeland	0.06	0.09	0.08	0.11
Bare Ground	0.08	0.13	0.10	0.09
Built Area (20% shade)	0.21	0.20	0.20	0.21
Water	0.23	0.21	0.20	0.23
Crops	0.35	0.14	0.13	0.36
Trees	0.77	0.77	0.77	0.75

In this set of CC values across land-cover classes, the most surprising point is that grasslands have a lower CC than bare ground, that is grasslands are warmer than bare ground. However, in arid zones such a CC relationship is possible because evapotranspiration from grasslands is minimal or absent during the dry season, and the albedo of dry bare soils can exceed that of dried grass. Additionally, due to surface roughness, dry grass cools more slowly than bare ground. There are examples of dry vegetation being warmer than bare soil from the tropical zone (Feldman et al., 2022) and from Central Europe (Hesslerová et al., 2013). Nevertheless, this CC relationship for Armenia requires careful verification. Changing any of the coefficients determining CC (evapotranspiration, albedo, and tree canopy cover (shade) can alter the ratio of CC among different land cover classes. This highlights the need for model calibration.

The ES provided by natural terrestrial ecosystems was estimated as the difference in indicator values between the 2023 land cover and a bare-ground scenario. In the bare-ground scenario, CC decreases markedly over areas that are currently forested and increases slightly over areas that are currently grassland in moderate cool, dry, and arid zones. Natural vegetation yields substantial cooling in forested areas, slight cooling in grasslands in moderate humid zone and slight warming in grasslands in other zones (Fig. 31A5-6).

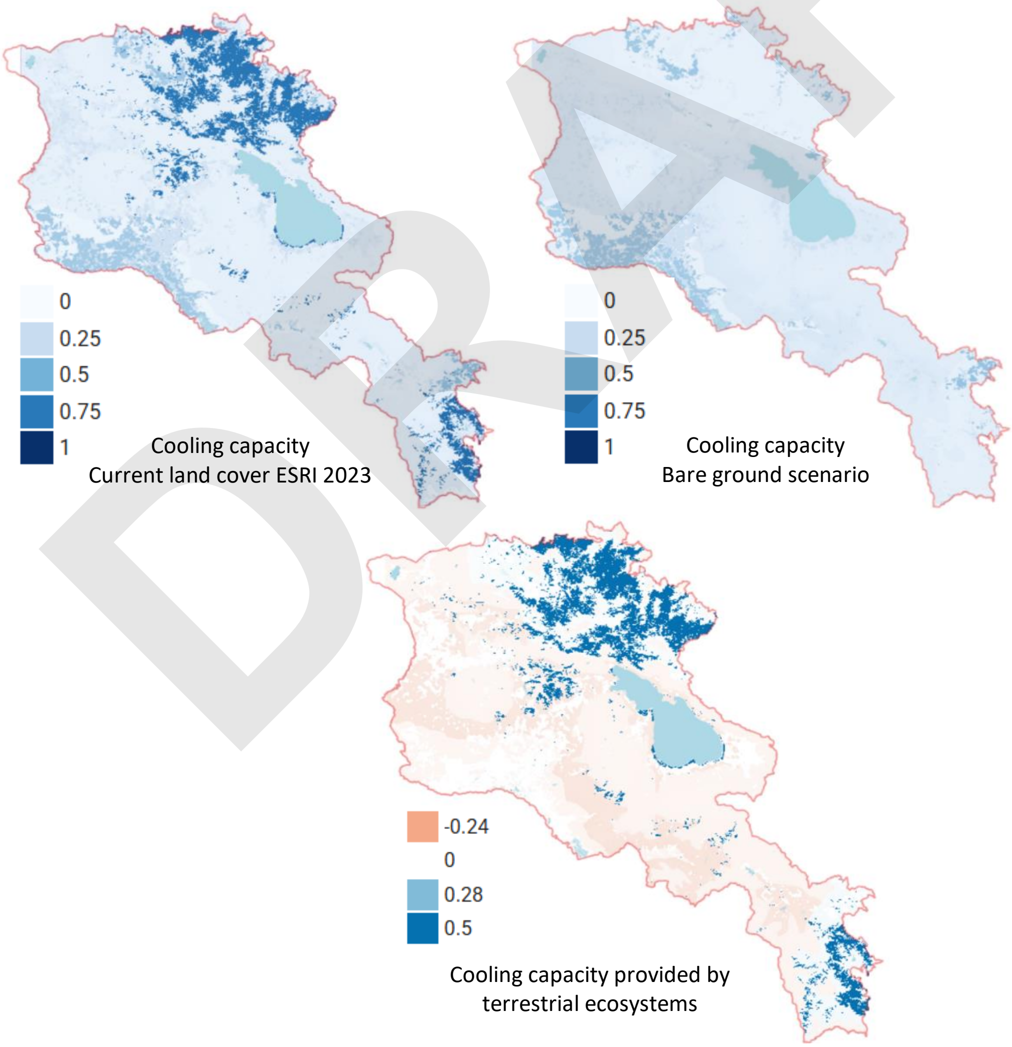


Figure 31A5-6. Maps of cooling capacity. [*For detailed maps see project Web GIS. section "Ecosystem Services/Urban Cooling"*]

Natural vegetation cools the marzes Tavush, Lori, Syunik, and Kotayk and slightly warms marzes that lack forests. In the marzes Tavush and Lori, where forest area is substantial, forest increases CC by 77% and 57%, respectively (Figure 31A5-7). On average in Armenia, CC for the current land cover is 0.19, while for the bare-ground scenario it is 0.15; thus, ecosystems on average cool the land surface, raising CC by 0.04 (21%).

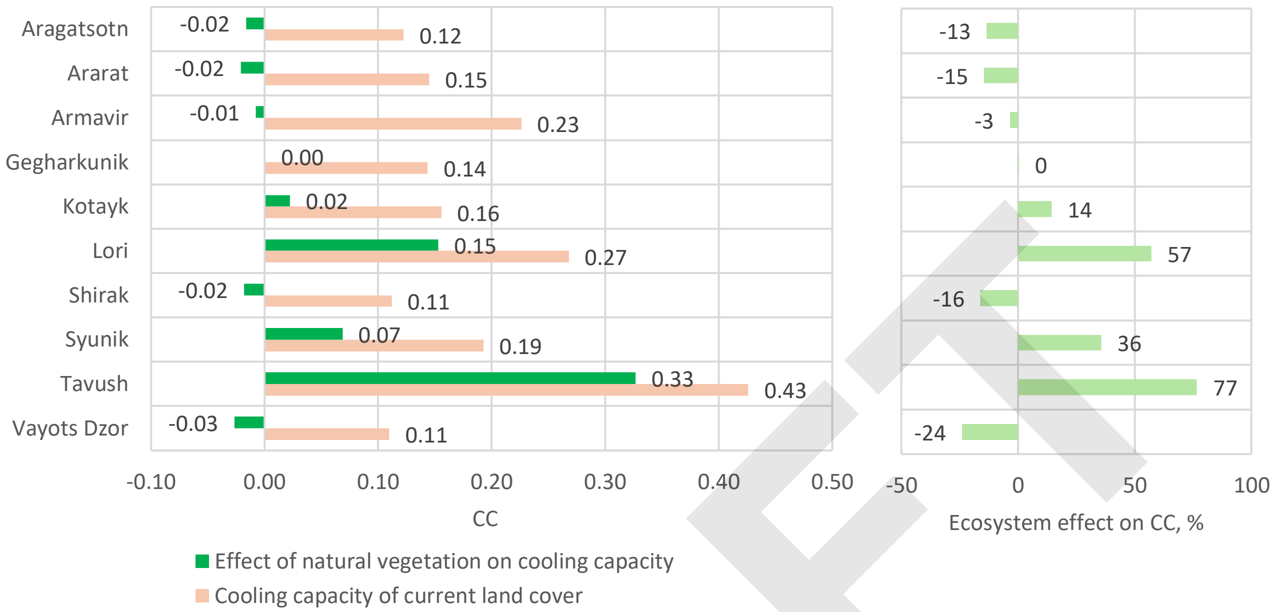


Figure 31A5-7. Cooling capacity of the current land cover and the effect of natural vegetation on cooling capacity

Since we did not assess ES within settlements, our estimate concerns the influence of surrounding ecosystems on CC within settlements, assuming a uniform 20% tree-cover (shade) for all settlements. Heat Mitigation index (HM) estimates the cooling effect of large green spaces (>2 ha) on surrounding urban areas. In our case, it shows the impact of the surrounding area on the settlements. HM is equal to CC if the pixel is unaffected by any large green spaces, but otherwise set to a distance-weighted average of the CC values from the large green spaces and the pixel of interest (Figure 31A5-8).

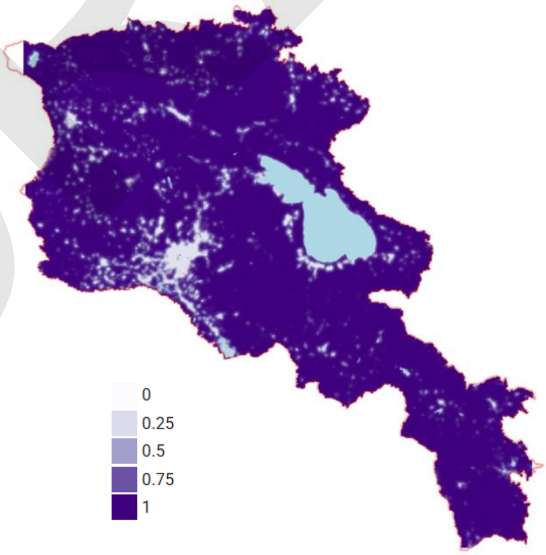


Figure 31A5-8. Heat Mitigation index. *For detailed maps see project Web GIS. section "Ecosystem Services/Urban Cooling"*

The cooling/warming effect of the surrounding ecosystems will depend on the CC of ecosystems, as well as by the geometry of the settlement boundaries, i.e., the proportion of the settlement's area influenced by the surrounding territory. Following the InVEST recommendation, we set the maximum cooling distance—the distance over which green areas larger than 2 ha exert a cooling effect—at 450 m. Across the 1,016 assessed settlements, average CC ranges from

0.06 to 0.50 (i.e., half of the maximum possible value). (Table of CC values for 1,016 settlements in Armenia). The effect of ecosystems on CC within settlements was calculated as the difference between CC values under the current land cover and under a bare-ground scenario. In most settlements (729, or 72% of those assessed), the surrounding ecosystems produce virtually no change in CC relative to bare ground. In 133 settlements (13%), the ecosystems reduce CC, i.e., exert a warming effect; these are evidently settlements surrounded by grasslands in one of three climatic zones—moderately dry, cold, or arid. In 154 settlements (15%), ecosystems increase CC, i.e., exert a cooling effect; these settlements are surrounded by forests or by grasslands in the moderately humid zone. For 20 settlements surrounded by forest, including Dilijan, Jermuk, Tsakhkadzor, the cooling effect is especially noticeable, increasing CC by 0.10–0.35 (Figure. Figure 31A5-9; Table of ecosystem effect on CC values for 1,016 settlements in Armenia).

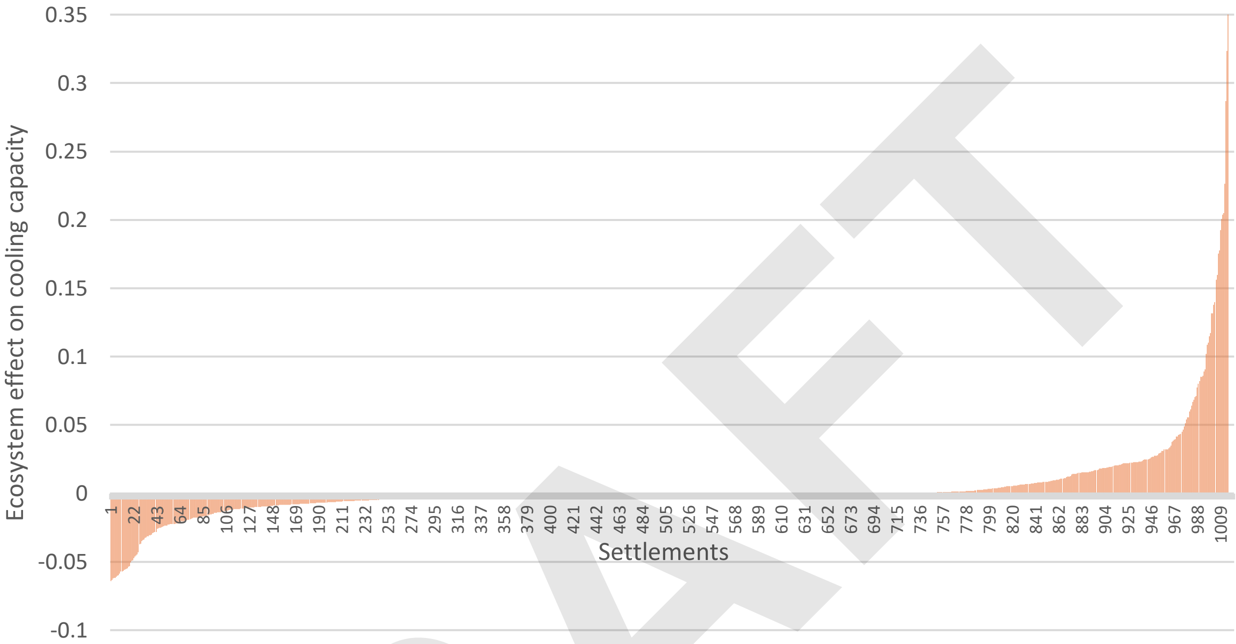


Figure 31A5-9. The effect of surrounding ecosystems on CC within settlements

ES changes from 2017 to 2023

From 2017 to 2023, there were slight changes in CC oppositely directed in different locations and marzes (Figure 31A5-10). Significant decrease in CC occurred in the Syunik due to replacement of some forests with grasslands, as well in the Ararat due to replacement of some croplands with grasslands and built-up areas. Increase in CC occurred in the Shirak and the Lori due to replacement of some grasslands with croplands (Figure 31A5-11; for changes in land cover see Section 2.2). Changes in CC in settlements range from a decrease of 61% to an increase of 65% (Table of CC value changes in settlements).

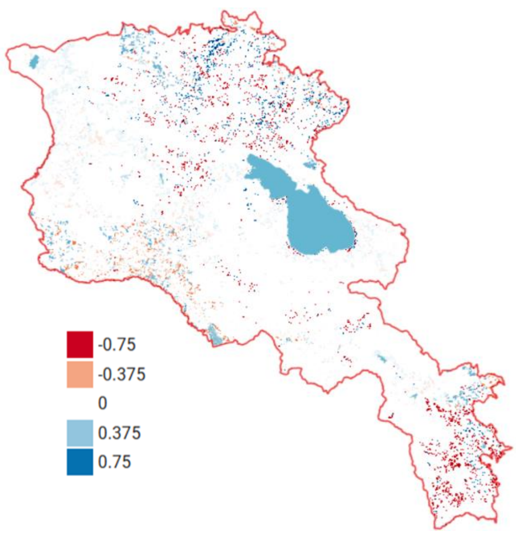


Figure 31A5-10. Changes in CC from 2017 to 2023.

[*For detailed maps see project Web GIS, section "Ecosystem Services/Urban Cooling/Dynamics"*]

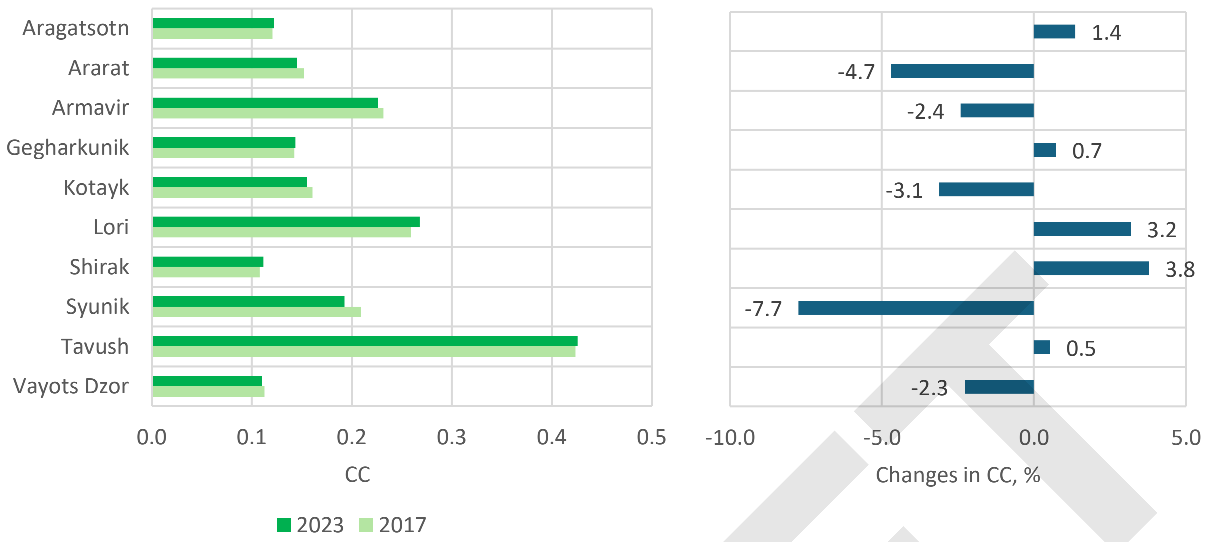


Figure 31A5-11. Changes in CC from 2017 to 2023 across marzes

3.1.A6. General issues of assessment of water-related ES

Terrestrial ecosystems perform between 11% and 96% of the modeled ES (Table 31A6-1). Ecosystems have the strongest impact on baseflow supply and erosion prevention, performing these functions almost entirely (93–96%). ES maps show that under the bare ground scenario, baseflow is almost absent (Section3.1.A2), meaning that the existing baseflow is almost entirely provided by terrestrial ecosystems. At the same time, under the current land cover, erosion is virtually absent (Section 3.1.A3), indicating that ecosystems almost completely prevent it. Only in the case of ES for flood mitigation under the average spring rainfall scenario (12 mm) was the effect of ecosystems negligible. Runoff retention and quick runoff values change only slightly in absolute terms between the current land cover and the bare ground scenario. However, even in this case, ecosystems reduce quick runoff by 14%.

Table 31A6-1. Results of ES modeling for the territory of Armenia.

ES and InVEST model	*Indicator*	*Land cover 2023*	*Bare ground scenario*	*ES Provided by natural ecosystems*	*The share of ES provided by ecosystems %*
Seasonal water flow regulation and baseflow provision SWY	Baseflow	51.3 mm (BFI * = 34%)	3.4 mm (BFI = 3%)	47.8 mm	+93%
	Quick flow	98.0 mm	120.2 mm	−22.2 mm	−18%
Prevention of soil water erosion and sediment transport to waterbodies SDR	Erosion	2.3 t/ha/year 6.8 Mt/year	48.6 t/ha/year 147.2 Mt/year	Avoided erosion −46.4 t/ha/year −140.4 Mt/year	−95%
	Sediment export	0.15 t/ha/year 0.47 Mt/year	4.5 t/ha/year 13.5 Mt/year	Avoided sediment export −4.3 t/ha/year −13.0 Mt/year	−96%
Flood risk mitigation, 50 mm rainfall scenario UFRM	Quick runoff, mm	13.3	17.4	−4.1	−24%
	Runoff retention, m^3	3.7	3.3	0.4	+11%
12 mm rainfall scenario UFRM	Quick runoff, mm	0.19	0.22	−0.03	−14%
	Runoff retention, m^3	1.18	1.18	0	0
Cooling effect UC	Cooling capacity	0.19	0.15	0.04	+21%

* BFI—baseflow index, BFI = B/(B + QF).

Consistency of the obtained results with other ES estimates for Armenia and expected ES performance across vegetation zones

Our average estimate of the erosion rate for Armenia, 2.3 t/ha/year, is very close to the values for Armenia (2.44–2.47) in the global database of modeled erosion values [65,66]. Neighboring countries (Georgia, Azerbaijan, Iran, Turkey) have similar estimates in this database—around 2–3 t/ha/year. According to Eurostat, erosion in most Mediterranean countries has a similar intensity, ranging from 2 to 5 t/ha/year [67].

The average share of baseflow in total flow, calculated based on SWY modeling results, is 34%, which corresponds to the baseflow index estimate for Armenia according to the AQUASTAT data and methodology of 35.5% (the overlap share of the internal renewable surface water resources) [68,69].

The modeling results for the prevention of erosion and sediment transport (SDR model) align most closely with the commonly accepted understanding of this ES. The SDR model identified forests as the most effective land cover class for preventing erosion, with rangelands and croplands performing worse. Among natural vegetation types, forests and woodlands provide this ES most effectively, followed by mountain meadows and then by steppes (Figure 5b,d). The model also showed that avoided erosion and avoided sediment export are the highest in areas with pronounced terrain and steep slopes, indicating that this ES is most important in those areas. While the SDR model gives plausible outputs, its accuracy depends heavily on soil, evapotranspiration, and rainfall data. The coefficients we used are based on global or European values, which should be adjusted to Armenian conditions and agricultural practices accurately.

The SWY model predicted the highest baseflow values—155 and 137 mm—in alpine and subalpine grasslands, while the forest zone showed a minimal baseflow of 29 mm, similar to that of the steppes (25 mm); both are lower than those in the semidesert and desert zones (Figure 5a,c). The proportion of baseflow contributed by ecosystems is also minimal in the forest and steppe zones (89%). This counterintuitive result, in our view, is explained by the combined effects of multiple factors that determine baseflow—precipitation, terrain slope, and soil permeability. Very high absolute baseflow values in mountain grasslands result from the high precipitation in the mountains. In other mountainous regions, higher baseflow values have also been found in upper elevation areas (e.g., [70]). The low baseflow values in the forest zone are most likely the result of forests occurring predominantly on the steep slopes of gorges and mountains. According to our assessment, the highest mean slope among the vegetation zones occurs in the forest and juniper zones —about 20°, whereas mountain grasslands and steppes occupy gentler slopes from 10° to 17°, and the semideserts and the single desert patch lie on plains with an average slope of about 6°. The moderate baseflow of 38 mm and the high proportion of it contributed by ecosystems (94%) in the semidesert zone are most likely due to its location in areas with the gentlest relief and a high proportion of highly permeable soils. The only small desert patch remaining in Armenia exhibits moderate baseflow of 34 mm an extremely high proportion of baseflow provided by ecosystems (98%), probably because it is entirely located on soils with the highest permeability (for detailed maps, see the project web-GIS [44]).

In this set of CC values across land-cover classes, the most surprising point is that grasslands have a lower CC than bare ground, that is grasslands are warmer than bare ground. However, in arid zones such a CC relationship is possible because evapotranspiration from grasslands is minimal or absent during the dry season, and the albedo of dry bare soils can exceed that of dried grass. Additionally, due to surface roughness, dry grass cools more slowly than bare ground. There are examples of dry vegetation being warmer than bare soil from the tropical zone (Feldman et al., 2022) and from Central Europe (Hesslerová et al., 2013). Nevertheless, this CC relationship for Armenia requires careful verification. Changing any of the coefficients determining CC (evapotranspiration, albedo, and tree canopy cover (shade) can alter the ratio of CC among different land cover classes. This highlights the need for model calibration.

Consistency of the tested InVEST models with Armenia's natural conditions

The SWY model does not account for snow accumulation and melt, which is a major factor in Armenia's highland hydrology. The approach we used in this study ignores snow sublimation and local variations in melt timing. For a more accurate assessment, it is clearly necessary to incorporate specialized models, such as SNOW-17, which can significantly improve runoff predictions [73]. Another significant limitation is the lack of accounting for geological structure, which is important for baseflow assessment.

Modeling the ES of flood risk mitigation (UFRM model) showed meaningful ecosystem effects only under an extreme rainfall scenario (50 mm). For average spring rainfalls (12 mm), the model barely registered any difference between current land cover and the bare ground scenario, which is due to low amounts of precipitation. It suggests the model may not be picking up more subtle but still important differences in landscape runoff retention under typical rainfall events. That raises questions about the model's sensitivity under more typical weather conditions. Moreover, the UFRM model accounts only for the water retention capacity of ecosystems but does not consider water flow across the terrain, which makes it poorly suited for the mountainous conditions of Armenia. Slope has a critical impact on the rate of water runoff, which is why topography must be taken into account—as was done, for example, in [10].

These issues point to a clear need for InVEST model calibration (i.e., adjusting the model to match observed local data) before using its outputs in ecosystem accounts. According to [11], among the publications that used SWAT, 79% carried out some form of calibration, whereas for InVEST, only 13% of the studies did so. However, calibrated InVEST models can provide a sufficiently reliable ES assessment for strategic decision-making [74,75]. Our experience shows that InVEST models can be useful at the scoping stage, a necessary step before initiating ecosystem accounting.

However, more accurate ES assessment and mapping across the entire territory of Armenia—essential for informed decision-making—are hindered because some important coefficients in InVEST models are assigned single values, either for the entire area (the number of rainy days in the SWY and UFRM models) or for broad land cover classes (Kc in the SWY model), assuming that land-cover classes are uniform across the assessment area. As a result, models do not account for differences among areas at varying elevations or across climatic zones within Armenia.

Thus, at the preliminary stage, InVEST models proved useful for demonstrating general approaches to integrating ES assessments and maps into Armenia's ecosystem accounting. However, given the aforementioned model uncertainties and simplifications, the estimates we obtained should be regarded as ES proxies rather than reliable data for management decisions or monetary valuation and should not be used directly in national accounting without proper calibration.

As ecosystem accounting and the corresponding data collection system develop, it may become reasonable to transition to the use of hydrological and climatic models that account for a greater number of processes and local data. However, this requires another milestone in Armenia, namely the open access to such data. At later stages, it is advisable to use different models for different purposes and decision-making contexts. InVEST models can be applied for rapid and simplified ecosystem service modeling to obtain a general overview. SWAT and other detailed hydrological and climate models are necessary for producing high-resolution and accurate assessments. Decision-support models (such as RIOS, AQUATOOL, and others) are useful for the practical application of ecosystem service assessments and maps in management contexts [12,76,77].

Potential bias in assessing the role of different terrestrial ecosystems in ES provisioning

According to the SEEA-EA guidance, one of the EA tasks is to evaluate how various ecosystem types contribute to ES provisioning [1]. However, using broad land cover classes as proxies for varied and complex ecosystems can lead to significant bias. InVEST models operate with broad land cover classes such as “forest” or “grassland”. Although this approach is practical, it may obscure significant ecological diversity and misrepresent the true functioning of particular ecosystem types [78].

Given high topographic and climatic variability in Armenia, these risks are exacerbated there. With elevations ranging from 375 to over 4,000 m above sea level, the area of the country includes both lowland semi-deserts and high alpine regions. Precipitation, soil properties, temperature regimes, and land use can all change quickly in this area, sometimes within a few kilometers [33]. In Armenia the category “grassland” encompasses diverse ecosystems, ranging from alpine meadows to semideserts, that differ fundamentally in their functioning and in their capacity to provide ES. Average values of ES indicators for grasslands do not reflect the diversity of ecosystem functions and services among the various types of meadows, steppes, and semideserts (Figure 5). Likewise, not all forests have the same function in regulating hydrology; their contributions are influenced by species composition, slope gradient, canopy density, and soil depth [21–23]. Thus, conducting ES accounting at the level of broad land cover classes fails to capture ecosystem-specificity, offers little for informed ecosystem-management decisions, and in some cases can lead to incorrect decisions. For example, using the average baseflow value for grasslands (59 mm) leads to underestimating the contribution of mountain grasslands with baseflow values of 137–155 mm to the total baseflow volume.

Biases in understanding the roles of different ecosystem types in delivering ES could have negative consequences for environmental policy. Globally, an example of such a bias is the underestimation of grasslands’ roles in water provision and soil protection, alongside a primary focus on the ecological value of forests. This often leads to afforestation of natural grasslands, resulting in negative impacts on water regulation and soil quality [28,79,80].

Even within vegetation zones—which partially account for the diversity of grasslands and woody vegetation—there remains a wide spread of ES values across individual polygons, indicating the high heterogeneity of environmental conditions and plant communities within them. This raises the question of whether a more detailed ecosystem classification and mapping should be used to assess ecosystems’ roles in delivering ES.

The feasibility of assessing the entire bundle of water-related ES

Water regulation is closely linked to the prevention of soil erosion, as well as the cooling effect of evapotranspiration. Tested InVEST models use the same data and coefficients (Figure 31A6-1). Therefore, it makes sense to consider water-regulating and soil-protection ecosystem services together as an integrated whole.

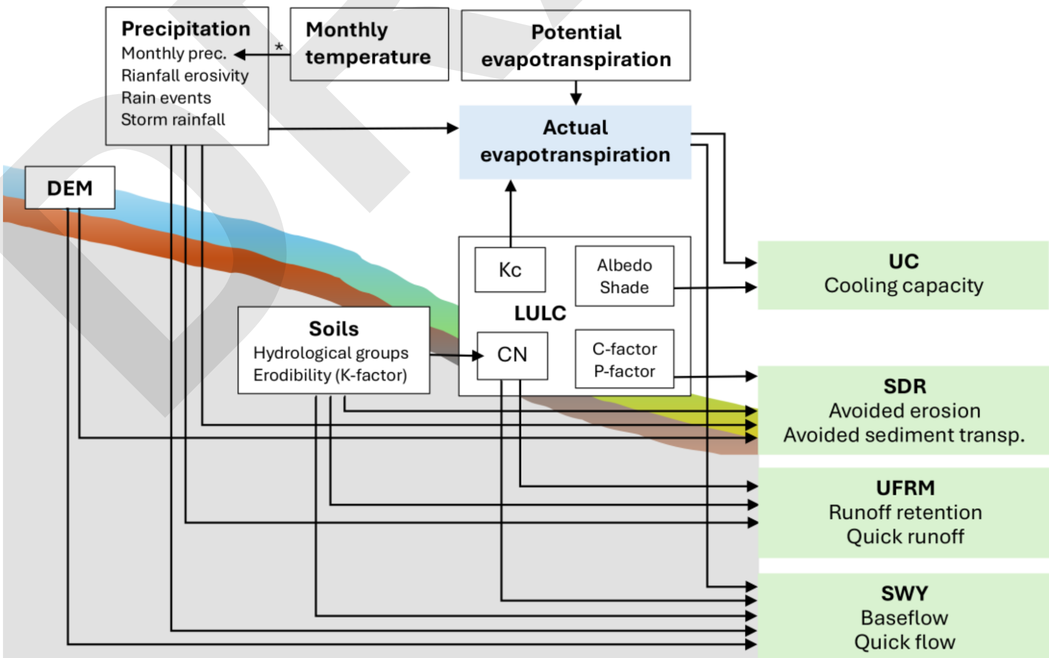


*Figure 31A6-1. The relationship between the coefficients used in the tested models. *Average monthly temperature values were used to adjust the average monthly precipitation, taking into account the snow season.*

Our preliminary testing of ES models did not include ES of rainfall pattern regulation, which was recently added to the recommended list of ES in the SEEA-EA framework [1]. In recent years, this ES has been increasingly recognized as fundamentally important, as it completes the hydrological cycle on land. Without accounting for this ES, vegetation appears only to evaporate moisture, reducing water availability on land. However, evaporated moisture in the atmosphere contributes to precipitation recycling, which increases the overall amount of rainfall and enables its transport further inland [24,76-79].

SEEA-EA recommendations imply a subcontinental scale of this ES, exceeding the territory of Armenia; however, several studies have also highlighted its relevance at the regional level, including in arid zones [77, 80-82]. We did not include this ES in our testing, as it is not yet represented in the set of relatively simple models like InVEST ready to use without specialized research. Moreover, as noted by Wierik et al. [83], research on this ES has focused on the global level or on tropical forests, while there is a knowledge gap for other zones, including temperate forests and grasslands.

According to estimates by Tuinenburg et al. [84], Armenia lies within a zone with high evaporation recycling ratios—typical for most land areas—meaning that nearly all evaporated moisture eventually returns as precipitation. The country also exhibits medium precipitation recycling ratios: in winter, 50–60% of precipitation originates from land evaporation, and in summer, this figure rises to 70–80%. However, these are only averaged estimates, which in reality may reflect a mosaic of areas where forests either increase or decrease water availability [85].

For Armenia, as a mountainous country, another potentially important but still poorly formalized function is the capture of atmospheric moisture by vegetation in upland areas, which act as “water towers” [24,76].

Models of ESs that return vegetation-evaporated moisture to land should be developed and included alongside other water-regulating ES in national EA.

3.1.B. Carbon storage in soil and tree biomass

The assessment of soil carbon stocks at 0-30 cm depth was made using data from the World Soils 250m Organic Carbon Stocks dataset (https://www.arcgis.com/home/item.html?id=496c19426413472194b10b2b0952fccd#) (Figure 31B-1). Carbon stock in tree biomass was estimated using the area of tree cover from Esri (2023) and the average carbon content of wood. According to the Acopian Center, a pilot study conducted in forests near the town of Vanadzor (northeastern Armenia) revealed a value of 98 tC/ha. However, data from State of the World's Forests (FAO, 2011) estimate the total carbon stock in living forest biomass in Armenia at 13 million tons, with an average of 48 tC/ha across the country. We used this average in our calculations.

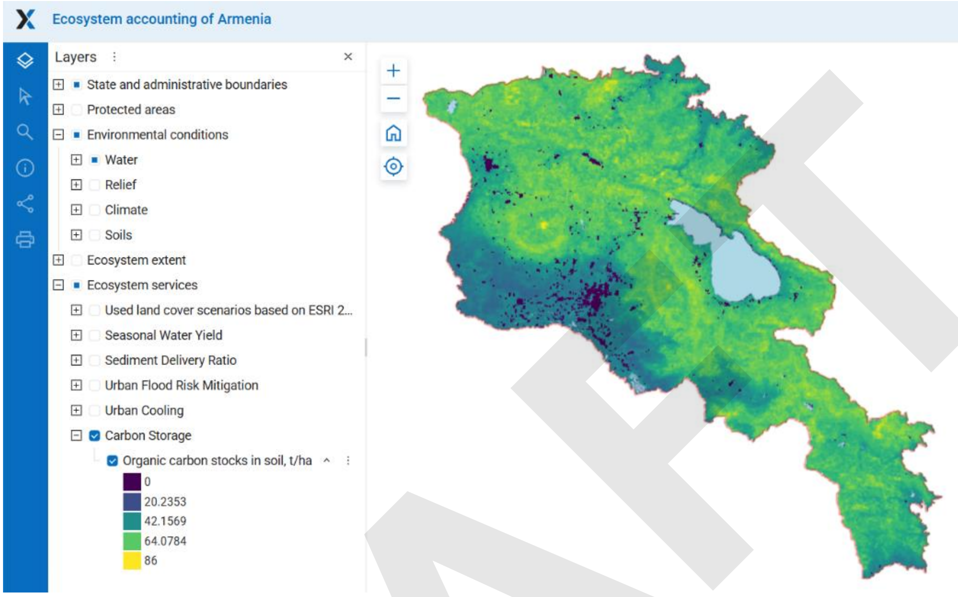


Figure 31B-1. Soil carbon stocks, t/ha; for details see project web-GIS (https://bccarmenia.nextgis.com), section Ecosystem Services

Carbon stocks in Armenia, marzes and vegetation zones

The average soil carbon content across provinces ranges from 62 to 32 tC/ha and across vegetation zones (Section 2.3) from 64 to 29 tC/ha. Total carbon stock in 0-30 cm depth soils in Armenia amounts to 158.4 MtC, and in tree biomass 15 MtC (in 2023). The total carbon stock in soils and tree biomass amounts to 173 MtC. Due to the relatively small forest area in Armenia, the main carbon stock (91,4%) is stored in soils.

Carbon content in the 30-cm soil layer in most marzes ranges between 52–61 t/ha. In Armavir and Ararat, it is lower (32 and 44 t/ha, respectively) due to the carbon-poor semi-desert soils (Figure 31B-2 a). The total carbon stock is highest in marzes Syunik, Lori, and Gegharkunik (25-28 MtC), and lowest in marz Armavir (4 MtC) because of low carbon content in soil and small area of ecosystems (Table 31E-1; Figure 31B-2 b). The carbon stock in tree biomass makes a noticeable addition to soil carbon only in marzes Tavush and Lori.

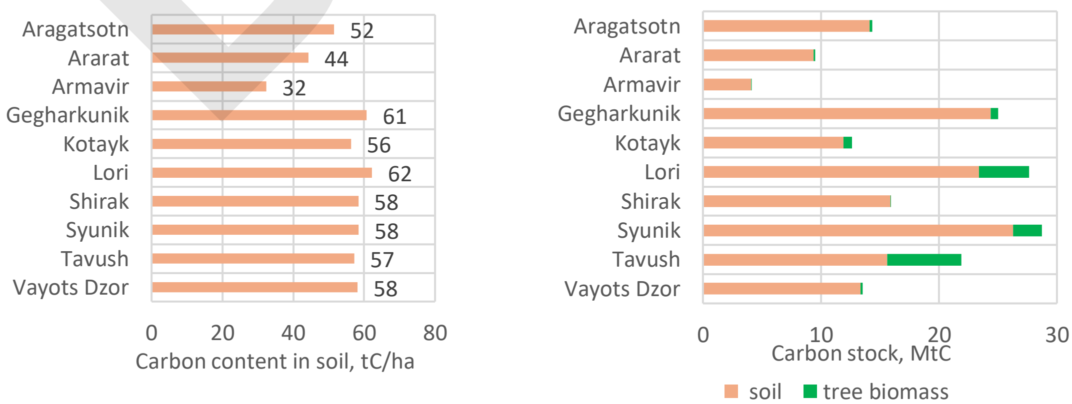


Figure 31B-2. Carbon stocks across marzes: a) Carbon content in the 30-cm soil layer, tC/ha; b) Carbon stock in soil and tree biomass, MtC. Area of the marz Gegharkunik is accounted excluding Lake Sevan

According to the World Soils 250 m Organic Carbon Stocks dataset, soil carbon content is highest in mountain grassland zones (64 t C/ha) and in the forest and steppe zones (57–59 t C/ha). The lowest carbon content is found in desert and semi-desert soils (29–35 t C/ha) (Table 31B-2; Figure 31B). Soil carbon stock is highest in the steppe, forest, and subalpine zones, and lowest in the juniper zone due to its limited extent. Total carbon stock is highest in the forest zone because of the substantial contribution from tree biomass.

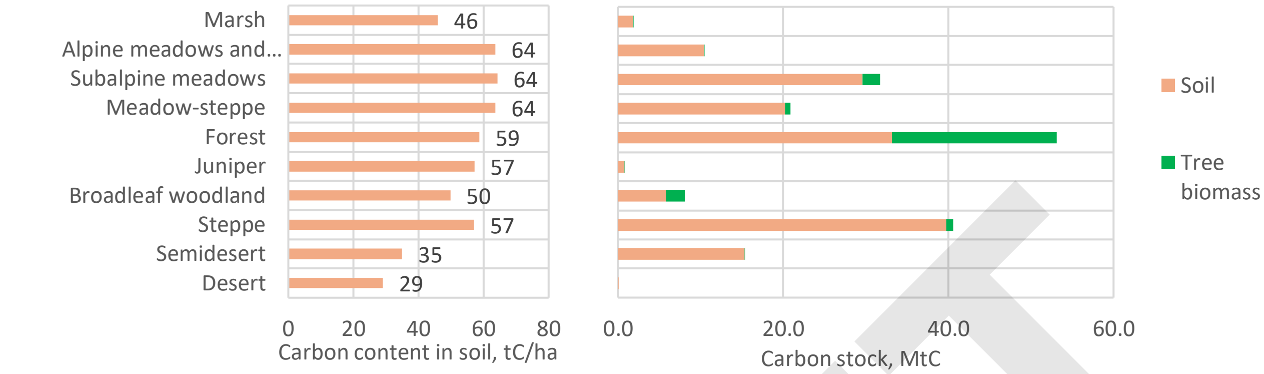


Figure 31B-2. Carbon stocks across vegetation zones: a) Carbon content in the 30-cm soil layer, tC/ha; b) Carbon stock in soil and tree biomass, MtC

Changes in carbon stock in tree biomass from 2017 to 2023

Changes in carbon stock were assessed based on changes in the area of tree cover, using ESRI data. Across marzes, the most significant absolute decline was observed in Syunik, and the most significant relative decline was observed in Armavir marz (Table 31B-1; Figure 31B-3). Across vegetation zones, stocks declined in all zones except the desert (which has no woody vegetation) and broadleaf woodlands. The largest decline occurred in the forest zone; however, compared with 2017, it amounted to only 4% (Table 31B-2; Figure 31B-4).

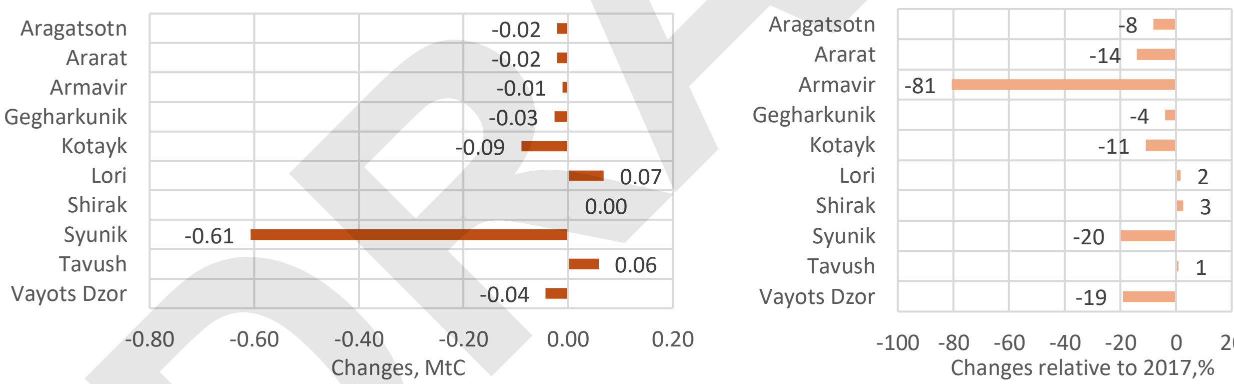


Figure 31B-3. Changes in carbon stock in tree biomass from 2017 to 2023 across marzes: a) Changes in carbon stock, MtC; b) Changes in carbon stock relative to 2017,%

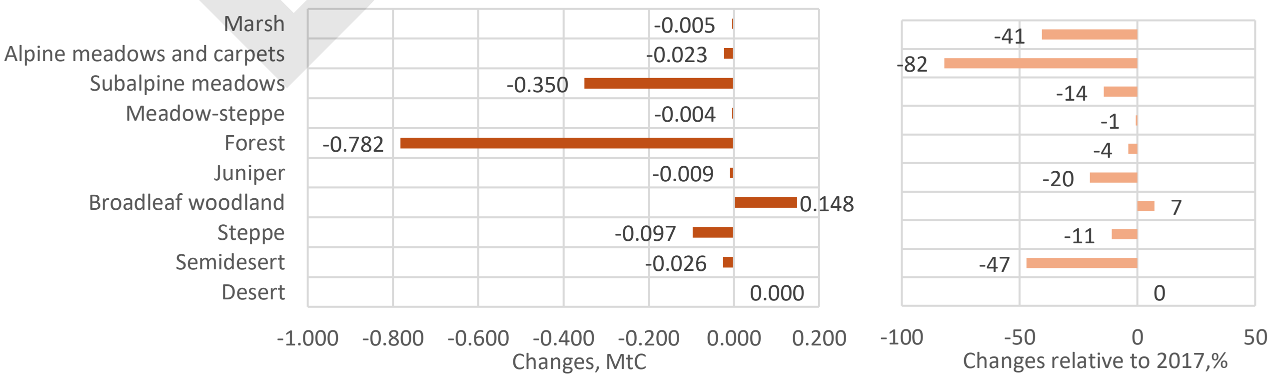


Figure 31B-4. Changes in carbon stock in tree biomass from 2017 to 2023 across vegetation zones: a) Changes in carbon stock, MtC; b) Changes in carbon stock relative to 2017,%

Table 31B-1. Carbon stock in marzes and changes in it from 2017 to 2023

	Carbon content in the 30 cm soil layer (tC/ha)	Area (excluding Lake Sevan), ha	Carbon stock in soil, MtC	Area of tree cover, ESRI 2017, ha	Area of tree cover, ESRI 2023, ha	Carbon stock in tree biomass, 2017, MtC	Carbon stock in tree biomass, 2023, MtC	Total carbon stock in soil and tree biomass, 2023, MtC	Changes in carbon stock in tree biomass from 2017 to 2023	
									MtC	% relative to 2017
Aragatsotn	52	273612	14.10	5254	4825	0.25	0.23	14.34	-0.02	-8.2
Ararat	44	211491	9.37	3047	2620	0.15	0.13	9.50	-0.02	-14.0
Armavir	32	126370	4.10	284	55	0.01	0.00	4.10	-0.01	-80.5
Gegharkunik	61	397392	24.14	13493	12956	0.65	0.62	25.01	-0.03	-4.0
Kotayk	56	211480	11.90	17174	15310	0.82	0.73	12.63	-0.09	-10.9
Lori	62	376300	23.41	86951	88374	4.17	4.24	27.65	0.07	1.6
Shirak	58	271863	15.87	1308	1343	0.06	0.06	15.93	0.00	2.6
Syunik	58	449335	26.27	63426	50774	3.04	2.44	28.71	-0.61	-19.9
Tavush	57	272624	15.60	130410	131633	6.26	6.32	21.92	0.06	0.9
Vayots Dzor	58	229654	13.36	4710	3813	0.23	0.18	13.54	-0.04	-19.0
All marzes	56	2820122	158.11	326059	311701	15.65	14.96	173.32	-0.69	-4.6

Table 31B-2. Carbon stock in vegetation zones and changes in it from 2017 to 2023

	Carbon content in the 30 cm soil layer (tC/ha)	Area, ha	Carbon stock in soil, MtC	Area of tree cover, ESRI 2017, ha	Area of tree cover, ESRI 2023, ha	Carbon stock in tree biomass, MtC		Total carbon stock in soil and tree biomass, 2023, MtC	Changes in carbon stock in tree biomass	
						2017	2023		MtC	% relative to 2017
Marsh	45.9	39055	1.79	246.8	146.6	0.01	0.01	0.02	-0.005	-40.6
Alpine zone	63.6	163794	10.42	588.6	106.4	0.03	0.01	0.03	-0.023	-81.9
Subalpine zone	64.2	460885	29.60	51282.2	43987.0	2.46	2.11	4.57	-0.350	-14.2
Meadow-steppe	63.6	318335	20.26	13415.2	13327.4	0.64	0.64	1.28	-0.004	-0.7
Forest zone	58.7	564380	33.14	432710.2	416416.2	20.77	19.99	40.76	-0.782	-3.8
Juniper	57.2	13560	0.78	901.2	720.7	0.04	0.03	0.08	-0.009	-20.0
Broadleaf woodland	49.8	117317	5.84	43015.7	46096.8	2.06	2.21	4.28	0.148	7.2
Steppe	57.1	696619	39.78	18417.5	16405.2	0.88	0.79	1.67	-0.097	-10.9
Semidesert	35.0	437940	15.32	1137.1	602.9	0.05	0.03	0.08	-0.026	-47.0
Desert	29.1	752	0.02	0.0	0.0	0	0	0.00	0.000	0

3.1.C. Pollination

3.1.D. Regulating ES of Protected Areas

At the present stage, we do not have access to official data covering all Armenian PAs for the period after 2014, official digitized maps of PA boundaries, or land cover data specifically refined for the territory of Armenia. Therefore, the following analyses are based on the available digital PA map referenced below and the global ESRI land cover dataset.

The use of the ESRI land cover dataset for relatively small PA areas leads to significant errors in area estimation. In the examples below, we demonstrate only the type of analysis that can, in principle, be conducted for ecosystem accounting of PAs based on land cover data. **All estimates are of methodological value only and should be refined using official PA boundaries and land cover data provided by the PAs.**

This example of accounting is based on the PA map provided by [Acopian Center for the Environment, American University of Armenia] (Figure 31D-1), the vegetation map prepared in the framework of our project (Section 2.3), and ESRI land cover data from 2017 and 2023.

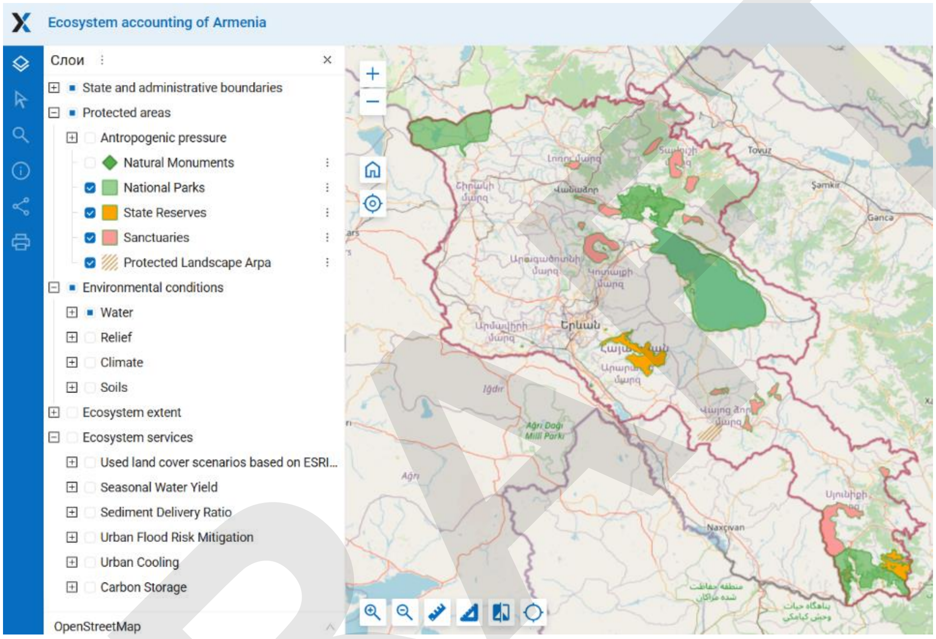


Figure 31D-1. The map of protected areas of Armenia. For details see [project WEB GIS, Protected areas here]. (The location of the Goravan Sands Sanctuary needs to be clarified)

ES of seasonal flow regulation and baseflow provision

In most PAs, the baseflow is lower than the national average for Armenia (Figure 31D-2). However, in several PAs, it significantly exceeds the average values. The highest baseflow has been identified in Aragats Alpine sanctuary, Arpi Lake National park and Pine of Banx sanctuary, which are located in regions with relatively high precipitation. These three PAs are located in alpine, subalpine and meadow-steppe vegetation zones (Section 2.6.B), which are characterized by both a high level of baseflow and a high proportion of baseflow in the total water flow (Section 3.1.A).

ES of flood risk mitigation

In most PAs, the runoff retention is higher than the national average for Armenia (Figure 31D-3). The lowest values of runoff retention are observed in PAs located in the Ararat Valley, which has been heavily modified by human activity. The pattern for runoff retention differs from that of baseflow, as it reflects the influence of land cover and soil type, but does not account for topography.

ES of prevention of soil erosion and sediment transport into waterbodies

Value of avoided erosion in most protected areas exceeds the national average for Armenia. This is explained by the fact that PAs are primarily composed of natural grasslands and forests, which effectively prevent erosion (Section 2.6.B). All PAs where Indicator avoided erosion exceeds 100 t/ha/year are mostly or entirely covered by woody vegetation, with the exception of the Goris sanctuary, which has a small forested area (Figure 31D-4).

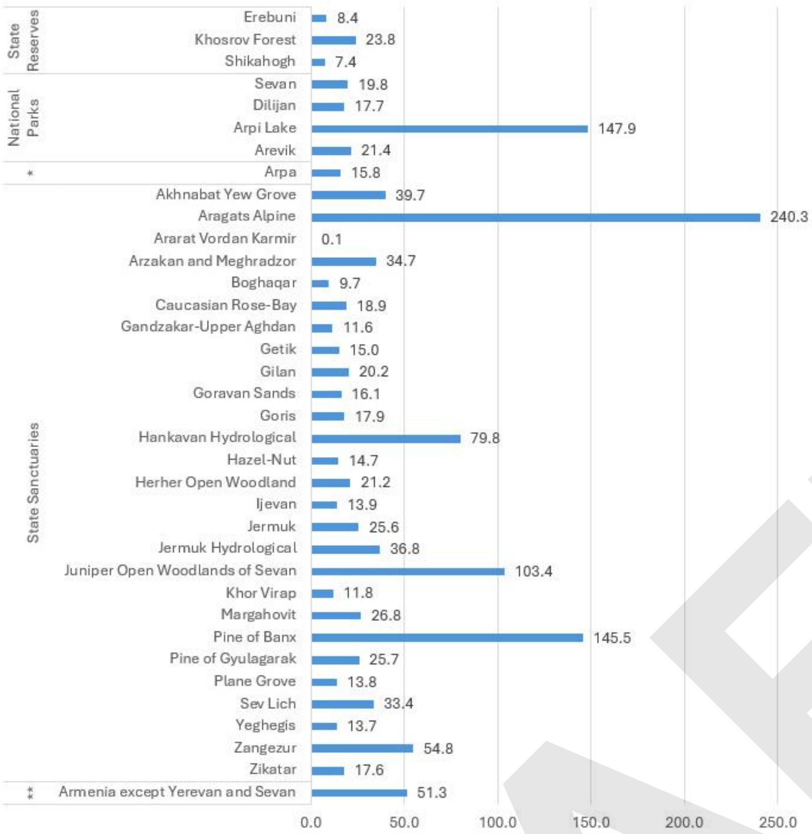


Figure 31D-2. Baseflow in PAs, mm

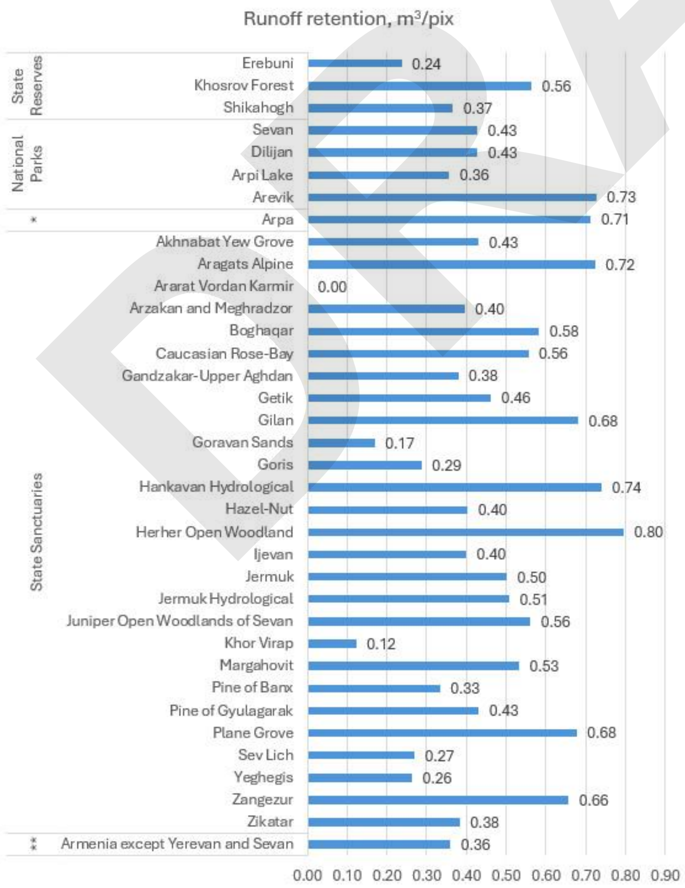


Figure 31D-3. Runoff retention in PAs, m3/pixel

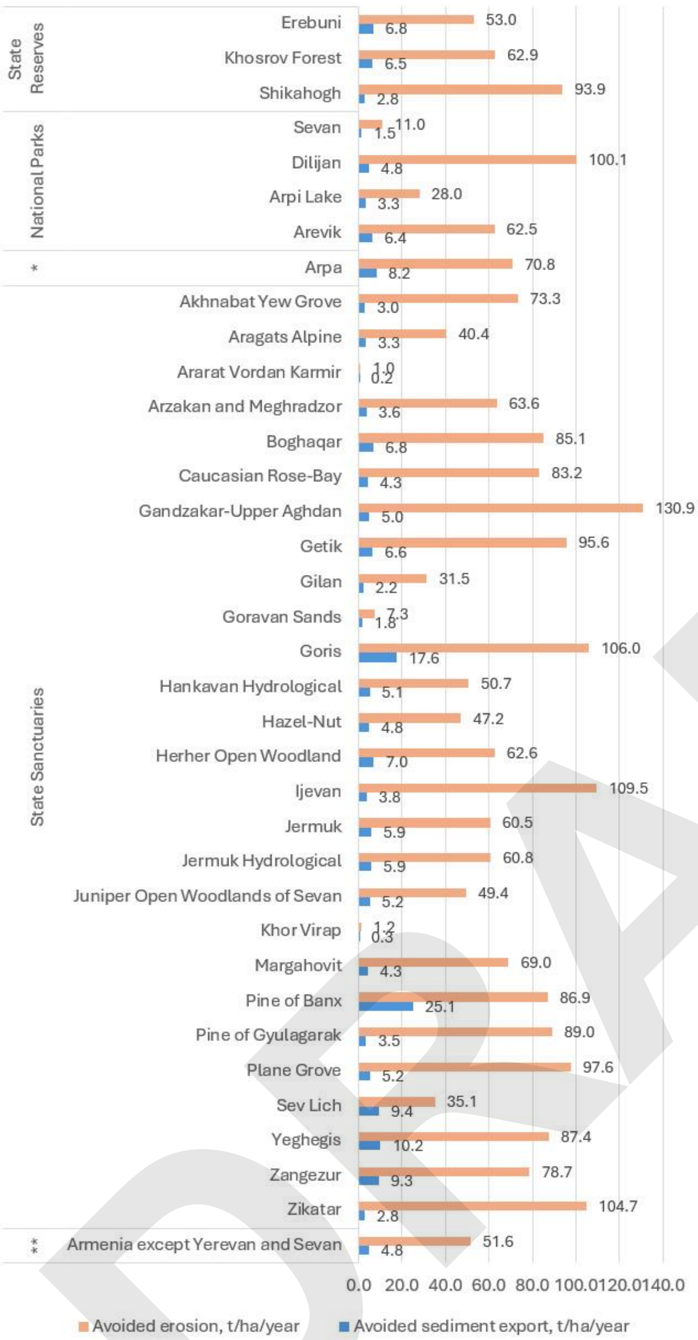


Figure 31D-4. Indicators of the ES of prevention of erosion and sediment delivery to water bodies

Carbon storage in PAs

Carbon content in soil in the PAs fluctuate around the national average for Armenia. PAs located in the semi-desert zone have the lowest soil carbon content. The total carbon stock depends primarily on the size of each PA. The highest carbon stock in tree biomass is found in Dilijan National Park, which has the largest forest area (Figure 31D-5). ES assessment for small PAs based on low-resolution maps is not advisable. For example, for the sanctuary Sev Lich, are inaccurate due to the low resolution (250 m) of the soil carbon map used (Figure 31D-6). The carbon map we used accounts for carbon content only in terrestrial ecosystems, assigning a value of zero to water bodies. The sanctuary Sev Lich includes part of a water body. Due to the low resolution of the map, pixels with zero values overlapped significant part of small terrestrial area of this sanctuary. As a result, both the average soil carbon content and the total carbon stock in this PA are significantly underestimated.

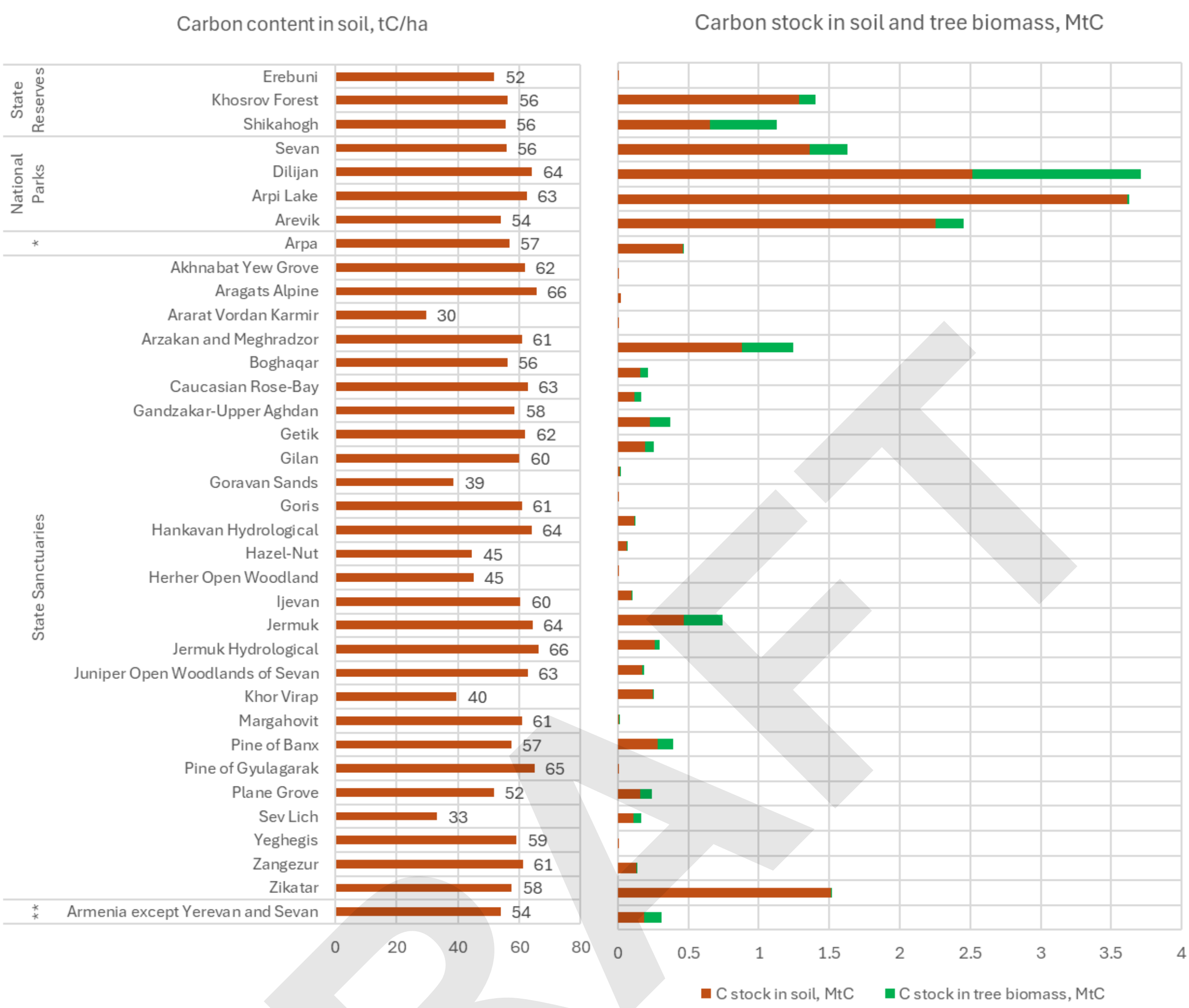


Figure 31D-5. Carbon content in soil and total carbon stock in Pas

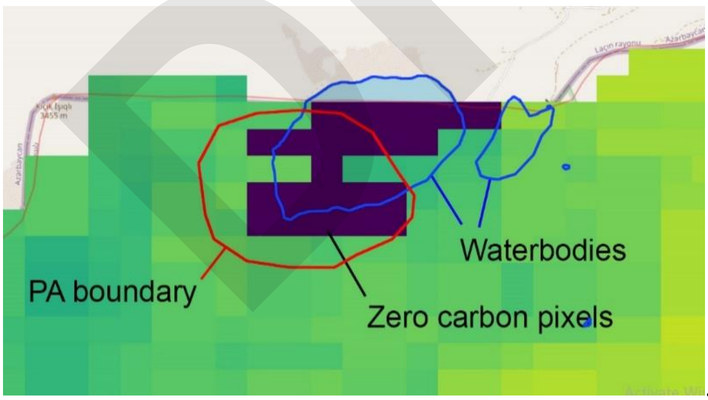


Figure 31D-6. An example of a significant error in estimating carbon content in a small PA is observed in the case of the sanctuary Sev Lich.