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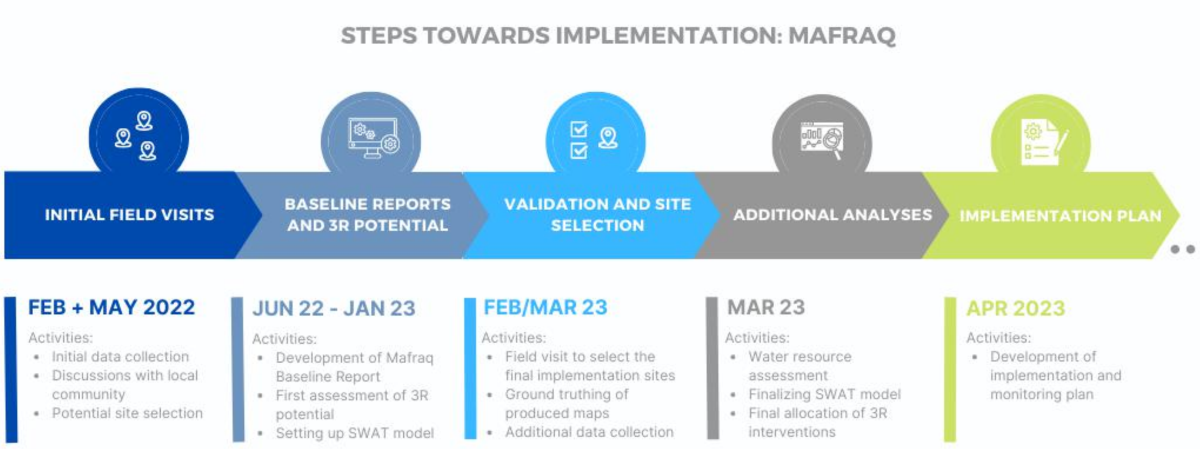
Subject
Draft implementation plan ‘in-stream ponds’ sub-catchment Mafraq, Jordan.

1 Introduction

The 2nd component of the 3R project focuses on piloting (a combination of) 3R interventions in various geographical and climatological settings in Jordan. The program's outcome is to actively support the development of a sustainable integrated water management approach by reducing water usage from unsustainable sources and increasing the water supply from sustainable sources. The latter can be achieved by supporting water harvesting and promoting using non-conventional sustainable water resources by implementing 3R interventions.

This document presents the draft implementation plan for the ‘in-stream ponds’ sub-catchment located in Mafraq governorate, Jordan. Within this implementation plan the sub-catchment’s background and key issues are shortly described, together with the tools and analyses used to assess the 3R potential. Based on this, conceptual designs of different types of 3R measures (including their siting) suitable for the particular sub-catchment are proposed. The document includes a monitoring plan that can be used to determine the current (baseline) situation and to evaluate the biophysical impact of the proposed interventions during later stages. To develop this document and come up with the conceptual designs, the team took the following successive steps:



How to read this document?

Chapter 2 briefly details the sub-catchment's current situation and key issues. Chapter 3 describes the analyses and tools used to assess the 3R potential of the Mafraq region and, more specifically, the sub-catchment. Chapter 4 describes the adopted implementation approach and the conceptual designs of the recommended interventions, including their siting. Chapter 5 provides a monitoring plan to evaluate the effectiveness of the 3R interventions. The final Chapter (6) describes the steps required before implementation to successfully implement and monitor the proposed interventions.

2 Background of the sub-catchment

Sub-catchment selection

Within the Mafraq region, various sites were visited during the initial field visits in May and September 2022. After these visits and the development of the Baseline Reports, the first potential sites were selected, and a more in-depth assessment of the 3R potential of the region was performed. During the follow-up field visit (February/March 2023), the results of the desk study were validated in the field, and the 'in-stream ponds' sub-catchment was designated as a high-potential site. The following main elements contributed to the high potential of the site:

- The sub-catchment is not transboundary and located entirely within Jordan territory. This fact facilitates the realization of a so-called **catchment approach**. Chapter 4 explains the importance of such an approach in more detail.
- The sub-catchment faces multiple challenges related to land and water management that are typical and common in other areas of Jordan. Successfully implementing 3R interventions within this sub-catchment therefore has **high upscaling potential**.
- Due to the various challenges, **different types of 3R interventions** can be demonstrated within one sub-catchment, **contributing to all 3Rs: Retention, Recharge, and Re-use.**
- The sub-catchment is located within one of the agricultural hotspot areas of Jordan. Hence the demand for water for agricultural use, and the number of water users, is high. Implementing 3R interventions that contribute to increased water availability (from sustainable sources) could, consequently, serve multiple farmers, resulting in a relatively **high number of potential beneficiaries**.
- The sub-catchment has a relatively small surface area, making the flood flows less destructive compared to larger catchments (e.g. the Syrian transboundary catchments), and implementing in-stream 3R measures less risky.

Description of the sub-catchment

A detailed description of the site and the findings of the initial field visit are reported in the Baseline Report (Acacia Water, 2022; section 6.3). The biophysical and socio-economic background of the greater Mafraq area can also be found within the Baseline Report (Chapters 4 and 5). Below only the most relevant characteristics of the sub-catchment regarding 3R implementation will be discussed. Additional pictures can be found in Annex 2: Field observations.

The sub-catchment is part of the Yarmouk basin and is located just north of Mafraq city. It is situated in one of Jordan's main agricultural zones, making intense groundwater abstraction for agricultural usage a common activity. At the outlet of the sub-catchment, next to Damascus Highway, several topographical depressions - resulting from gravel excavation - exist within the landscape. As the topographical depressions are surrounded by agricultural lands (currently irrigated by groundwater), these depressions could function as a sustainable alternative water resource for agriculture. Despite this, the floodwater harvesting potential of these topographical depressions is currently not fully utilized.

Figure 1. Picture of one of the in-stream depressions filled with flood water from the Feb. 2023 flood event (source: Acacia Water, March 2023).

Upstream of the topographical depressions, the wadi divides into two tributaries. The branch from the south discharges the water from the Al Ghadeer Alabyadh dam, which is located approximately 3 km south of the topographical depressions. The dam was built in 1966 and was designed to store 0.7 MCM of water. Due to the high siltation rates in the 127 km2 upstream catchment, however, the storage capacity has been reduced with an estimated annual average rate of 0.016 MCM (Shatnawi, 2012). In 2017 - after not maintaining the dam for 34 years - the capacity remained at only 250.000 m3 (0.25 MCM). In 2020, the dam was rehabilitated by the FAO. The presence of the dam means most sediments coming from the upstream catchment are trapped before reaching the topographical depressions. This intends that intervening in the upstream parts of this catchment will primarily influence the situation at the dam and less at the topographical depressions. For this reason, the dam's larger upstream catchment was considered less relevant for the implementation of 3R measures, and it was decided to focus on the second, smaller, upstream sub-catchment instead.

The second branch, coming from the southwest, discharges a smaller catchment area of about 10 km2. In the downstream part of this smaller sub-catchment, the area is rocky, and various basalt outcrops can be found. Several Bedouin families reside with their livestock on the bare and rocky hills. The lands are consequently primarily used as grazing lands for livestock, making them susceptible to erosion. As a result, gully and rill formation and topsoil erosion are evident issues here.

In the middle part of the sub-catchment, the terrain is mainly flat to gently sloping and dominated by agricultural lands used for rainfed barley. Due to the lack of precipitation, the fields are predominantly fallow, making the relatively thick soils susceptible to erosion. Incorrect land management, for example, by ploughing in the wrong direction, only exacerbates this problem.

The upstream part of the sub-catchment is characterized by gently sloping, primarily bare lands. During the rainy season, some areas become sparsely vegetated with grasses and function as open rangelands. In this part of the catchment, attempts have been made to conserve soil and water. In XX, continuous contour trenches were constructed on the hills spreading over an total area of around 3 km^2, of which half is located within the sub-catchment In addition, Zaï pits were constructed as can be observed from satellite imagery. The influence of the interference in the landscape was observable during the field visit as the hills were slightly greener compared to adjacent hills without trenches.

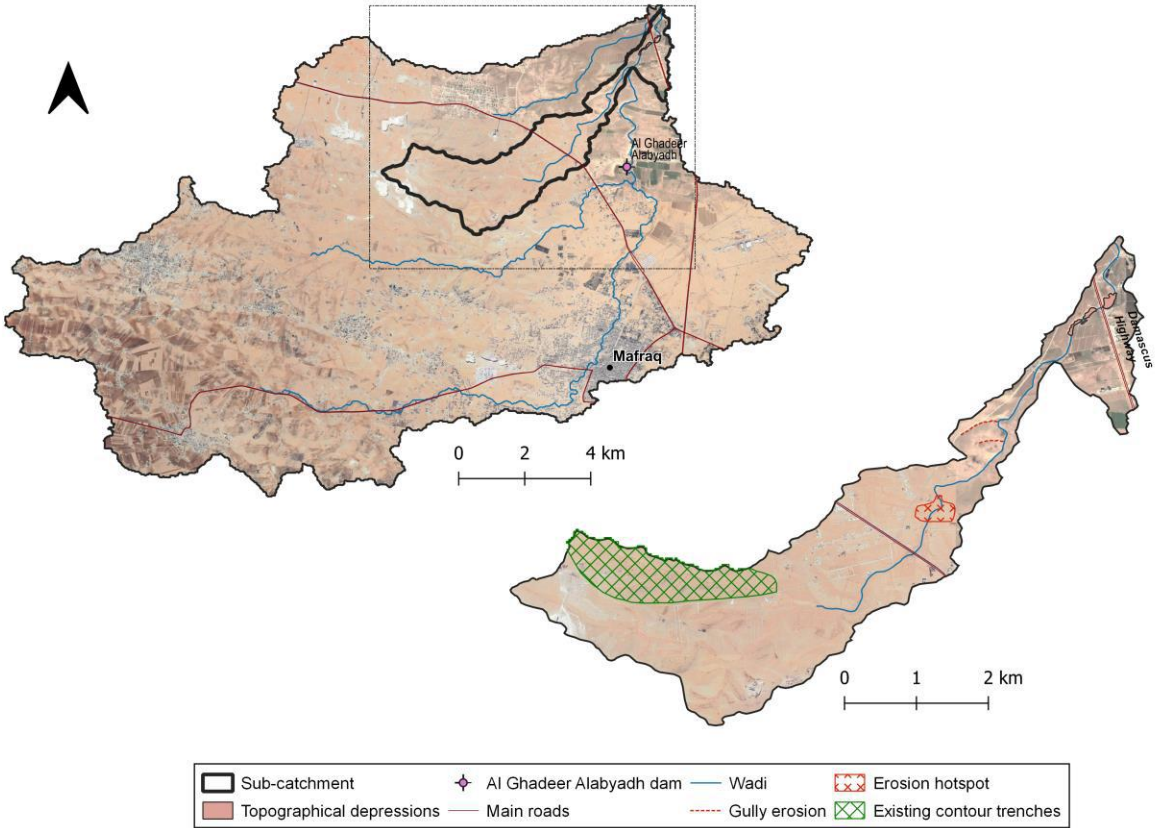


Figure 2. Overview of the catchment (top left) and a zoomed-in map of the selected sub-catchment (bottom right).

Key issues

The following key challenges are identified within the sub-catchment:

- Due to the high agricultural activities in the region, the **over abstraction of groundwater** is a regional problem. Near Mafraq, a strong rate of decline in the A7/B2 aquifer was registered at observation well AL1521 (at King Hussein Airbase), where ground water levels have been dropping with 12m/yr since 2013. In 2017, the saturated thickness of the same aquifer was estimated at <100 m in the most downstream and middle part of the sub-catchment. In the most upstream part, delineated by the road from Mafraq to Irbid, the aquifer is likely to be already unsaturated (BGR, 2019).

- Another major problem in the area is **soil erosion.** Incorrect land management, such as ploughing downhill instead of along the contour, and incautious interfering in the landscape – e.g. the construction of poorly designed earthen dams and contour trenches - make the area susceptible to erosion. The already weak soil structure due to sodic properties of the soils and overgrazing of natural vegetation and crop residues further increases this problem. As a result, fertile top soil is easily flushed away, leading to high sediment loads in the water and a reduced productivity of the land.

Figure 3. Pictures of soil erosion due to incorrect ploughing observed in the middle of the sub-catchment (source: Acacia Water, March 2023).

- **Poor water management** only put more pressure on the already scarce water resources. The pumping of groundwater from 300 – 600 m depth to store it into open reservoirs is a common practice in the whole region (Figure 4), resulting in high water losses due to evaporation. The first idea behind the storage in open reservoirs is to reduce the pumping costs by pumping the needed water at once. The second explanation is to be able to have a sufficient amount of water during the peak water consumption months in summer as the pump capacities are often too small (personal communication, May 2022). Obviously, from a water management point of view, storing precious groundwater into open reservoirs, where the water is exposed to extremely high evaporation rates, is not the most efficient. Of course it is not only the storage of water but also the cultivation of crops with a relatively high water consumption, such as fruit trees, grapes and olives, in an arid area with high temperatures which might be questionable. Additionally, the cultivation of vegetables during peak water consumption months of July and August is often happening.

Figure 4. Pictures from an existing reservoir filled with ground water and a newly constructed reservoir near the topographical depressions (source: Acacia Water, March 2023).

3 Tools for 3R implementation

This chapter presents multiple tools that can be used for selecting and allocating 3R interventions. The tools provide technical guidance to achieve well-informed and strategic 3R intervention planning.

3.1 3R potential mapping

The 3R potential map highlights the potential in an area for interventions which promote the 'Retention, Recharge and Re-use' (3R) of water. This potential is based on the area's biophysical context considering the following main parameters: land cover, climate, and slope. The recommended measures are divided into three categories: general practices (GP), Soil and Water Conservation (SWC), and water harvesting structures (WHS).

1. **General practices** - the first category refers to the most general recommendation, mainly based on land cover type. These general practices are generally more focused on behavior change of local land users, which can lead to the most permanent change, but will take time and effort to implement;
2. **SWC** - the second category consists of far-ranging, quite specific interventions related to Soil and Water Conservation (SWC). These are relatively intensive measures but are straightforward and can have very high impact;
3. **Water harvesting structures** - the last sub-category specifies technical interventions focusing on the direct capture and storage of water to make it available for different users and uses (domestic, agriculture, livestock).

For potential future work and upscaling, the 3R potential map could provide stakeholders, government officials and land and water management planners insight and support into the suitability of various 3R measures within different biophysical environments. Within this project, the 3R potential map serves as a starting point for selecting possible 3R measures. It provides an initial long-list of potential interventions that fit within the characteristics of a certain landscape. The final selection and allocation of interventions, is based on the field visits and additional analyses as described in the remaining part of this chapter.

Figure 5 displays the 3R potential map of the Mafraq region (larger map can be found in Annex 3: Produced maps). Suitable interventions for each zone are shown in Table 1. A description of all interventions is provided in the '3R intervention manual Jordan' (Acacia Water, 2022).

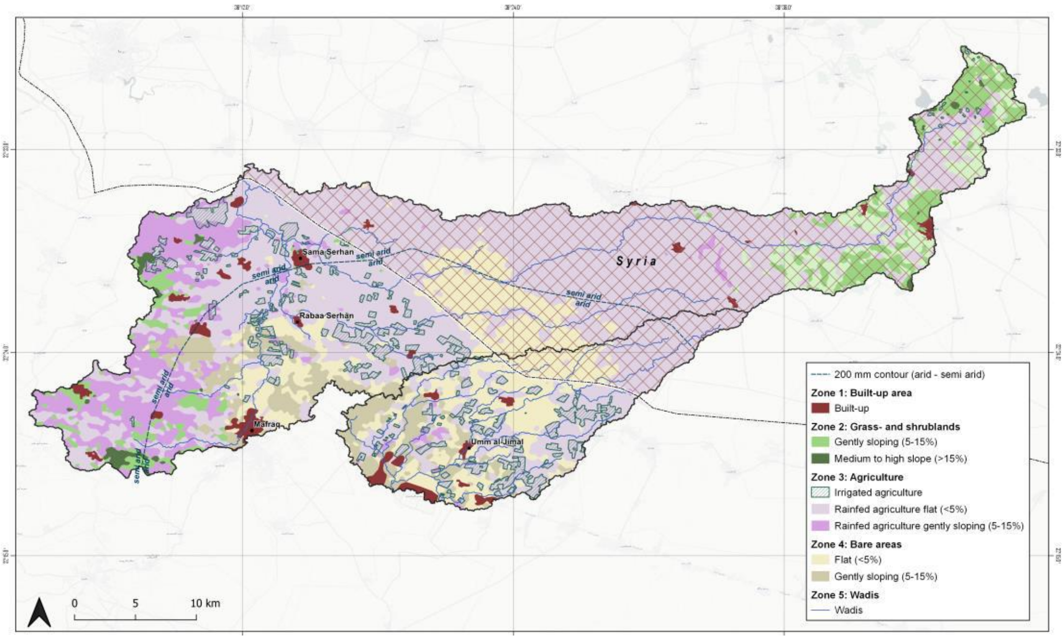


Figure 5. Validated 3R potential map for the Mafraq region. The map shows the identified 3R potential zones, based on the areas biophysical context. Suitable measures are provided per zone and can be found in Table 1.

Table 1. 3R interventions suitable per zone. The measures are distinguished in three categories: general practices (GP), Soil and Water Conservation (SWC), and water harvesting structures (WHS).

Zone	Siting specifications			Intervention type		
	Land cover	Climate	Slope	GP	SWC	WHS
	Built-up area	-	-	Sponge town measures. Greywater reuse systems	Green areas for contour and recharge	Roof water harvesting, cisterns
	Grass- and shrublands	-	Gently (5-15%)	Grazing management (Al Hima)	Contour bunds, semi-circular bunds, contour trenches	Cisterns, hillside dams
		Semi arid (>200 mm)	Medium to high (>15%)		Contour stone bunds, eyebrow terraces, contour trenches	Cisterns, hillside dams
	Irrigated agriculture	-	-	Smart agriculture	Mtumbwi system	Hafirs, greenhouse roof water harvesting
arid	Rainfed/fallow agriculture	Arid (<200 mm)	Flat (<5%)	Conservation agriculture	Mulching, contour bunds, Negarim micro-catchments, Zaï pits, V-shaped micro-catchments, contour trenches, semi-circular bunds, flood water spreading	Hafirs, charco dams, cisterns
arid			Gently (5-15%)	Conservation agriculture, incl. contour ploughing	Mulching, contour stone bunds, V-shaped micro-catchments, semi-circular bunds, contour trenches	Cisterns, hillside dams
semi arid	Rainfed agriculture	Semi arid (>200 mm)	Flat (<5%)	Conservation agriculture	Mulching, contour bunds, contour trenches, Zaï pits, semi-circular bunds, flood water spreading, vegetation buffer strips	Hafirs, charco dams
semi arid			Gently (5-15%)	Conservation agriculture, incl. contour ploughing	Mulching, contour stone bunds, semi-circular bunds, Meskat system, vegetation buffer strips	Cisterns, hillside dams
	Bare areas	-	Flat (<5%)	Area closures, in combination with revegetation	Vallerani system, Negarim micro-catchments, contour bunds, contour trenches, semi-circular bunds, flood water spreading	Hafirs, charco dams
			Gently (5-15%)	Area closures, in combination with revegetation	Vallerani system, contour stone bunds, contour trenches, semi-circular bunds	Cisterns, hillside dams
	Wadis	-	Flat (<5%)	Riverbank protection, wadi bed cultivation	Gully reshaping, refilling, revegetating; erosion control structures (gabions or gully plugs)	Subsurface (recharge) dams, gabions
			Gently (5-15%)			Check dams, gabions

A zoomed map of the 3R potential within the selected sub-catchment is depicted in Figure 6. As the figure indicates, all lands belong to Zone 3 or Zone 4 and are characterized by an arid climate (annual average rainfall <200 mm). This gives us the following long-list of potentially suitable interventions:

- Mulching;
- Contour bunds;
- Negarim micro-catchments;
- Zaï pits;
- V-shaped micro-catchments;
- Contour trenches;
- Semi-circular bunds;
- Flood water spreading;
- Vallerani system;
- Mtumbwi system;
- Gully plugs;
- Check dams;
- Gabions;
- Subsurface dams;
- Charco dams;
- Hillside dams;
- Greenhouse roof water harvesting;
- Cisterns;
- Hafirs

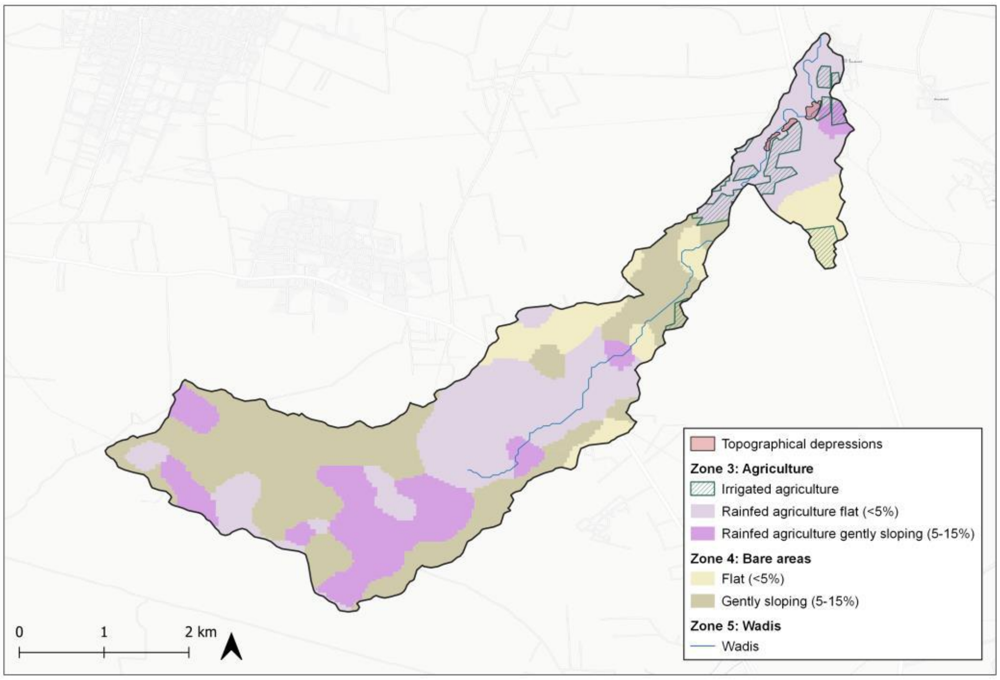


Figure 6. 3R potential within the selected sub-catchment.

3.2 Water resource assessment

Selecting 3R measures is not only dependent on the biophysical context. Other important aspects to consider are the available water resources, the water demand and the intended use of the water in a certain area. An analysis of the water demand and supply is essential to estimate the size and the number of interventions required to reach an area's specific demand.

Also the intended water use should be considered. For drinking water for example, where high quality is desirable, closed storage in tanks or storage as groundwater are most suited. The demand for livestock or agriculture may be suited with water from a lower quality, which broadens the range of possible 3R interventions to open water storage and storage as soil moisture (the latter mainly for crops or grazing lands). Here, we focus on making water available for agricultural use, therefore the agricultural water demand was analyzed.

Water demand

To evaluate the agricultural water demand of the selected sub-catchment the total irrigated area was estimated by performing a remote sensing analysis. To do this cloudless Landsat 9 tiles were downloaded for the area of interest from USGS Earth Explorer ([EarthExplorer (usgs.gov)]). Landsat is a multi-spectral dataset consisting of 11 bands all reflecting different wavelengths (Figure 7). By analyzing and combining different bands, information on various topics (e.g. vegetation status, land cover, geology, mineral composition) can be collected.

Spectral Band	Use Area	Wavelength	Resolution
Band 1	Coastal/Aerosol	0.433 – 0.453 µm	30 m
Band 2	Blue	0.450 – 0.515 µm	30 m
Band 3	Green	0.525 – 0.600 µm	30 m
Band 4	Red	0.630 – 0.680 µm	30 m
Band 5	Near Infrared	0.845 – 0.885 µm	30 m
Band 6	Short Wavelength Infrared (SWIR 1)	1.560 – 1.660 µm	30 m
Band 7	Short Wavelength Infrared (SWIR 2)	2.100 – 2.300 µm	30 m
Band 8	Panchromatic	0.500 – 0.680 µm	15 m
Band 9	Cirrus	1.360 – 1.390 µm	30 m
Band 10	Long Wavelength Infrared	10.30 – 11.30 µm	100 m
Band 11	Long Wavelength Infrared	11.50 – 12.50 µm	100 m

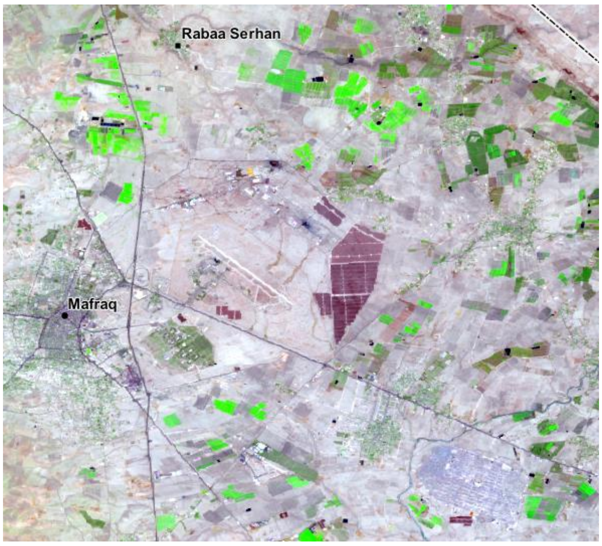


Figure 7. Specifications of the different Landsat bands (left), and example of band combination 6,5,4, for the Mafraq area (right). The irrigated plots are clearly observable in green, the open water reservoirs are indicated by the dark blue/black colors.

The band combination 6,5,4 was used to detect the irrigated and open water surfaces (reservoirs). The detected surfaces were subsequently extracted by performing a supervised classification [1]. To account for variations in crop calendars, imagery was analyzed for different seasons (Apr., Sept. and Dec. 2022). The results were combined into

[1] The supervised classification was done by using the Semi-Automatic Classification Plugin in QGIS.

a Water Infrastructure (WI) map. As almost all reservoirs in the Mafraq region are used for irrigation, the WI map indicates areas with high agricultural water demand. Based on this map, proper siting of 3R interventions can be ensured.

As Figure 9 indicates, zones of high agricultural activity can be found in the region North of Mafraq, West of Sama Serhan, and in the area close to the Syrian border. The highlands towards the West of Mafraq are less dependent on irrigation as most agriculture in this area is rainfed, which is reflected in the lower density of reservoirs. Nearby the topographical depressions, six reservoirs and a hafir (Figure 8) can be found, reflecting a relatively high density of agricultural water users and thus potential beneficiaries. It should be noted that just downstream of the depressions, another small structure is located. Consequently, the potential upstream-downstream effects should be carefully considered when implementing 3R measures in the selected sub-catchment.

Figure 8. Full hafir next to wadi (source: Acacia Water, March 2023).

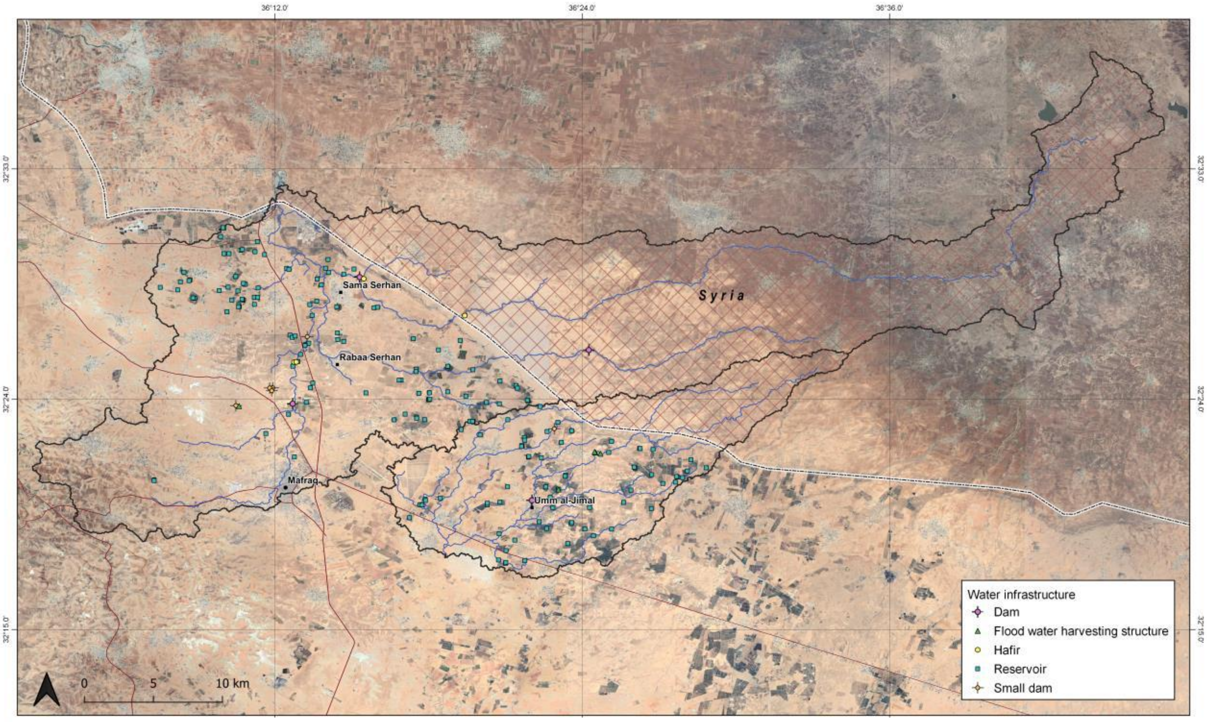


Figure 10. Water infrastructure map of the Mafraq region. The locations of the water harvesting infrastructures were derived from remote sensing analyses.

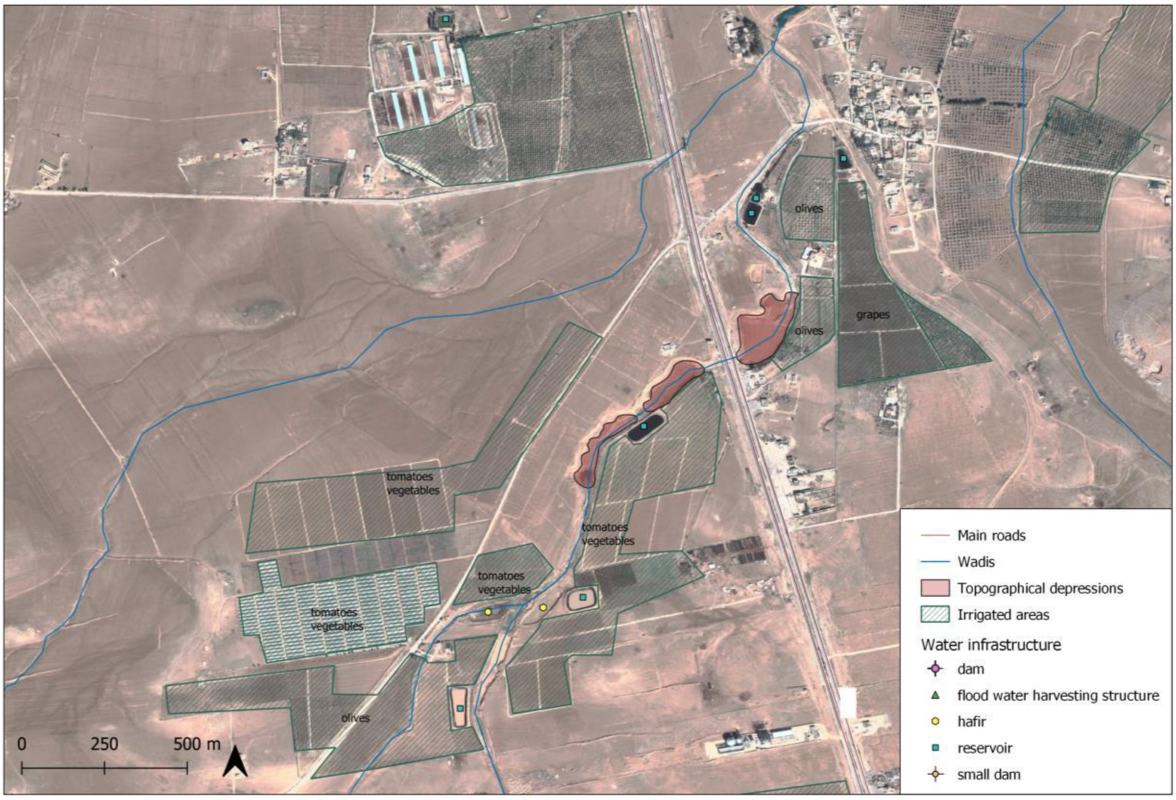


Figure 9. Map showing the irrigated areas and the existing water harvesting structures surrounding the topographical depressions.

The total surface area of irrigated lands adjacent to the topographical depressions equals 91 ha. Of this total area, about 25 ha is covered by olive trees, 10 ha by grapes and the remaining 56 ha by tomatoes and other vegetables (Figure 9). In Mafraq, irrigation generally starts in March and continues until November, with maximum amounts of groundwater pumping and irrigation during June-August (Al-Bakri, 2015).

Considering the surface areas and the crop water requirements as estimated by Al-Bakri (2015) (FAO 56 method), and assuming that full irrigation was practiced from March to November, the annual agricultural water demand of the fields can be estimated at 688,690 m^3 or 0.69 MCM. This water demand is however based on an (unrealistic) irrigation efficiency of 100%. Especially in Mafraq water losses are very high due to the storage in open reservoirs in summer and leakage of water during conveyance. Assuming an overall irrigation efficiency of 70% (Al-Bakri, 2015), the agricultural water demand would increase up to 0.9 MCM annually.

Table 2. Crop water requirements estimated by using the FAO56 method for various vegetables and trees in the Mafraq area (Al-Bakri, 2015).

	Crop Evapotranspiration (mm)												
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Total**
Trees													
Olives	24	28	73	100	129	138	146	133	104	74	42	23	**1014**
Fruit trees			57	100	129	178	188	152	104	69	29		**1006**
Grapes			31	71	92	168	177	162	126	47	29		**905**
Vegetables													
Tomatoes (Mar-Jun)			50	107	159	227	193						**736**
Tomatoes (Jun-Nov)						95	156	192	170	98			**712**
Tomatoes and vegetables						95	156	186	145	67			**649**
Cauliflower				80	148	168	219	98					**712**
Eggplant				68	139	185	240	176					**808**

Water supply

A hydrological model called SWAT (Soil Water Assessment Tool) was developed for the sub-catchment to create insight in the water balance and the available water resources. SWAT uses spatial data of catchment characteristics such as information on topography, land cover, soils, and stream patterns, combined with climatological timeseries and water use to simulate water flow through the catchment.

Input data and model setup

The model's input data was generated using open-source data only, including remote sensing datasets and data from the available literature. Soil maps were derived from ISRIC SoilGrids at 250m resolution, and the WaPOR Land Cover Classification (Level 2, 100m resolution) dataset was used as land cover input. Where necessary, datasets were validated and adjusted based on field observations. Rainfall data was obtained from the satellite-derived CHIRPS dataset; all other climate parameters were obtained from the Climate Forecast System Reanalysis (CFSR) database. The model was run for 14 years (2000 - 2014), simulating at daily time steps and including a 4 year warm-up period. The model setup is shown in Figure 11.

To guarantee the use of proper input data, the CHIRPS dataset was compared to observed rainfall data from the Mafraq gauging station. The analysis indicated that CHIRPS provides a good representation of the average precipitation in the area, although the extremes are less accurately reflected by the dataset (Annex 1: Climate analysis). Nevertheless, CHIRPS was still used as observed rainfall time series that are spatially distributed over the study area and cover a sufficient amount of time were lacking. This means, however, that the model results only represent the hydrological situation under 'average' conditions and do not correctly reflect the situation under extremely dry or wet circumstances.

As only open-source datasets are used and data for calibration purposes is lacking, the model outputs serve as a first insight into the water balance of the area. The absolute numbers obtained from the simplified model are expected to differ from reality, however, it still helps us better understand the hydrological situation in the sub-catchment. Further improvements to the model could be made by, for example, incorporating more detailed and location-specific information on the soil parameters or calibrating the model based on discharge measurements. Key to this is an operating discharge monitoring network, of which the installation is highly recommended throughout the country.

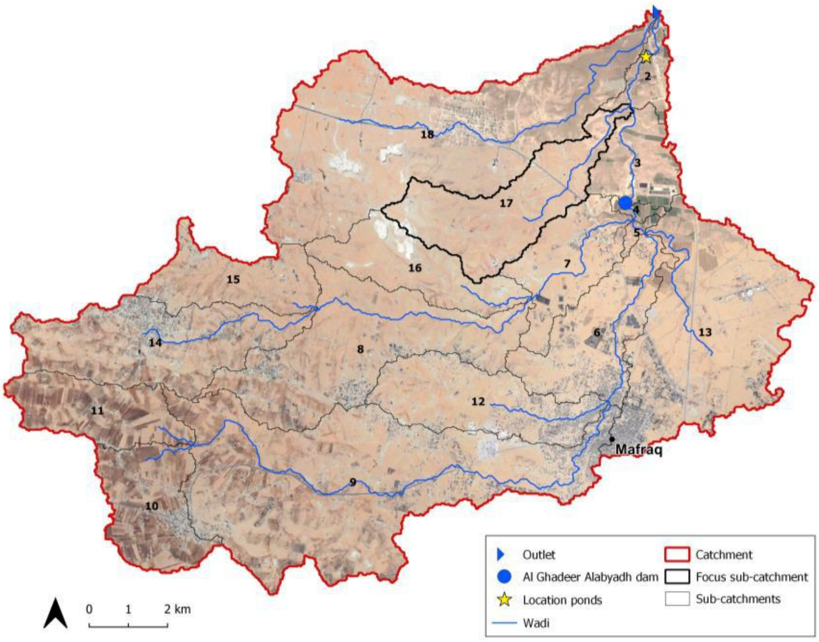


Figure 11. SWAT model setup. The ponds are located in sub-catchment 2, just upstream of the catchment outlet in the northeast. The focus area for 3R implementation is sub-catchment 17.

Model results

Table 3 shows the average water balance for the modelled basin over the years. As the results indicate, evaporation losses over the catchment are substantial, reaching almost 94% of the total precipitation. As a result, the amount of water available as surface runoff or for infiltration that can be used for water harvesting is minimal.

Due to the high silt and clay content of the soils, infiltration is relatively low. The water that does infiltrate may be 1) held in the soil and later evaporate, 2) slowly make its way to the surface-water system via lateral underground flow, or 3) percolate to the deeper aquifer. In this case most water returns as evaporation, and only very small amounts recharge the deeper groundwater or leave the system by lateral flow. Return flow (or base flow) from the shallow aquifer to the wadis is very low, which is caused by the deep groundwater table and the relatively flat landscape.

Table 3. Summary of the different elements of the hydrological cycle in mm, and in percentage compared to the precipitation.

Water balance	mm	%
Precipitation	178	100
Evapotranspiration	168	94
Lateral flow	0.2	0.1
Return flow	0	0
Surface runoff	6.3	3.5
Groundwater recharge	0.3	0.2
River flow at basin outlet	3.5	2

Figure 13 indicates the annual average generated surface runoff by SWAT. The annual runoff coefficient of the catchment was estimated at 3.5%. On the western side of the sub-catchment, annual average rainfall is higher, indicating greater runoff rates. In areas where heavy clay soils (Vertisols) are present (sub-catchment 10 and 11), runoff is also high due to the low infiltration capacity of these soils. Besides, in the regions with rainfed agricultural and in the built-up area around Mafraq city runoff is high. The high runoff rates of the agricultural fields were also observed in the field during a rain event in March 2023 (Figure 3). Significant runoff rates can also be found in most bare areas, especially when the lands are sloping, which is for example the case in the downstream part of sub-catchment 17 (Chapter 2).

Figure 13 also indicates the outflow of all reaches. The impact of the dam is clearly visible in the figure as a large decrease in outflow can be observed in between sub-catchments 3 and 4. Besides that, the results show no unexpected patterns, and outflow increases towards the downstream parts of the basin. The model showed that the location of interest (sub-catchment 2) receives water 3 times a year on average, corresponding to the information obtained from the local community (personal communication, May 2022).

Two different scenarios were simulated to assess the inflow into sub-catchment 2: the first containing a clean reservoir with the original storage capacity of 0.7 MCM (from now on referred to as *full capacity* scenario), and the second comprising a silted reservoir with only a 50% storage capacity (*50% capacity* scenario). It was assumed that the Al Ghadeer Alabyadh dam only overtops when it is full and no controlled water release occurs from the spillway (personal communication, March 2023).

The results show that at full storage capacity the dam is expected to overtop only 3 times in a 10-year period, whereas at half capacity the dam experiences an 50% annual chance of overtopping (Figure 12). Over the simulated period, the annual average discharge of sub-catchment 17 was approximately 70,000 m^3. Sub-catchment 3 discharges significantly more with an annual average outflow of around 235,000 m^3 and 387,000 m^3 for the *full capacity* and *50% capacity* scenario, respectively. Sub-catchment 3, however, encounters strong annual fluctuations in discharge; high discharges are only observed when the dam is overtopping. In dry years, sub-catchment 17 contributes to most of the inflow into the 'in-stream ponds' catchment (sub-catchment 2). Note that the model is uncalibrated and the exact numbers possibly deviate from the simulated outcome.

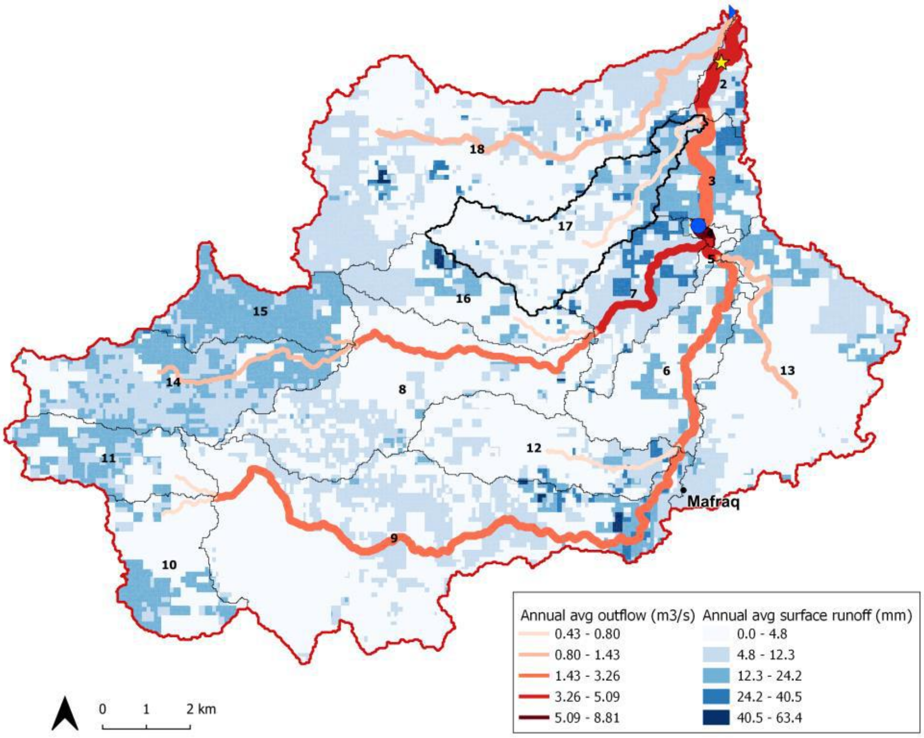


Figure 13. Annual average surface runoff (mm) throughout the catchment and annual average outflow per reach in m^3/s (*full capacity* scenario). The color of the reach outflow indicates the amount, while the thickness of the line indicates the size of the upstream area contributing to the total stream flow in that reach.

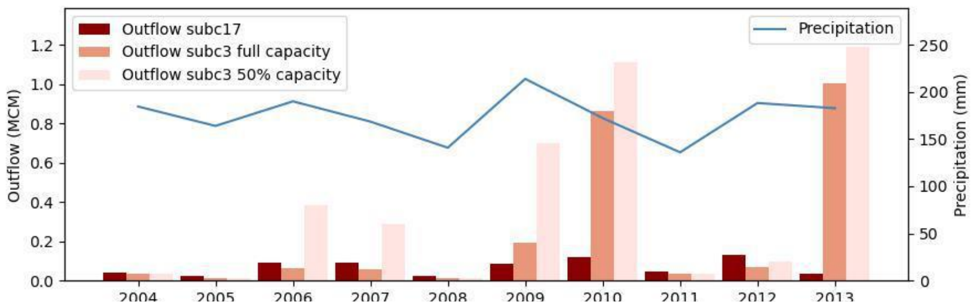


Figure 12. Total yearly streamflow (in million m^3, MCM) at the outlets of sub-catchment 3 and 17 for both scenarios, plotted with the basin annual average precipitation (mm).

4 3R opportunities

The dropping groundwater levels are alarming and threaten the future of agriculture in the region. To ensure sufficient yields in the future, groundwater pumping should be reduced, and alternative, more sustainable sources of water should be used. Accordingly, the prime focus of the proposed 3R interventions is to:

Increase the flood water storage potential to provide an alternative and long-term sustainable water source for agriculture in order to reduce groundwater abstraction for irrigation.

By slowing down and storing flood water in the existing depressions, the water can be used to irrigate the surrounding fields, creating a more sustainable and cheaper alternative than the pumping of 'fossil' groundwater for irrigation. However, to develop effective solutions in the longer term, it is necessary to consider another critical issue in the sub-catchment: poor land management.

Inadequate land management has led to severe soil erosion at different locations within the catchment. When not tackling this issue, siltation will strongly reduce the long-term efficiency of the proposed structures, and maintenance costs will increase. Besides, the degradation of lands influences soil fertility and eventually hampers water infiltration into the soil. This negatively affects the availability of water as soil moisture and the fraction of water that percolates to the deeper aquifer and becomes available as groundwater (Figure 14). A decreased water availability means a less dense vegetation cover, which is vital in protecting soils against the erosive forces of rain and wind. Due to this interconnection, it is crucial to consider all three elements (Soil-Water-Vegetation) to prevent further deterioration of the scarce natural resources and to provide long-term solutions.

Rather than letting rain and runoff cause damage, the water in the sub-catchment should be stored and turned into an asset. The existing reservoirs should be filled with flood water instead of ground water and infiltration into the soil should be enhanced to increase soil moisture and recharge groundwater. This will ensure an increased water buffer during dry periods and will generally lead to more fertile soils and less erosion and degradation. All these factors are likely to positively contribute to the socio-economic situation in the long term.

To turn water into an asset, the connection of the elements, Soil-Water-Vegetation, should be considered. Focusing on one resource or one issue at a time often does not give the best results. Taking a step back and realizing the relationship between different resources and different issues will allow for more long-term and practical solutions. Consequently, we propose integrated solutions, that cover all 3Rs, and improve not only the direct availability of water but also the health of the soils and vegetation cover. The proposed interventions should be combined with a reduced pumping of 'fossil' groundwater for agricultural use.

A catchment approach

To provide effective integrated solutions, it is important to assess the area from a hydrological catchment perspective. A catchment approach takes into account the connection between Soil-Water-Vegetation, and the potential upstream-downstream influences of these different elements. In specific, implementing water harvesting measures upstream will influence the situation downstream. Also, the implementation of Soil and Water Conservation measures (SWC) might (positively or negatively) affect the situation downstream (Figure 14). Allocation of 3R interventions should therefore be done from a broader scale, and the activities should start from the most upstream part of the sub-catchment.

Besides, the effectiveness of 3R interventions is often increased when implementing a combination of measures, instead of a single intervention. Implementing a large number of small interventions within one sub-catchment as opposed to one or just a few large interventions, can reach more people, is more sustainable and is often just more cost-effective.

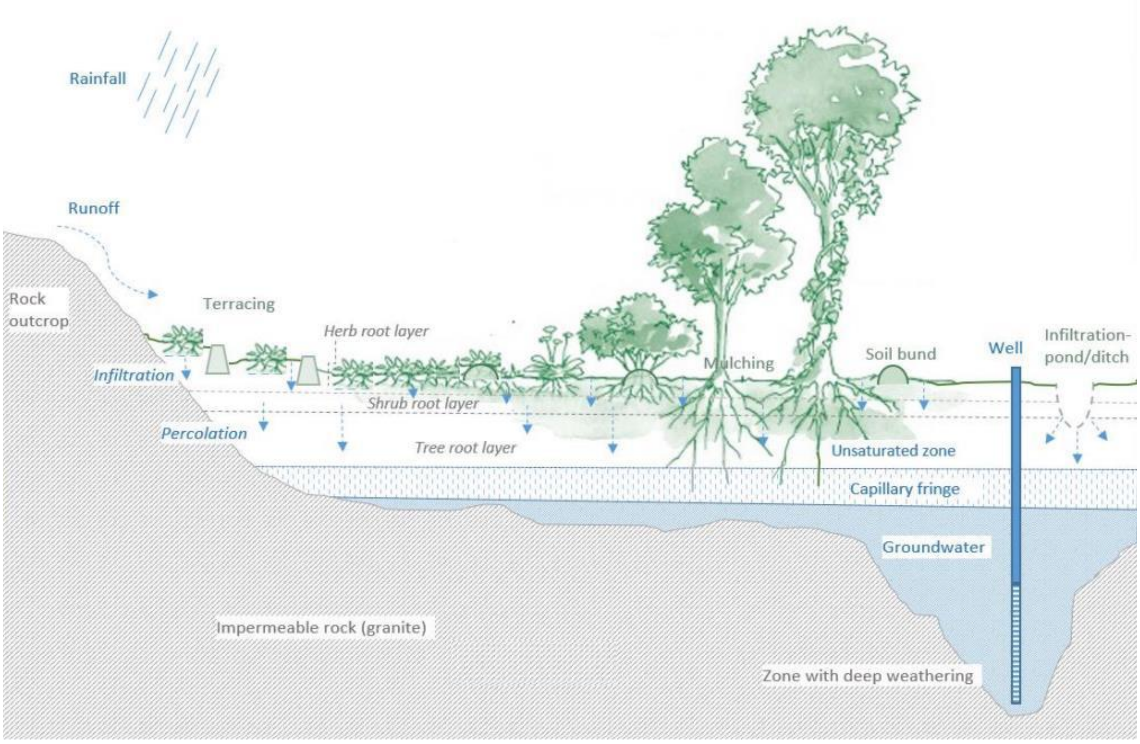


Figure 14. Illustration of the connection between Soil-Water-Vegetation and how the combined application of 3R, SWC and agricultural practices can lead to successful dryland farming.

Recommended interventions

Figure 19 shows the allocation of the proposed interventions within the sub-catchment. Below, all interventions and their benefits are shortly explained. A more elaborate explanation on the interventions can be found in the '3R intervention manual Jordan' (Acacia Water, 2022).

1. The construction of a cascade of five **gabions** in between the depressions to create four flood water storage ponds (Figure 16). By constructing permeable dams made of rocks or boulders, and wire for support, water is slowed down and retained in the ponds. By creating leaky structures, not all water will be captured, avoiding downstream conflicts. The potential in-stream storage capacity of the ponds is estimated at 64,000 m^3 (Figure 16), while the already existing off-stream structures (reservoirs and hafir) could store an additional 86,000 m^3 (Table 3). All together this adds up to a total storage capacity of ±150,000 m^3, covering 18% of the estimated annual agricultural water demand in the area. According to the SWAT results, there is a 60% chance in any given year that the total storage capacity can be filled with flood water (both scenarios). The chance that only the in-stream structures can be filled is 20% in any given year. In the remaining 20% of the cases, the in-stream structures will only reach half to three-quarter of their total capacities. Note that these are just rough estimations. In order to create long-term effective solutions, it is crucial to consider the soil erosion occurring in the upstream catchment area. When neglecting this issue, siltation is likely to strongly reduce the life expectancy of the proposed structures and frequent maintenance is required. Besides, suspended solids in the flood water increase the risk of clogging of drip irrigation pipes, resulting in the need of filters and additional costs. Following a catchment approach is therefore essential, and upstream SWC measures should be implemented in combination with the gabions.

Table 4. Estimated storage capacity of the structures. Capacities were estimated based on the surface area and an average depth.

	Structure		m^3
In-stream	1.	Pond 1	21,000
	2.	Pond 2	19,000
	3.	Pond 3	19,000
	4.	Pond 4	5,100
Off-stream	5.	Reservoir 1	10,000
	6.	Reservoir 2	20,000
	7.	Reservoir 3	11,000
	8.	Reservoir 4 (new)	40,000
	9.	Hafir	4,500
	Total capacity		149,600

2. The construction of **stone bunds** (contour bunds) on the bare, degraded hills in the middle part of the sub-catchment reduce soil erosion and increase soil moisture by intercepting surface water runoff. Soil will build up behind the bunds and indigenous grasses or shrubs can be planted. By doing so, the vegetation cover will recover, eventually providing fodder for livestock. The stone bunds should be constructed along lines of equal elevation (contour lines). The spacing between the bunds depends on the steepness of the slope, but generally ranges between 20-50 m. The stone bunds could be constructed by using a cash-for-work program in which the local Bedouins are involved so that ownership is created.

3. To control the erosion in the middle catchment, the construction of a cascade of **gully plugs** is recommended. Gully plugs do not give direct access to large amounts of water, but slow down runoff, enhance infiltration and capture sediments that otherwise would be transported downstream. The gully plugs can be constructed by using available stones. To stabilize the banks, the gully should be revegetated through native seedlings. The total number of plugs depends on the slope, the depth, and the length of the gully, of which the latter is estimated at 300 m. A detailed assessment of the morphology of the gully system should be carried out before the final design can be determined by a qualified engineer. More information and an example of constructed gully plugs in Jordan can be found on WOCAT: WOCAT SLM Technologies

4. The construction of two **check dams** will reduce the sediment loads in the flood water, improving its quality, and reducing downstream siltation. A check dam is a barrier across a wadi that reduces the velocity of the runoff and causes upstream pooling. Silt is trapped behind the dam and flood water might be harvested for direct use, for example for livestock drinking. Drinking water for livestock is currently trucked to the Bedouins residing in the middle part of the catchment (Figure 15). Constructing check dams could at least water the livestock for some periods a year, saving the locals costs of buying water. In addition, the pooling of the water allows for increased infiltration to the groundwater. Check dams can be made of any material that is locally available; in this case stones.

Figure 15. Livestock drinking from truck water in the middle of the catchment (source: Acacia Water, March 2023).

5. The implementation of **contour ploughing** is an effective and relatively simple measure preventing soil erosion. Contour ploughing involves tilling the soil along the contour lines of the land, creating a series of small ridges and furrows. By doing so, water is intercepted and slowed down as it flows downhill, reducing the impact of rainfall on the soil and allowing water to penetrate deeply into the soil.

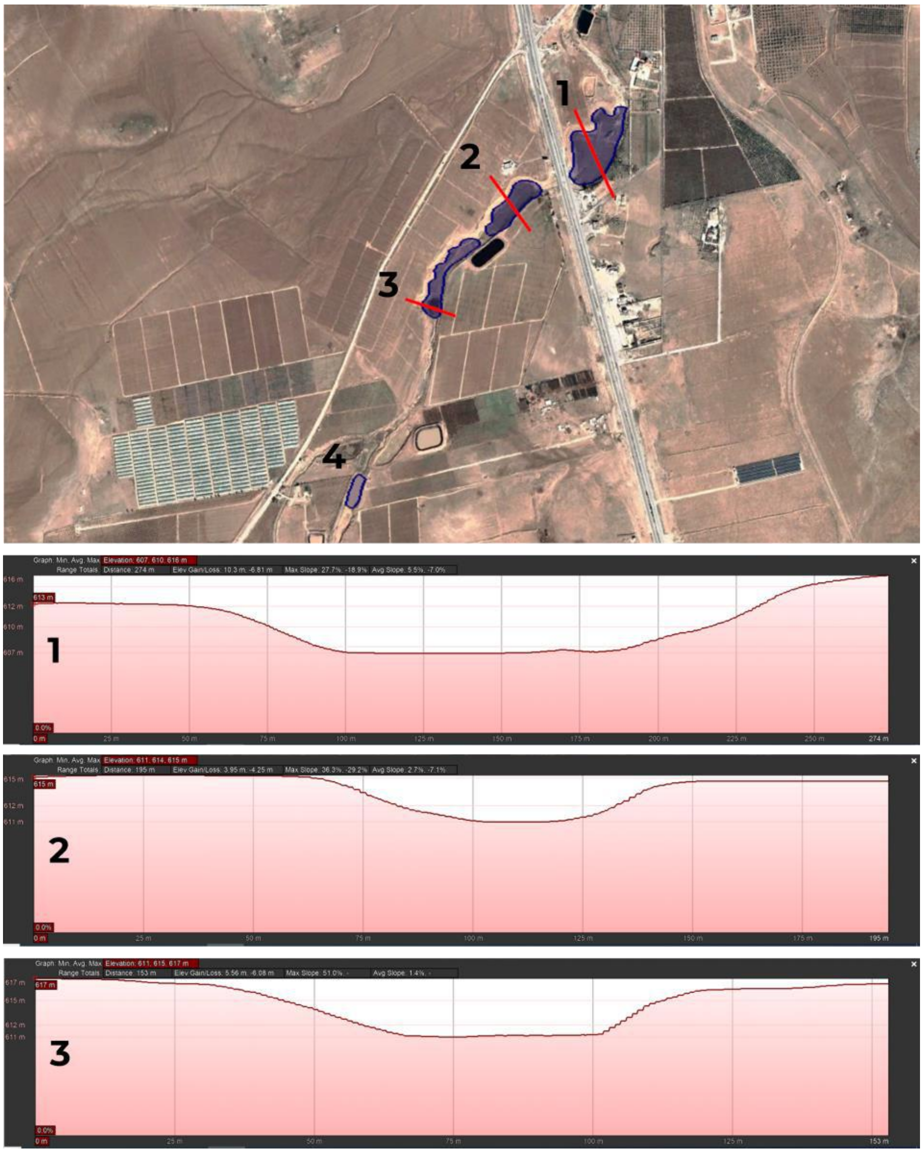


Figure 16. Topographic profiles of the four in-stream flood water storage ponds (red lines). The total storage capacity was estimated based on the average depth of these cross-sections and the surface areas of the depressions (in blue).

6. Within the middle part of the sub-catchment, three earth dams have been constructed. From this location, the upstream catchment measures ca. 8 km^2. The poor design of these embankments, in combination with the questionable allocation within the sub-catchment, results in flood water flowing around the embankments, eroding the ends of the dam walls. In larger catchments (i.e. greater than 5-8 km^2) and rivers of a flashy nature, rock spillways are basically essential, while a proper spillway is lacking in the current design. In order to prevent further erosion, the ends of the walls should be stabilized and the embankments should be redesigned. The first step that we can take is to stabilize the dam walls by creating leaky wings to prevent the further wash-out of the dam. Large stones and rocks can be utilized for the construction. Grasses (long-rooted) should be planted between the stones to reinforce the structure. The floor of the

embankment should also be covered with stones interplanted with grass to prevent erosion. In addition, adequate upstream protection measures are essential for any earth dam. Advice from a qualified local engineer should be sought to redesign the structure. When rehabilitating the structures, the engineer should also supervise the construction.

Figure 17. The three earth dams on satellite imagery (left), and the eroded wings of the most upstream embankment (right).

7. As mentioned in section 2, continuous contour trenches were already constructed in the upper catchment area. It was observed in the field however, that some trenches did not exactly follow the contour. When trenches are 'off-contour' they basically become a drain, and water starts flowing towards the lower end of the trench, which might lead to small gully formation. It is therefore advised to **restore** the **trenches.** As shifting parts of the existing trenches is quite inconvenient, a more straightforward solution is the construction of small stone barriers within the continuous trenches. In this manner, water can be slowed down within the trench so it can still seep into the ground, preventing the formation of a small stream washing away the soil. An example on how to easily fix the trenches is shown in Figure 18.

Figure 18. Example of a small stone barrier in the existing continuous trenches (source: Acacia Water, March 2023).

8. On the bare hills in the upper part of the sub-catchment the **Vallerani system** is proposed. Vallerani ploughing is a form of micro water harvesting and can support vegetation recovery and/or rehabilitation of degraded rangelands. The overall idea is to construct small water harvesting pits (or trenches) along the contour so that runoff water can be captured and infiltration is supported. Native shrub seedlings can be planted to boost the development of vegetation cover. An example of the successful implementation of the Vallerani system in Jordan can be found below: WOCAT SLM Technologies

Proposed interventions	Restoration of existing contour trenches, Vallerani system in combination with planting of native seedlings
Benefits	• Reduced soil erosion; • Increased infiltration; • Biomass enhancement.
Monitoring	• Soil moisture content (TEROS 12) • Biomass enhancements (remote sensing analysis; NDVI) • Tipping bucket rain gauge

Impression of area

Proposed interventions	Contour ploughing, rehabilitation of most upstream earth dam
Benefits	• Reduced soil erosion and sediment loads in water; • Reduced loss of fertile topsoil; • Increased infiltration; • Easy to implement.
Monitoring	-

Impression of area

Proposed interventions	2 check dams, stone bunds, gully plugs
Benefits	• Reduced sediment loads in flood water; • Increased infiltration and enhancement of vegetation cover; • Increased fodder and water for livestock.
Monitoring	• Soil erosion and deposition (erosion pins) • Biomass enhancements (remote sensing analysis; NDVI)

Impression of area

Proposed interventions	5 gabions
Benefits	• Increased water availability as sustainable alternative to groundwater pumping; • Reduced pumping costs.
Monitoring	• Water levels (TD divers + staff gauges) • Siltation of ponds (erosion pins) • Telemetric climate station

Impression of area

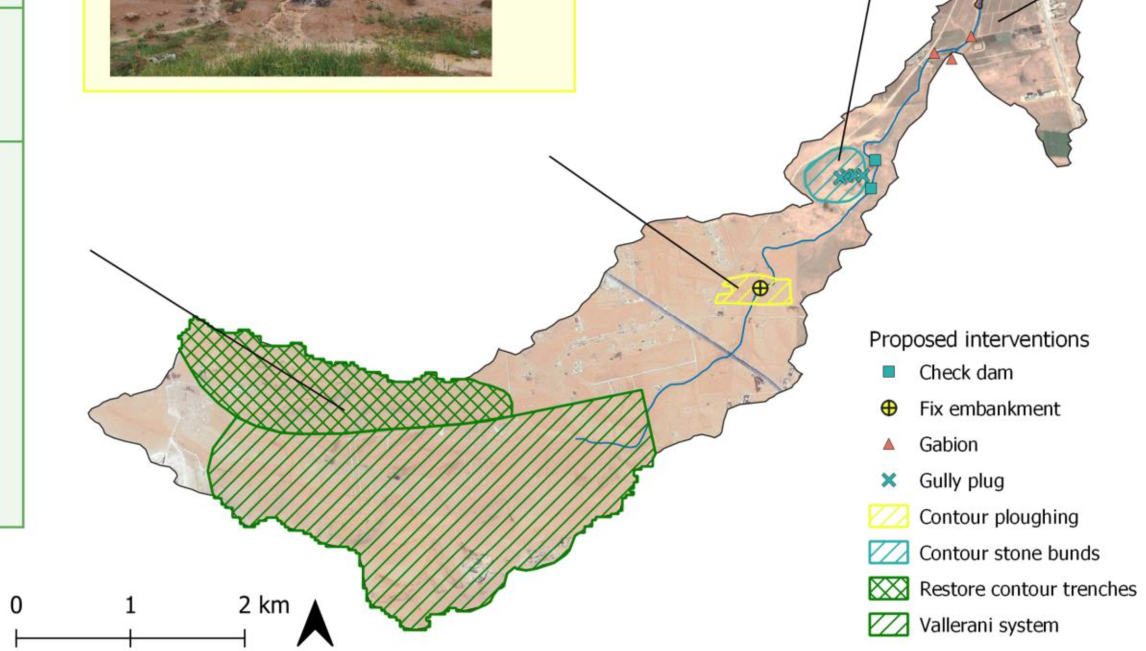


Figure 19. Allocation of 3R interventions within the sub-catchment.

General recommendations:

Most abovementioned interventions are hard measures and imply the construction of physical structures. Scarcity is resolved, however, not only by increasing water availability through the implementation of such hard measures, but also by managing demand through soft measures focusing on community-scale efforts and decision-making. 3R implementation is in general most effective when hard and soft measures are combined. Some additional recommendations for the sub-catchment are therefore provided below. These recommendations focus on the soft path and strive to improve the overall productivity of water use (and land) rather than to seek sources of new supply.

- As water is a scarce resource, the **cultivation of crops that consume less water** is highly recommended. Almonds, cactus or jojoba are three examples of crops that have lower water requirements compared to, for example, stone fruits and olives. The latter two also have an excellent tolerance to high salinities (up to 2000 and 2500 ppm respectively). Almonds and jojoba trees both do not require large amounts of water to produce economically (Tal & Rabbo, 2010). Also, cacti cultivation could be a promising alternative in areas with limited rainfall. Cacti have multiple products that could benefit local livelihoods - for example the production of fodder for livestock and fruits for human consumption and medicinal use. In addition, cactus have the ability to grow in marginal lands with little input, and they cover the soil preventing soil erosion. An example of the successful implementation of cacti cultivation in Jordan can be found here: WOCAT SLM Technologies
- **Adjusted cropping patterns** should be adopted to restrict the cultivation of vegetables during the summer months of July and August and reduce peak water consumption. The cultivation of crops in spring should be promoted to prevent evaporative losses from storage in open reservoirs and to shift the peak water demand to a period with higher water availability.
- To improve the irrigation efficiency, **smart agriculture** should be implemented. The objective of smart agriculture is to increase the quality and quantity of crops while optimizing human labour and reducing negative environmental impacts. To achieve this, monitoring and applying data is crucial and smart sensors have to be installed, for example, to measure the amount of irrigation water applied, the soil moisture status, and the meteorological conditions. Besides, the most appropriate and efficient irrigation technique should be selected, which means farmers have to switch from sprinklers to (subsurface) drips. The soil moisture status in the root zone should be continuously measured and daily crop evaporation estimated. Based on the monitoring data, the irrigation water supply can be fine-tuned increasing the irrigation efficiency and reducing the overall water demand.

Another advice is to **reduce evaporative losses** caused by storing groundwater in open reservoirs, especially when taking into account the future increasing temperature trend (

- Annex 1: Climate analysis). One example on how to reduce evaporation losses is by installing floating solar photovoltaic (FPV) systems on the irrigation reservoirs. In this way, water is conserved by reducing evaporation losses while sustainable electricity is provided at enhanced yield that can be utilized locally. From a case study in Mafraq, it was estimated that installing such a system could lead to 42% savings compared to an uncovered reservoir (Farrar, Bahaj, James, Anwar, &

Amdar, 2022). Another possibility is to apply the groundwater directly to the land, instead of storing it in open reservoirs.

- The implementation of the **'Al-Hima' land management** system could prevent further degradation of the rangelands in the sub-catchment. 'Al-Hima' is a historical and traditional system of land management in the Arab region that encourages the sustainable, shared use of common resources amongst local communities. What underlies 'Al-Hima' is the development of grazing protocols through which herds are regularly and systematically moved to 'rested' areas with the intent to maximize the quality and quantity of forage growth (Myint & Westerberg, 2015). By allowing the 'resting' lands time for regeneration, the vegetation can renew energy reserves, rebuild shoot systems, and deepen root systems. This all maximizes overall biomass production in the long-term and prevents further erosion. Another, more formal, term for such a system is managed rotational grazing.
- When new seedlings are planted as part of the proposed interventions (e.g. in combination with the stone bunds), **(temporary) area closures** are advised. The area closures should be in place until a certain degree of recovery of the vegetation cover has been attained. These closures can be realized by fencing or by (community) agreements. Another possibility is the planting of a live fence of cactus or similar thorny vegetation.

5 Monitoring plan

To assess the effectiveness of the proposed measures a monitoring plan is drafted. Monitoring allows us to measure the actual impact of the proposed interventions over an extended period. It helps identify the changes in, for example, vegetation cover, soil moisture status, and erosion rates. By comparing monitored data with baseline conditions, it is possible to assess whether the selected interventions are achieving their intended objectives.

Long-term monitoring also generates valuable data and lessons learned that can be shared with other regions and projects in Jordan. It contributes to the collective knowledge base, enabling the replication and scaling up of successful 3R interventions. The obtained data can inform best practices and guidelines, and support future decision-making processes, fostering a more evidence-based approach to 3R implementation in the country. Monitoring data also facilitates effective communication and collaboration among different stakeholders involved in soil and water conservation initiatives.

Despite the short project duration of only three years, setting up a monitoring network is strongly advised for abovementioned reasons. Preferably, monitoring continues for a 5 to 10 year period to be able to assess the long term effects. This, however, requires a strong commitment to the monitoring and evaluation process beyond the timespan of the project, and is only possible when there are direct incentives for the people involved. Capacity building of local stakeholders, policy makers and land managers is therefore crucial.

The suggested monitoring plan focuses on the monitoring of the biophysical impacts of the proposed interventions.

- Climate data are of high relevance for water resource management and can be used to estimate different components of the water balance. It is therefore advised to install a **telemetric climate station** at the ‘in-stream ponds’ allowing the quantification of precipitation and the calculation of the potential evaporation (through monitoring daily averages of solar radiation, temperature, relative humidity and wind speed). In addition, monitoring climatic variables in combination with water levels (see third bullet), enables the quantification of infiltration from the ponds.

- To assess the spatial variability of rainfall within the catchment, two additional tipping-bucket **rain gauges** should be installed: one at the Al Ghadeer Alabyadh dam (if monitoring system non-existing there), and one in the upstream catchment area. Both rain gauges should preferably be installed in an open area and be connected to a data logger to obtain continuous time series of precipitation data.

- To measure the volumes of water in the storage ponds, water levels must be monitored. The most common method for water level measurement is to use an electronic pressure transducer that is submerged in a stilling well (or a steel 2” tube with perforations), in which the water level moves with that of the river or, in this case, pond. The sensor is connected to a datalogger and a modem, so that the data is automatically transmitted at regular programmable intervals to a dedicated server. Here, it is recommended to install four pressure sensors in each of the different ponds, and one sensor in the reservoir of the Al Ghadeer Alabyadh dam. An example of a suitable sensor is the TD Diver (van Essen, the Netherlands; https://www.vanessen.com), which is an absolute pressure and temperature measurement device integrated in a 22 mm diameter stainless steel tube that also contains the datalogger and power supply. The Diver has sufficient memory for two years of continuous measurements at 15-minute intervals and costs around €500 each. As long as the Diver is not submerged in water it measures atmospheric pressure. Once the Diver is submerged this is supplemented by the water's pressure: the higher the water column the higher the measured pressure. Due to variations in atmospheric pressure, barometric compensation is needed to convert the Diver pressure readings into water level data. To do this, the air pressure measurements from the telemetric climate station at the 'in-stream ponds' can be used. The barometrically adjusted water values can be related to a reference point such as a staff gauge. With each Diver, it is advised to install a staff gauge for visual water level measurements as reference.

More information on the Diver and its installation can be found in the product manual: TD-Diver-DI8xx-ProductManual-en (vanessen.com)

- Groundwater level monitoring is important to assess potential contributions of the proposed interventions to groundwater recharge. At the waste water treatment plant, approximately 3 km south of the 'in-stream ponds', a monitoring well exists (AD 3027). The available data, however, shows that the last measurement took place in April 2022. In addition, the measuring interval has decreased from monthly measurements to annual or bi-annual measurements over the past decades. To be able to review the effectiveness of the interventions on groundwater recharge, the monitoring at this well should be improved. If there are any problems with the equipment, a new Diver should be installed to obtain continuous timeseries. If the monitoring equipment is still functioning, a measuring protocol should be made in agreement with the MWI, in which the measuring interval and data sharing process will be clarified.

Figure 20. Examples of pressure sensors. The left sensor represents an absolute pressure and temperature sensor with the datalogger integrated in the housing. The right sensor is air pressure compensated with a capillary vent in the cable.

- An inexpensive and intuitive method to estimate hillslope soil erosion and deposition is to use **erosion pins**. Erosion pins are suitable for measuring erosion at long time scales such as annual erosion rate; however, it is challenging to use the erosion pins for estimating soil erosion in short time scales (e.g. a specific rainfall event or specific day). The method uses metal pins that are driven into the ground perpendicular to the slope, with a washer at a known distance from the top of the pin (Figure 21). In theory, erosion undermines and lowers the washer, resulting in a new distance from the pin top that equals the depth of erosion that occurred between measurements. An increase in distance from top of the pin to soil surface indicates erosion; a decrease indicates deposition. The washer around the pin facilitates the measurements. It is advised to install at least 20 erosion pins in a grid on the stone bunds hillslope. By placing a transect of pins just behind the bund (upslope) the accumulation of sediment behind the bund can be monitored over the years. Another series of pins should be installed in between the bunds to monitor erosion. Ideally, a second - reference - study plot with an additional 20 pins will be installed on a hill with similar characteristics. In this manner, the effectiveness of the intervention can be evaluated. The measurements have to be carried out by an observer (student research?) after each rainy season and after each dry season. The pins should be inspected for damage or disturbance throughout the season.

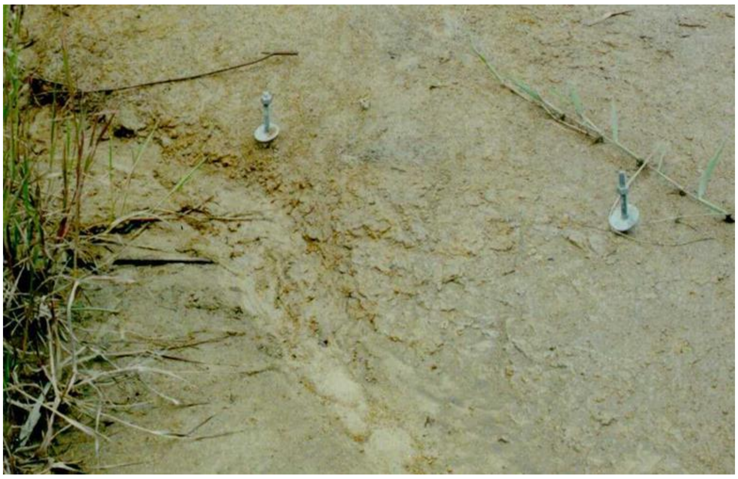


Figure 21. Example of erosion pins with washers (source: SERC Carleton College).

- The accumulation of sediments in the storage ponds can also be monitored by using erosion pins. In each storage pond it is recommended to install three erosion pins. After a flood event, an observer can measure the deposition of silts. To carry out the measurements, the ponds have to be dry. Turbidity of the flood water can also be analyzed by taking water samples and carrying out a sediment analysis in a laboratory to obtain the Total Suspended Solids (TSS). The latter method is, however, likely to be more time-consuming and costly.

- To monitor potential biomass enhancements in the sub-catchment a **remote sensing study** can be carried out. A proxy that can be used for this study is the Normalized Difference Vegetation Index (NDVI). The NDVI is an indicator of greenness of an area that can be derived from satellite imagery. NDVI is closely related to vegetation cover and soil moisture. Values range from zero to one, representing bare areas with no vegetation (0) to areas fully covered by vegetation (1). To set the baseline an analysis of the historical NDVI should be performed, which afterwards can be compared to future data to assess potential changes in vegetation cover.

- To measure changes in soil moisture content in the upper catchment (Vallerani system and contour trenches) the installation of TEROS 12 sensors is advised. TEROS 12 is a long-life, accurate and easy-to-install sensor with sharpened stainless steel needles that easily slip into the ground (Figure 22). The sensors (± €300 each) have to be connected to a data logger to be able to perform telemetric measurements. One single data logger (YDOC), costs about €600 euros, has three sensor ports and is solar powered. To be able to measure the effect of the trenches on soil moisture content, one sensor can be installed in the bottom of the pit, while a second sensor can function as reference and be placed outside the pit or trench. The sensors can be installed at different depths to measure, for example, top soil moisture, soil moisture in the root zone or, in case of vegetation with a fairly shallow root system, below the root zone to quantify the amount of water draining down the profile. In this case, it is recommended to install the sensors at 30 cm depth. For each location (Vallerani and contour trenches), it is advised to install at least two sensors inside, and two reference sensors outside the trench or pit to account for spatial differences.

Figure 22. TEROS 12 sensor for soil moisture measurements.

6 Next steps

Before implementation can start, the following activities should be carried out:

- When increasing the water availability, a possible scenario is that the farmers will not reduce their pumping, but will extend their farms by using the stored flood water as an additional source rather than a substitute of the groundwater. To make the construction of the flood water storage ponds sustainable and prevent this situation from happening, **agreements on the beneficiaries' water use** should be made with the farmers before implementation. Ideally, a consensus should be reached on how much the farmer will reduce his/hers pumping in years with sufficient water. **Awareness raising** about the consequences of long-term over abstraction of groundwater and aquifer depletion is therefore key. Besides it should be made clear that reducing the pumping rates will also benefit the farmer from an economic perspective as the pumping costs will likely decline.
- For some of the interventions it is advised to use a cash-for-work program for implementation. By **setting up cash-for-work programs** and involving the local community, a sense of ownership can be created. Due to this participatory approach, community members are more likely to support any future calls to assist in repair or maintenance work. Besides, it will increase the likelihood that any communal benefits are shared in a fair way.
- All land-users in the sub-catchment area should be encouraged to participate in the proposed SWC activities, including the maintenance of structures and vegetation cover. To enable this, direct incentives in addition to cash for work are required. This can be achieved through the identification of direct benefits to communities (e.g. higher water availability, improved access to fodder and water for livestock, additional sources of income), combined with **awareness raising and capacity building.**
- As already mentioned, a qualified local engineer has to be contracted to develop the final designs. The team should collectively **evaluate the final designs** made by the engineer, before implementation starts.
- During implementation the holistic catchment approach has to be followed, meaning that the activities should **start in the most upstream part** of the sub-catchment. For safety reasons, in-stream activities should be carried out during the dry season.
- To collect sufficient data to set up a proper baseline, it is recommended to **install** the (reference) **monitoring equipment** as soon as possible. In addition, the existing monitoring protocol at the Al Ghadeer Alabyadh dam should be checked (e.g. water levels, release rates from dam, GW monitoring well AD3027).
- For the successful implementation of SWC measures, a **high resolution Digital Elevation Model (DEM)** of the sub-catchment is needed. To obtain a detailed DEM, drones are a quick and effective data collection tool that can conduct photogrammetry or LiDAR missions. LiDAR works by sending pulses of light to the earth's surface and measuring the time it takes to reflect back. This method is very powerful, even in densely vegetated areas, but also costly. The photogrammetry technique is a more affordable and acceptable compromise, especially in bare areas such as Jordan. DEM generation by photogrammetry uses high-resolution overlapping photographs to recreate a survey area. These geo-referenced images are processed and merged together using sophisticated software to create highly detailed DEMs.

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Annex 1: Climate analysis

Data from the Mafraq meteorological station (AD0016) was obtained and compared to the satellite-based CHIRPS dataset. Over the 1981-2021 period, the annual average observed rainfall at the Mafraq station equaled 130 mm. The data showed strong fluctuations in precipitation in between years, ranging from 300 mm to only 30 mm (Figure 23).

Compared to CHIRPS, the annual and monthly averages are quite similar; CHIRPS however slightly overestimates average rainfall. Extreme events are however not properly captured by CHIRPS, and variations in monthly and annual precipitation are smaller. For example, the year 1988 was an extremely wet year with an observed annual rainfall of 303 mm. According to CHIRPS the total rainfall in this year was ca. 100 mm less. In 2012, the area faced a major drought, while according to the CHIRPS dataset Mafraq still received 143 mm of rainfall, which is higher than the annual average precipitation.

The scatterplot in Figure 23 also shows that CHIRPS shows less extremely dry or extremely wet months compared to the observed data at the Mafraq station (AD0016). The observed trendline is not linear but flattens at higher amounts of rainfall. This means that rainfall in the wettest months is often underestimated by CHIRPS. The figure also indicated that there are quite some dry months where almost no rainfall was observed, whereas according to the CHIRPS dataset these months were not completely dry. During some months these dry months received even 30 - 40 mm of rainfall according to CHIRPS. Obviously, we should bear in mind that observed rainfall data also contains inaccuracies, for example due to malfunctioning or not functioning of the rain gauges.

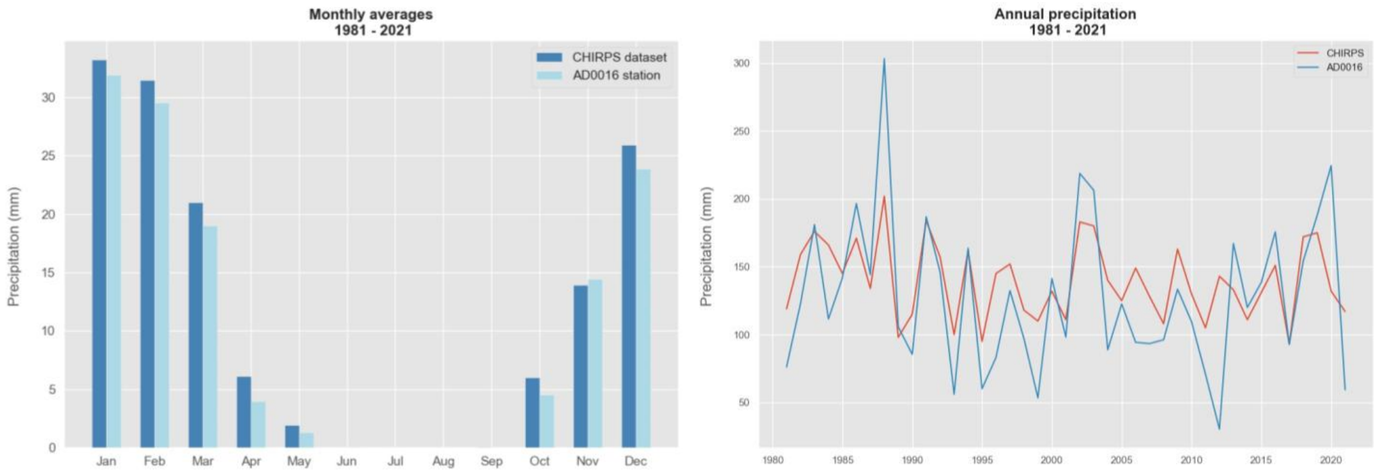


Figure 23. CHIRPS vs. observed rainfall at Mafraq meteorological station (AD0016) over the 1981 - 2021 period.

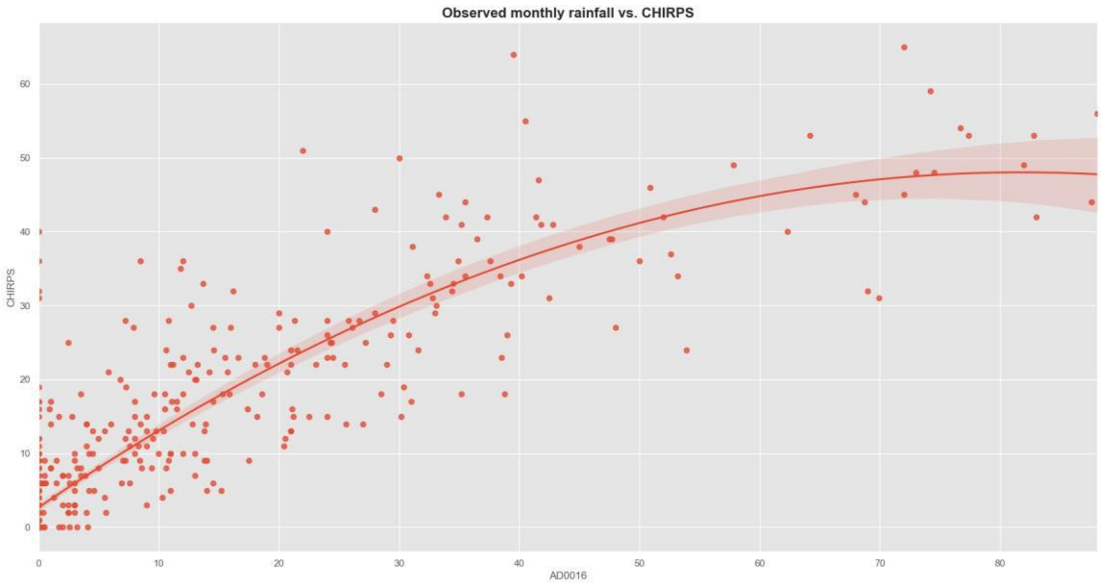


Figure 24. Scatterplot with the observed rainfall on the x-axis and the CHIRPS rainfall on the y-axis.

Future trends

Data from the CMIP6 climate modelling experiment was used to gain insight into future precipitation and temperature trends. The CMIP6 experiment includes 13 Global Circulation Models with ensembles for temperature (68 ensembles) and precipitation (66 ensembles) projections from 1850 until 2100. Due to the uncertainty of the carbon emission pathways in the coming decades, CMIP6 uses different shared socioeconomic pathway scenarios (SSP) for its projections. The SSP245 pathway represents the "middle of the road" scenario.

In Mafraq, the months of December and February are projected to become drier in the near and far future. The mean annual precipitation is projected to slightly decrease towards the far future (SSP245). The temperatures are expected to increase in all months, with an increase in mean temperature of XX °C in 2050 compared to the reference period (SSP245). August will suffer from the highest temperature increases, with increases of XX °C in the near future (2031-2040) compared to the reference period.

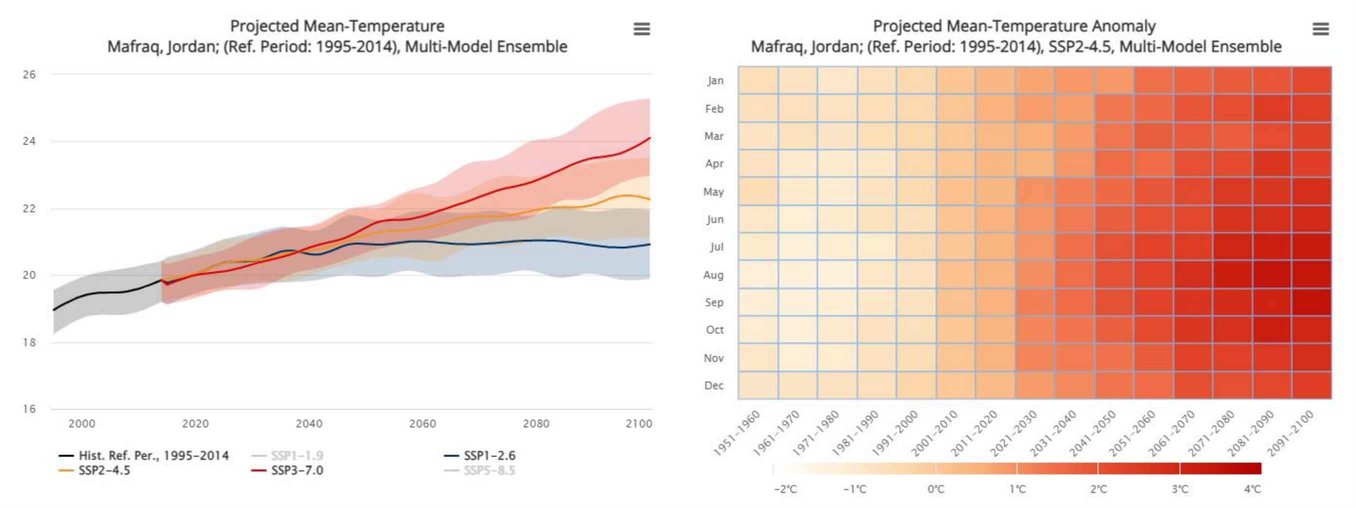


Figure 25. CMIP6 ensemble mean temperature projections for different scenarios (left), and projected monthly anomalies for the "middle of the road" SSP245 scenario (right).

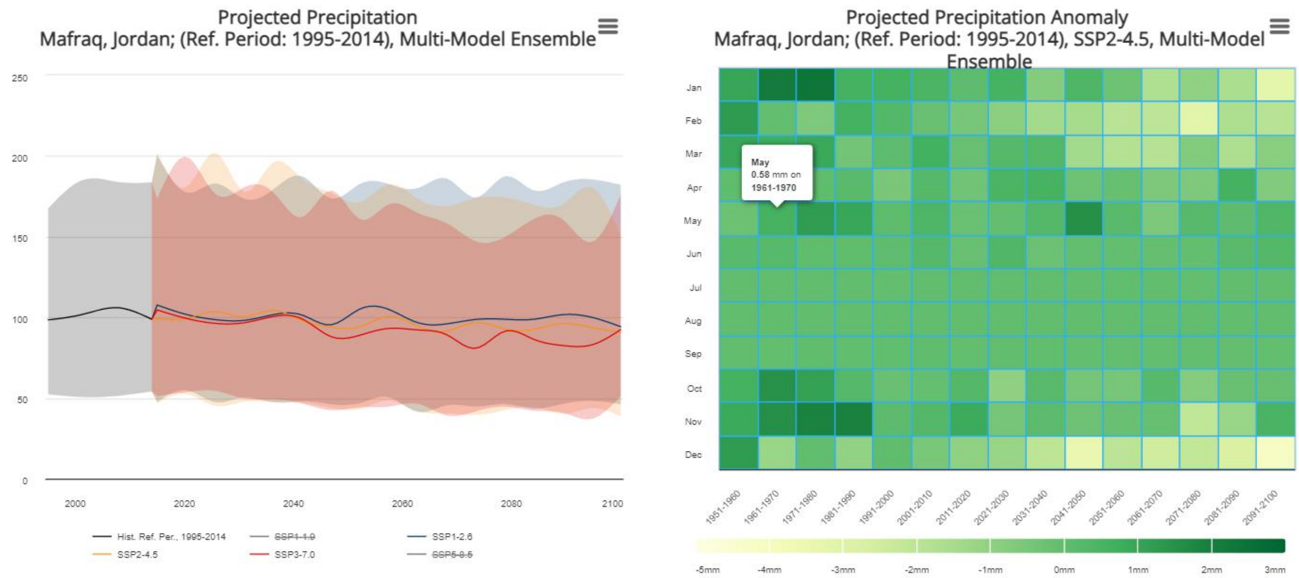


Figure 26. CMIP6 ensemble mean precipitation projections for different scenarios (left), and projected monthly anomalies for the “middle of the road” SSP245 scenario (right).

Annex 2: Field observations

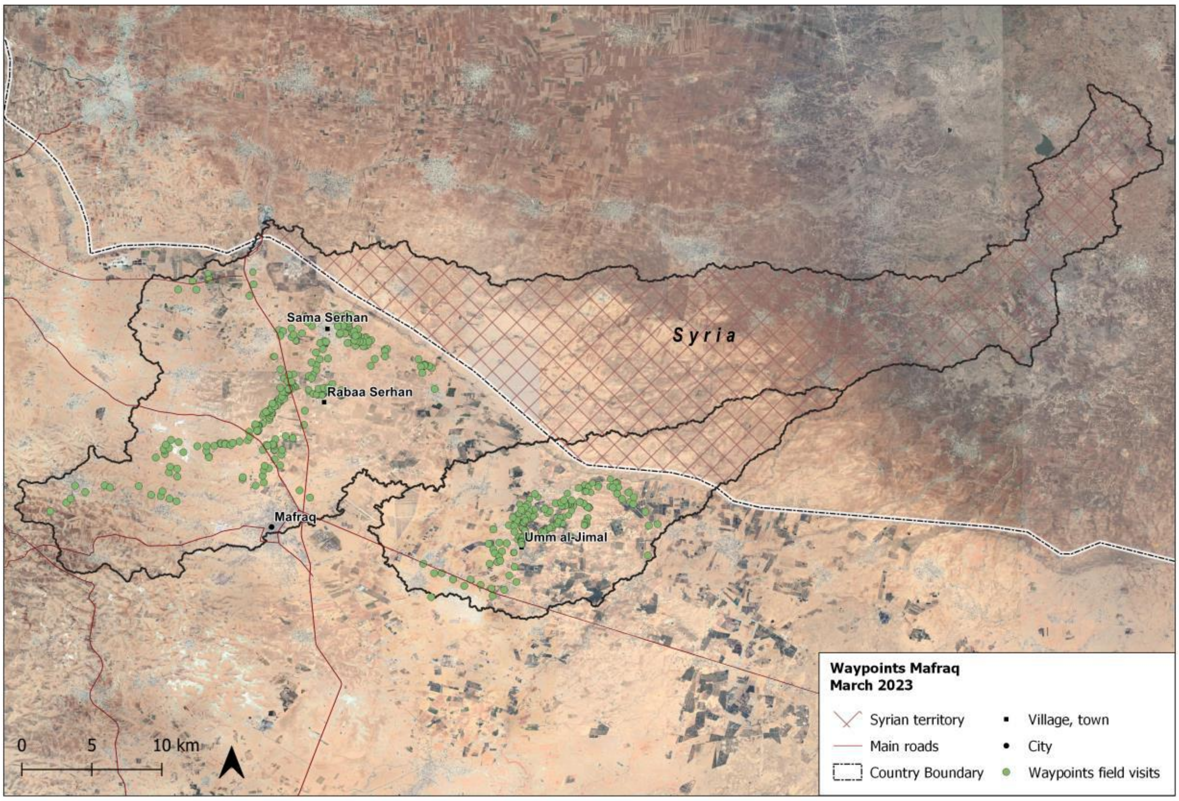


Figure 27. Waypoints of all locations visited during the field trips in Mafraq.

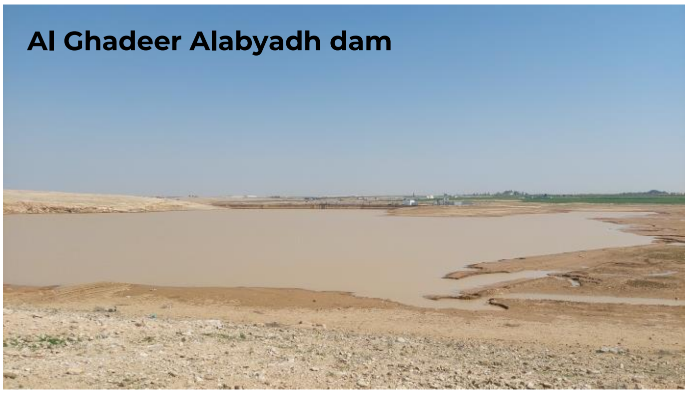

First in-stream depression


Second in-stream depression


Third in-stream depression


Fourth in-stream depression

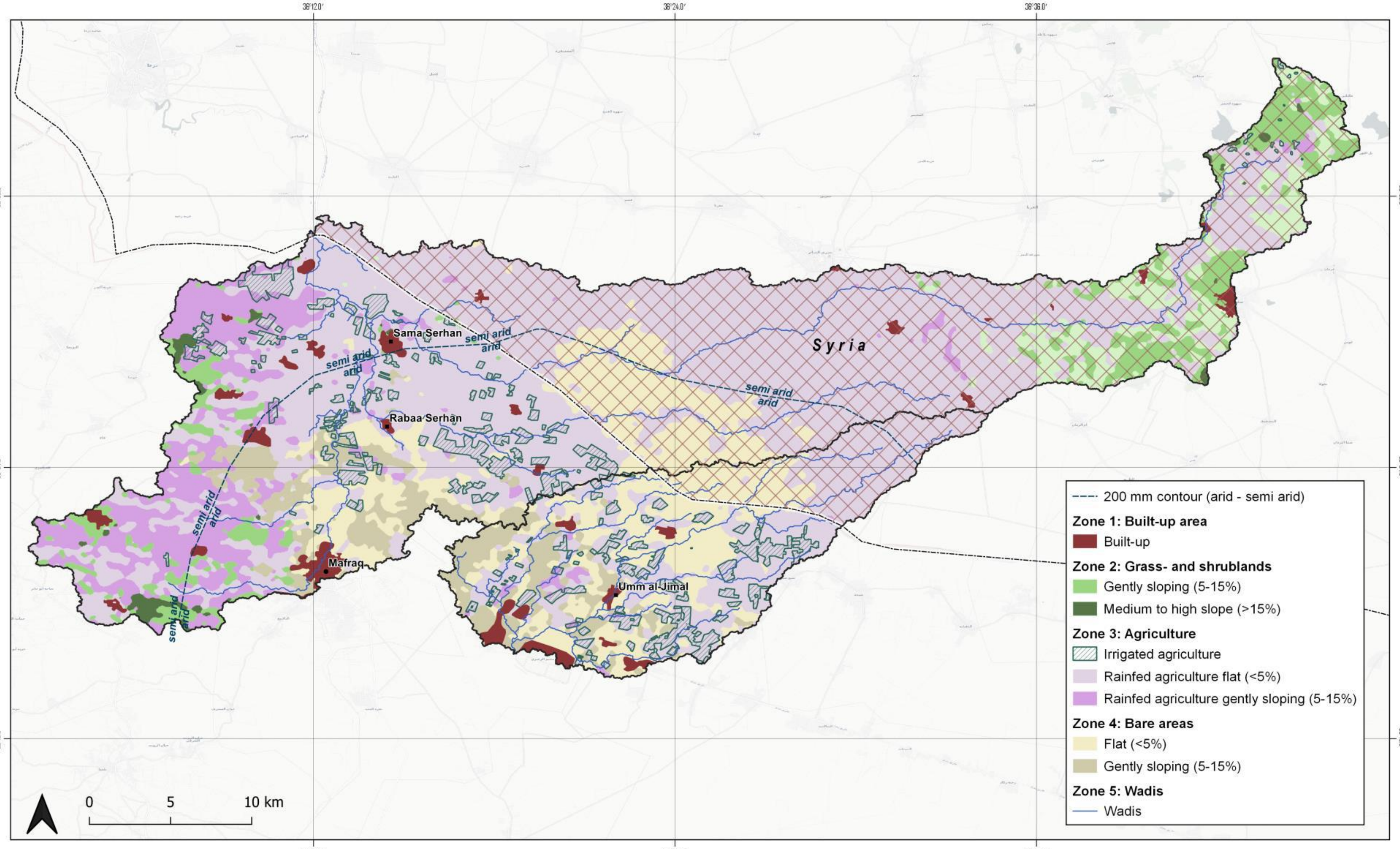

Check dam location 1


Al Ghadeer Alabyadh dam


Erosion at embankment

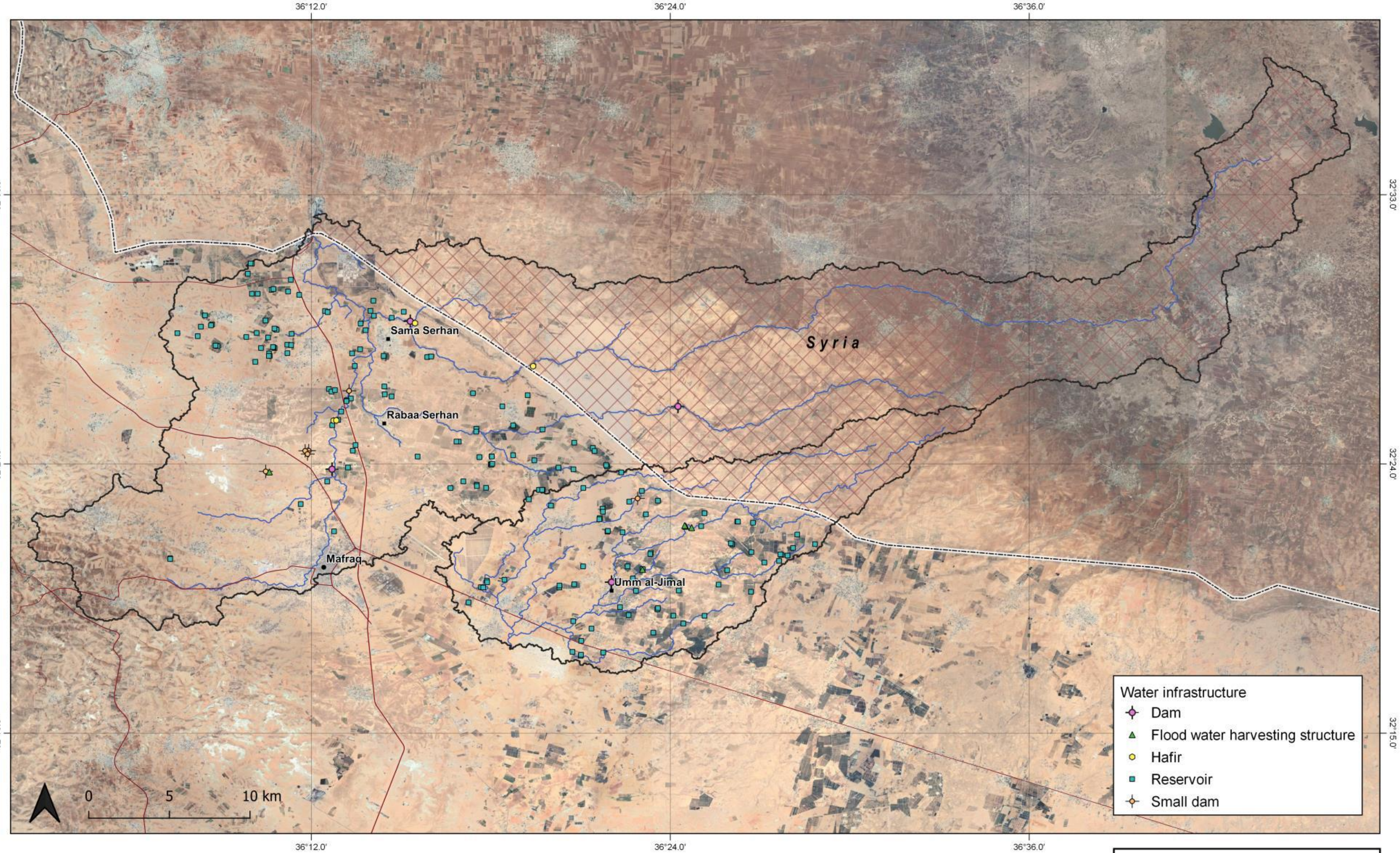

Water flowing in wadi tributary - middle catchment

Annex 3: Produced maps



Syrian territory
Watersheds
National border
Village, town
City

3R potential map of the Mafraq region - RWH Jordan			
Final version			
Scale:	1:135000	**Date:**	April 2023
Map format:	A3	**Projection:**	WGS 84
Author:	Acacia Water		



Water infrastructure map of the Mafraq region - 3R Jordan
Final version

Scale:	1:135000	Date:	April 2023
Map format:	A3	Projection:	WGS 84
Author:	Acacia Water		