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Economic Feasibility of Rainwater Harvesting Applications in the West Bank, Palestine

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Abstract: Freshwater resources are uncertain in Palestine and their uncertainty is expected to intensify due to climate change and the political situation. Yet, in this region, a stable freshwater supply is vital for domestic and agricultural uses. Rainwater harvesting could help to increase freshwater availability. This study investigates the economic feasibility of two rainwater harvesting applications in the West Bank, with eyebrow terracing in olive groves in rural areas and domestic rooftop harvesting in urban areas. Cost-effectiveness is estimated using a spatially explicit cost–benefit analysis. Three land zones varying in suitability for the implementation of eyebrow terracing in olive groves are analyzed. The potential increase in olive yield is estimated with a crop–water balance model. The potential amount of rainfall that can be harvested with domestic rooftop harvesting is calculated based on the average rooftop area for each of the 11 governorates individually. Costs and benefits are considered at the household level to calculate the economic feasibility of these two applications. Although eyebrow terracing enlarges soil moisture availability for olive trees and thereby increases olive yield by about 10–14%, construction costs are too high to make implementation cost-effective. Similarly, rooftop harvesting can harvest about 30% on average of the annual domestic water demand and is worthwhile in the northern and southern governorates. Yet, in this case, construction costs are generally too high to be cost-effective. This obstructs more widespread adoption of rainwater harvesting in the West Bank, which is urgently needed given the large impacts of climate change. Providing subsidies for rainwater harvesting could help to make adoption more attractive for households.

Keywords: rainwater harvesting; cost–benefit analysis; aridity; urban; rural; rooftop harvesting; eyebrow terracing; Palestine

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1. Introduction

Freshwater availability is uncertain in Palestine and is expected to become even more limited due to climate change, rapid population growth, expansion of agricultural activities, and political implications [1]. Palestine is characterized by an arid to semi-arid climate. Access to freshwater resources from aquifers is very limited and has been decreasing over time due to Israeli control of Palestinian water resources [1,2]. As such, Palestinians are seeking to have new water alternatives such as rainwater harvesting. However, due to climate change, precipitation is expected to decrease along with an increase in dry spells and an increase in evapotranspiration due to increasing temperature [3]. Together, this is leading to increased water insecurity.

Yet, freshwater availability is vital for people's daily lives in Palestine, mainly for domestic water use and irrigation water in agriculture. Ensuring the availability and sustainable management of water and sanitation—which is described in Sustainable Development Goal 6—is not only vital in itself, but is also "essential for enhancing food security, health and wellbeing of citizens (SDG 2, 3 and 14), and the resilience of Palestinian communities in the face of water confiscation and intensifying climate change (SDG 13)" [2]. Even though the majority of homes are connected to the water grid in Palestine (i.e., 91%) [4], the water supply is irregular and intermittent, and about one-third of distributed water is lost due to leakages in the water grid [2]. As a result, the average water consumption is low and households facing intermittent supply or who are not connected to the water grid are forced to buy tanked water at highly inflated tariffs [2]. As such, coping with increasingly uncertain water supply is critical for Palestine.

To cope with increasing uncertainty in water availability, the government of Palestine is intending to promote more widespread adoption of rainwater harvesting [2,5]. Rainwater harvesting is already practiced in Palestine to some extent. It forms an additional source of water for domestic consumption and agriculture use [6]. Implementation is promoted on a small scale by local communities and non-governmental organizations to alleviate temporal and spatial water shortages. People typically collect rainwater from roofs or rock catchments and store it in cisterns in order to meet part of their water needs [6]. More widespread adoption of rainwater harvesting could help to increase water security in the region.

Rainwater harvesting is applied widely in arid regions around the world as a means to provide water for agricultural and domestic uses [7,8] and is an important method to adapt to climate change [9–11]. It is a relatively low-key solution to increase water security for households [12], and is seen as a low-regret adaptation measure to climate change [1]. It is also promising to upscale rainwater harvesting in rural areas in order to increase crop production [13]. Other benefits include—amongst others—reduced soil erosion, reduced runoff peak flow, flood mitigation, and increased groundwater recharge [14]. Many different rainwater harvesting systems exist that can be adapted to local climatic, biophysical and socio-economic conditions, and are suitable for either the urban or rural context. Rainwater harvesting is also relatively cheap to implement and a lot of experience and technical knowledge is available for successful implementation given its long history [15].

Previous studies show that the success of the implementation of rainwater harvesting systems depends heavily on their economic feasibility [14,16,17] next to their technical design and identification of suitable sites [11,18,19]. Technical design and site suitability have been studied previously for Palestine and show that a range of techniques and suitable locations exist to apply rainwater harvesting [5,20,21].

Yet, the economic feasibility of implementing rainwater harvesting for households in Palestine is unknown. The economic feasibility of rainwater harvesting can be calculated using a cost–benefit analysis [22]. Previous cost–benefit studies about rainwater harvesting in residential areas in other countries show that rainwater harvesting may be an efficient strategy, but cost-efficiency depends largely on local water prices, besides cistern size and type ([23] for Jordan; [24,25] for the USA). Often, water tariffs are heavily subsidized and very low (e.g., [23]), making it hard for alternative water sources that require initial investment and maintenance costs to be cost-efficient. Furthermore, often investment costs are the main economic barrier for households to install rainwater harvesting, especially in the global South [14,17,26], even though installation may supplement household income when harvested rainwater can be used as irrigation water for crop production [26].

In the context of climate change and increasing uncertainty in water availability, and in a region that is primarily dependent on rainwater for its freshwater input, it is essential to know whether implementation of rainwater harvesting can increase water availability and whether adoption can be cost-effective on a larger scale. Especially, given that the Palestinian government is considering promoting rainwater harvesting as a strategic option to overcome water shortages in Palestine on a larger scale [2,5]. When implementation can be economically feasible, the Palestinian government could consider to stimulate the adoption of rainwater harvesting, for example, by the means of financial stimuli, such as subsidies.

This study aims to investigate the economic feasibility of the implementation of two rainwater harvesting applications in a rural and urban setting in the West Bank of Palestine. Two types of rainwater harvesting that are commonly practiced in the West Bank will be investigated: (1) eyebrow terraces in olive cultivation in rural areas, and (2) domestic rooftop harvesting in residential areas [5]. A crop–water balance model is set up to estimate the impact of rainwater harvesting by the means of eyebrow terracing on olive yield. A rainwater harvesting calculation tool is used to estimate the amount of rainwater that can be harvested on domestic rooftops. The resulting estimates are used to calculate the costs and benefits of the two selected rainwater harvesting applications. These costs and benefits are weighed in spatially explicit cost–benefit analyses to determine whether the implementation of these two techniques is economically feasible for Palestinian households.

This study approach has two novel aspects. In contrast to previous studies that mainly focused on analyzing one technique applied in either an urban or rural setting, the current study will investigate two techniques in two distinct landscapes of the West Bank. It is expected that along with differences in the amount of rainwater that can be harvested, the costs and benefits of rainwater harvesting implementation will be different as well for rural and urban rainwater harvesting. Another novel aspect is that the cost–benefit analyses that are undertaken in this study are spatially explicit. This allows for us to account for spatial variability in local climatic, biophysical and socio-economic conditions that determine the suitability and effectiveness of rainfall capture, and ultimately cost-effectiveness of harvesting in specific regions of the West Bank. As such, it can offer insight into which parts of the country can be promising to implement rainwater harvesting.

2. Materials and Methods

2.1. Study Area

The study area is the West Bank of Palestine, which is subdivided into 11 governorates (Figure 1). The surface area of the West Bank is about 5660 km^2 [27]. The West Bank has a Mediterranean climate with climate zones ranging from dry sub-humid, semi-arid, arid to hyper-arid zones. The long-term annual average varies between 133 mm in the proximity of the Jordan River (in Jericho) and 658 mm in the central mountains (in Salfit), with an annual average value of about 420 mm for the entire West Bank [28].

In 2018, the West Bank had 2.9 million inhabitants and a population density of 522 persons/km^2 [26]. Gross Domestic Product accounted for USD 10,715.9 million and Gross Domestic Product per capita for USD 4154.2 in 2017 [26]. Agriculture (combined with fisheries) accounted for 7.1% of the national GDP in Palestine in 2018 [26].

Land use in the West Bank consists of arable land (supporting grains), irrigated farming (supporting vegetables), permanent crops (including olives, grapes, citrus, and other fruit trees), rangeland (including rough grazing and subsistence farming), woodland and forest, built-up areas and Israeli settlements [29]. The latter category is not considered in this study, since it is not controlled by the Palestinian Authority.

2.2. Implementation of Eyebrow Terraces

2.2.1. Spatial Characterization Using Archetype Analysis

A spatial characterization was made of the West Bank using archetype analysis for the implementation of eyebrow terraces in olive groves. Archetype analysis uses socio-ecological indicators to systematically identify regions with similar conditions (so-called archetypes) for the implementation of rainwater harvesting [13]. To this end, a baseline map was prepared based on land use in the West Bank [29]. Suitable land use classes were selected in which eyebrow terraces can be implemented, either in existing or new olive groves. Suitable land use classes were arable land supporting grains and permanent crops, including olives, oranges and grapes. The land use map shows that olive groves cover the largest area of the permanent crops (about 80%). It also shows that the selected area suitable for olive terracing covers 1617 km^2, which constitutes about 29% of the West Bank (Figure 2).

Subsequently, three biophysical variables were used to define suitable areas for olive cultivation on eyebrow terraces: precipitation, slope and available soil water capacity (AWC) [5].

Figure 1. Map of the West Bank, showing the 11 governorates.

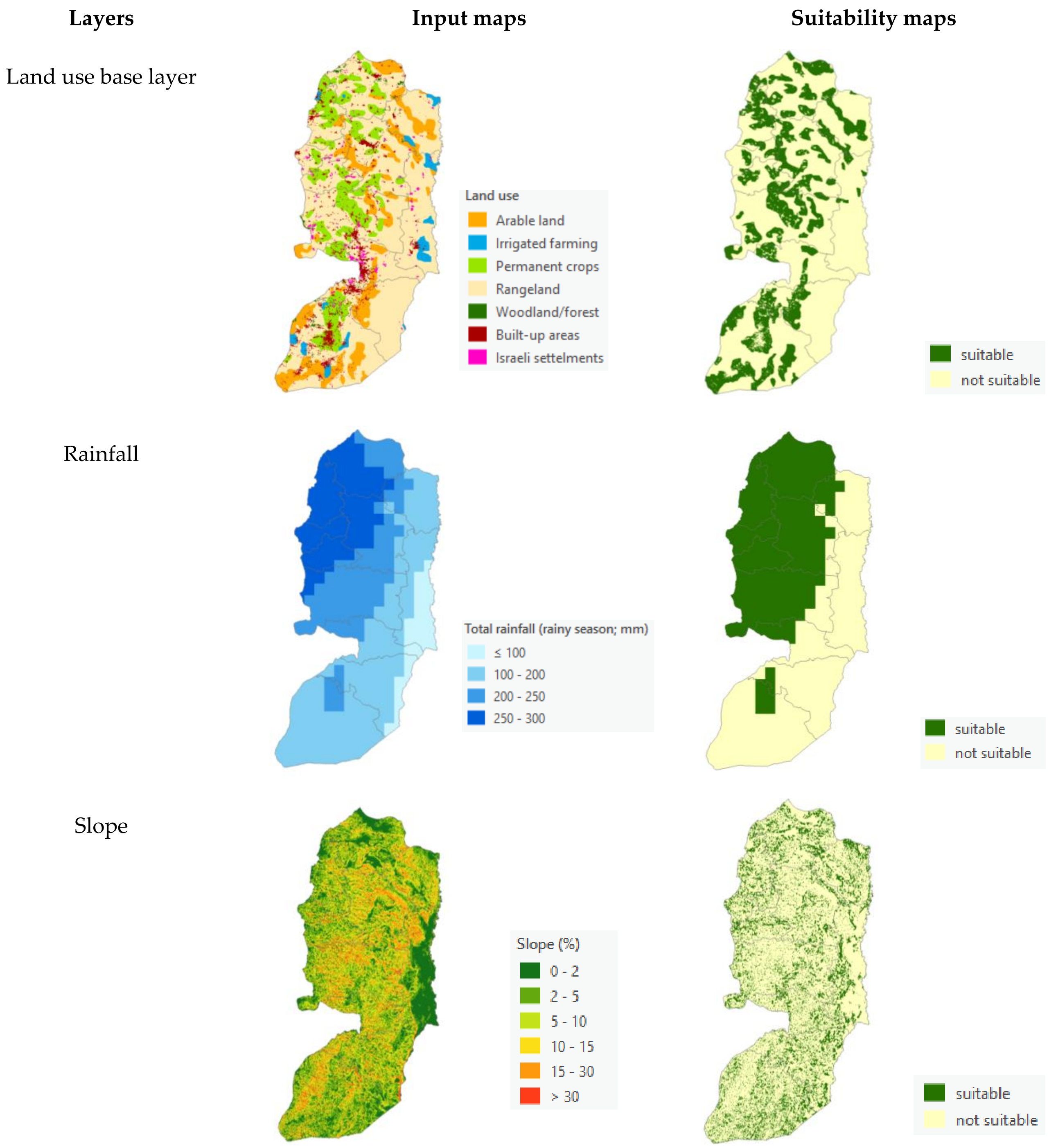


Figure 2. *Cont.*

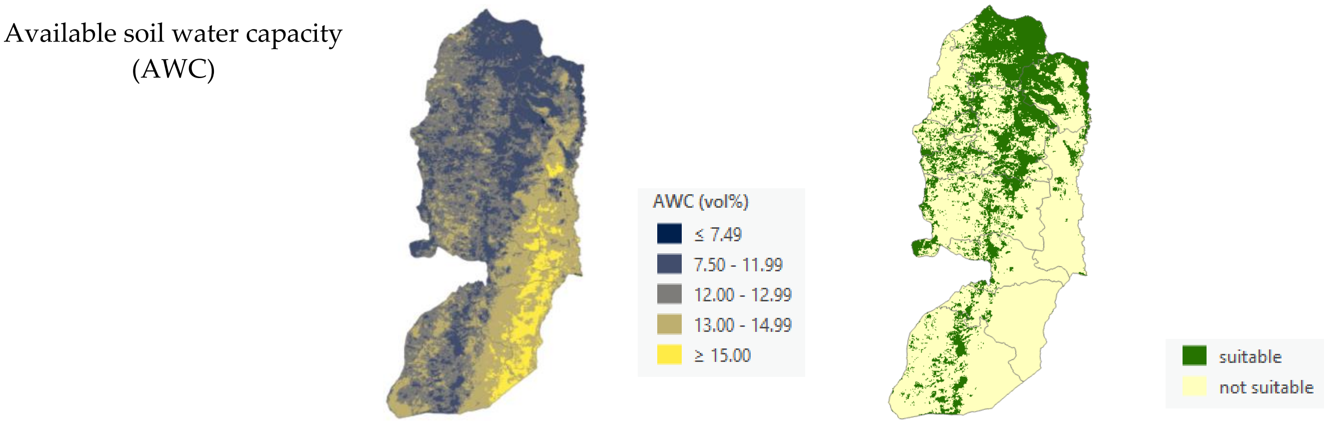


Figure 2. Archetype analysis using land use, rainfall, slope and available soil water capacity (AWC) to identify similar regions in the West Bank that are suitable for eyebrow terracing.

Precipitation

In order to define which areas are suitable for rainwater harvesting with eyebrow terracing, the precipitation (i.e., rainfall) in the wet season was analyzed. The wet season takes place from Nov–Dec–Jan–Feb–Mar in the West Bank and contributes to about 75% of the annual precipitation [30]. Monthly precipitation maps were summed up for each annual wet season to have the total precipitation of the wet season. Historical total monthly precipitation data (in mm) for the time period 2000–2018 were collected at a spatial resolution of 2.5 arc-minutes (i.e., about 5 km) from CRU-TS 4.03 [31] and downscaled with WorldClim 2.1 [32].

From the total wet season maps, the wet season with, on average, the lowest amount of precipitation was defined as the driest rainy season. The wet season with, on average, the highest amount of precipitation was defined as the wettest rainy season. Within the 2000–2018 time period, the rainy season in 2016/2017 was the driest with a total average of 194 mm (±61 S.D.), while the rainy season in 2002/2003 was the wettest with a total average of 503 mm (±175 S.D.). Based on the amount of precipitation in the driest rainy season, the West Bank was classified into two classes: (1) dry region ($\leq$200 mm) and (2) wet region (>200 mm). The wet region was defined as suitable for eyebrow terracing with olive groves (Figure 2).

Slope

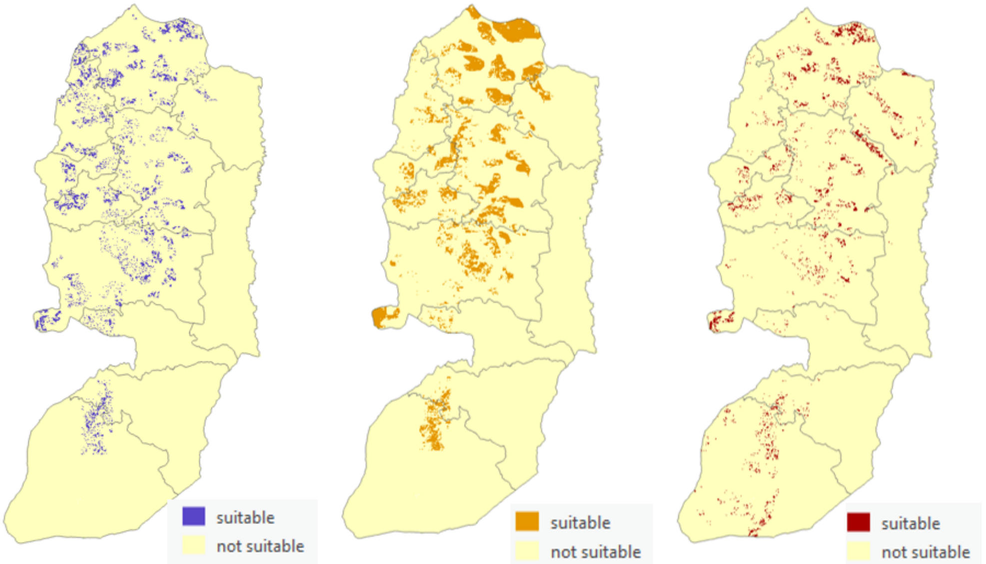
The slope was analyzed to define which areas in the West Bank can be suitable for the implementation of eyebrow terraces. The slope was calculated in percentage (%) based on the Digital Elevation Map (DEM) [29]. In the West Bank, slopes range between 0 and 82% and are on average 7.7%. A slope between 2 and 5% was defined as suitable for the construction of eyebrow terraces for olive trees (Figure 2) [5].

Available Soil Water Capacity

Available soil water capacity (AWC) was analyzed to determine which areas in the West Bank are suitable for the implementation of olive terracing. Maximum available soil moisture (in mm/m) was collected from the SoilGrids 2017 dataset having a 250 m spatial resolution [33]. Data for available soil water capacity (‘AWCh1’) with a field capacity at pF 2.0 were selected in order to include the widest possible range for water uptake at field capacity [34]. Data were extracted at a maximum of up to 1 m depth, which included 6 soil layers for AWC. From this data, the bulk estimate for available soil water capacity within 1 m of soil depth was calculated by taking the average of the upper and lower boundary of the depth interval (i.e., soil layer 1 at 0 cm and soil layer 6 at 100 cm; after [33]). A boundary value of $\leq$12 vol% was taken as suitable for the implementation of eyebrow terraces for olive cultivation (Figure 2) [5].

Suitability Zones

Based on the generated suitability maps in Figure 2, three maps with suitability zones for the implementation of eyebrow terraces were created. The land use suitability map was used as a base layer. For the first suitability map, the rainfall and slope maps were overlaid with the base layer and the areas that were overlapping in all three input maps were identified as suitable. This resulted in the rainfall and slope suitability map (Figure 3). In a similar fashion, a rainfall and AWC suitability map (using the rainfall, AWC and base-layer maps) and an AWC and slope suitability map (using the AWC, slope and base-layer maps) were generated (Figure 3; Table S1). This resulted in three different maps indicating land areas that are suitable for the implementation of eyebrow terraces for olive trees. Characteristics of the three suitability zones are listed in Figure 3.



Suitability zone	Rainfall & slope	Rainfall & AWC	AWC & slope
Map			
Surface area (km^2)	215	437	133
Surface area of WB (%)	4.0	8.4	2.4
Existing olive groves (%)	70	61	46
Arable land with grains (%)	30	39	54

Figure 3. Maps showing the three suitability zones for implementation of eyebrow terraces in olive groves based on (1) rainfall and slope, (2) rainfall and available soil water capacity (AWC), and (3) AWC and slope. Characteristics of the three suitability zones are listed, including surface area and percentage of coverage by olives and grains. Note that some spatial overlap occurs among the three suitability zones since they are partly selected based on the occurrence of the same suitability factor.

2.2.2. Crop–Water Balance Model

A crop–water balance model was created to estimate the impact of (limited) water availability on potential olive yield. This is a spreadsheet model that is based on a model developed by de Graaff [35], which allows for us to estimate the impact of soil water conservation measures on potential crop yield at the field-scale. For this study, the model was set up to estimate olive yield reduction (in %) at a monthly time step.

Models were created to calculate the potential yield of olive trees for the implementation of eyebrow terraces in the three defined suitability zones (see Figure 3). For each zone, a business-as-usual scenario (without terracing) and a scenario with terracing were defined to calculate the differences in olive yield.

The crop–water balance model has both static and dynamic data input. Static data input is the same for all scenarios, while dynamic data input is calculated specifically for each of the three suitability zones. Dynamic data inputs are precipitation, potential evapotranspiration, available soil water capacity and run-on.

Dynamic Data Input

The total monthly precipitation maps that were generated in Section 2.2.1 were used to calculate the mean monthly precipitation maps over the time period 2000–2018 (in mm/month). Based on these maps, the mean monthly precipitation was calculated for the three suitability zones.

Potential evapotranspiration was collected from the Global Aridity Index and Potential Evapotranspiration (ETo) Climate Database [36]. This dataset provides the monthly mean potential evapotranspiration over the 1970–2000 time period with a spatial resolution of 30 arc-seconds (i.e., about 1 km). These maps were downscaled for the West Bank. For each month, the average potential evapotranspiration (in mm/month) was calculated over the 1970–2000 time period. Based on these maps, the monthly average potential evapotranspiration was calculated for the three suitability zones.

Available soil water capacity was obtained from the SoilGrids 2017 dataset as previously described in Section 2.2.1. The mean bulk estimate (in mm/m) was calculated for the three suitability zones.

The amount of rainfall run-on on eyebrow terraces in the three suitability zones was calculated using the following formula:

$$RnR = R * \frac{RnA}{RfA} * \frac{CN}{100}$$

in which RnR is rainfall run-on (in mm/month), R is rainfall (in mm/month), RnA is a run-on area (in m^2), RfR is runoff area (in m^2) and CN is curve number (in %; Figure S1). For CN, a curve number map of the runoff area for the West Bank was used, which was obtained from Shadeed and Almasri [37] and calculated using a GIS-based Soil Conservation Service (SCS)-CN method. The curve number represents the runoff response to rainfall (in %) in which high curve numbers indicate that a large amount of the rainfall will be runoff and vice versa. Average curve numbers for the three suitability zones were calculated based on the curve number map.

The above formula assumes that runoff from the surrounding runoff area will be harvested as run-on on eyebrow terraces. The run-on area was taken as the mean surface area of eyebrow terraces for olive trees reported in the West Bank, being 17.5 m^2. The runoff area was calculated by taking an 8 m by 7 m planting distance between olive trees, resulting in a 56 m^2 surface area from which the run-on area was extracted. This resulted in a runoff area of 38.5 m^2.

Static Data Input

Several other biophysical variables needed as input for the crop–water balance model were defined. The rooting depth for olive trees without terracing was set at 1.2 m and with terracing at 1.7 m [38], since it is assumed that deeper rooting depths are created when terraces are built, based on experiences from a study in Tunisia [39] and given that terracing has been generally found to be favorable for increasing tree rooting depth [40]. The soil depth was set at 1 m for the West Bank, since soil depth should be set higher than the rooting depth in the run-on area.

Input data for crop water requirements (in mm/month) and yield response to water stress (in mm/month) were growth-stage-specific. Input for these two variables was based on mean values for olive trees in terraced areas in Tunisia [39]. The following growth stages have been distinguished (in months): initial (Mar), development (Apr–May–Jun), mid (Jul–Aug), and late (Sep–Oct–Nov).

For business-as-usual scenarios, runoff was taken as 2% during light rainfall events (<30 mm) and 20% during heavy rainfall events ($\geq$30 mm); this was based on studies by Hammad et al. [41,42] who measured the runoff coefficient for two winter seasons in the

Ramallah Governorate. In the scenarios with terracing, runoff was taken as negligible since terraces are assumed to be very effective in capturing rainfall.

Model Validation

In order to validate whether the estimated actual soil moisture content (in mm/m) in the model was realistic, reference values for actual soil moisture content were collected from the literature. In a study at the Wadi Natuf catchment in the Ramallah Governorate, the lowest recurring soil water contents in the field at different soil depths were measured based on continuous soil moisture measurements over several years for various locations [43]. Based on location data, we calculated an average minimum soil moisture content of 44 mm/m for a business-as-usual situation, and an average minimum soil moisture content of 28 mm/m was found for terraces. The values found in our models for actual soil water content vary slightly around these reported literature values.

2.3. Implementation of Rooftop Harvesting

Calculations for the implementation of domestic rooftop harvesting are made for the 11 governorates of the West Bank individually (Figure 1) because the governorates vary greatly in the amount of built-up land (e.g., from 1.2% in Tubas to 10.5% in Jerusalem), the number of inhabitants (e.g., from about 50,000 in Jericho up to about 715,000 in Hebron) and the amount and pattern of rainfall. As such, the surface area of built-up land and rooftops was calculated for each governorate specifically.

First, the mean surface area of the rooftops of households in each governorate was calculated. The surface area of urban areas in each governorate was calculated based on the land use map.

The surface areas of urban areas were divided by the number of households in each governorate, which was estimated based on the population in each governorate and the average of six persons per household in the West Bank. As built-up land also included other buildings than domestic rooftops (such as infrastructure, office buildings and industry), the surface area was corrected by a division by four to approach the overall average rooftop surface area of 150 m^2 for the West Bank [28]. In practice, this resulted in an overall average rooftop area of 154 m^2 for the West Bank (Table 1).

Table 1. Estimated average rooftop surface area per household for each governorate in the West Bank.

Governorate	Average Rooftop Surface Area (m^2/Household)
Jenin	110.7
Tubas	123.9
Tulkarm	171.9
Nablus	106.8
Qalqiliya	90.4
Salfit	132.0
Ramallah and Al-Bireh	176.2
Jericho	307.5
Jerusalem	128.4
Bethlehem	185.7
Hebron	162.2
Total average	154.2

The potential amount of rainfall that can be harvested on average and the needed storage capacity of the water tank were calculated for each governorate using the SamSamWater Rainwater Harvesting Tool [44]. This tool uses rooftop size, rooftop type (with associated runoff coefficient), household size and its water demand, and spatial location (for the average amount of rainfall) to estimate the amount of rainfall that can be harvested on a monthly basis for a year with average rainfall. To point down the spatial location, centroids of the built-up land in each governorate were calculated using ArcGIS. The flat rooftop type was selected—having a runoff coefficient of 0.7—since there are typically flat roofs in the West Bank. The average household size was set at six people per household. The average water demand was set at 87 L/capita/day based on the daily consumption rate per capita in the West Bank [45], resulting in a 522 L/household/day water demand per household.

2.4. *Spatially Explicit Cost–Benefit Analysis*

By the means of spatially explicit cost–benefit analysis, it was calculated whether the implementation of eyebrow terraces and domestic rooftop harvesting can be economically feasible. The cost–benefit analysis for the implementation of eyebrow terraces is spatially explicit in such a way that it calculates the costs and benefits explicitly for the three land zones that are suitable for eyebrow terrace implementation (Figure 3). The cost–benefit analyses for the implementation of rooftop harvesting are calculated for each of the 11 governorates of the West Bank, individually.

Different scenarios are considered in the cost–benefit analyses as well. Cost–benefit analyses for eyebrow terraces were conducted for the business-as-usual and terracing scenarios in the three suitability zones. Cost–benefit analyses for rooftop harvesting were conducted for a scenario with 100% construction costs for installation on 100% of the rooftops and a scenario with 50% construction costs for installation on 50% of the rooftops, because households in the West Bank may already have some form of water reservoir installed at their homes. All cost–benefit analyses were calculated for a time period of 20 years and reported in EUR values for the year 2018. Data that were used as input were taken for the year 2018 (if not reported otherwise).

2.4.1. Eyebrow Terraces

In the cost–benefit analysis for eyebrow terraces, investment, maintenance and production costs, and benefits were accounted for. For the suitability zone, a business-as-usual and terracing scenario were estimated. The largest differences between these two scenarios were expected in the yield of olives and grains and labor costs. As such, these two factors were explicitly considered. The costs for fertilizers, pesticides, machinery, irrigation and seeds were assumed to be largely similar between the two scenarios. The cost–benefit analyses were calculated on a per-hectare basis.

The estimation of costs included investment, maintenance and production costs. The initial investment costs were the construction costs of terraces estimated at 3495 EUR/ha, including the manual construction of terraces estimated at 3410 EUR/ha and the incidental use of machinery estimated at 85 EUR/ha. Yearly maintenance costs of the terraces were estimated at 43 EUR/yr. These estimations were obtained from fieldwork for different projects by the Palestinian Hydrology Group (personal communication, S. Hamdan, 2020). Investment and maintenance costs for building terraces were estimated for the terracing scenarios only since no investment or maintenance costs were involved in the business-as-usual scenarios as no terraces were built. Here, the conventional cultivation of grains and olives is practiced.

Production costs were calculated for both scenarios. Costs were based on the quantity and price of labor. The price of a laborer in the West Bank was estimated at 341 EUR/month. For olive cultivation, one month of work per year was assumed, while half the amount of work was assumed to be needed for grain cultivation.

The estimation of benefits depended on crop price, crop yield and crop cover fraction. The crop price for olives, wheat and barley was calculated based on the producer price (i.e., farm gate price) which was collected from FAOSTAT [46] for the time period of 1997–2019. The annual averages for olives, wheat and barley were calculated as 1130, 386 and 320 EUR/tonne, respectively.

Crop yields for olives were calculated based on yield reduction outcomes from the crop–water balance model and the maximum recorded olive yield in the West Bank. A maximum yield of 2.4 tonne/ha was observed (for 2010) from olive yield data for the West

Bank over the time period 1994–2018 [46]. Absolute effects of yield reduction for olive production in the West Bank were calculated by assuming that the highest recorded olive yield in the West Bank was not limited by water. Crop yields for wheat and barley were collected from FAOSTAT [46] for the West Bank. The 5-year average of 2014–2018 was calculated in tonne/ha based on these data.

Crop yield was expected to be affected by the implementation of terracing in existing olive groves and on arable land producing grains in the terracing scenarios. In existing olive groves, terraces were built in year 1, due to which there was no olive production this year (e.g., due to potential damage to the olive trees). In year 2, olive trees were assumed to produce olives at full production capacity. On arable land, olive trees were planted in year 1. Since these olive trees were expected to only start bearing fruit from year 5 onwards, up to year 4, grains were still cultivated in-between the newly planted olive trees. In this setup, the production of grains was assumed to be at 80% of the normal production. In year 5, terraces were built and grains were no longer cultivated. The newly planted olive trees were assumed to start bearing fruit from year 5 onwards with a 14% annual increase in olive production up to maximum production in year 12.

To determine crop cover fraction, the ratio between olives and grains was calculated based on the three suitability zones and the land use map (Figure 3). In the West Bank, grains constitute a mix of wheat and barley. The proportion between these grains was set at 64% wheat and 36% barley, based on calculating the 5-year average of the harvested area [46].

2.4.2. Rooftop Harvesting

Cost–benefit analyses were calculated for installing rooftop harvesting in the 11 governorates of the West Bank. By accounting at the level of governorates, governorate-specific differences in rainfall, rooftop surface areas and connection to the water grid can be explicitly considered. Investment, maintenance and production costs were accounted for in the cost–benefit analyses. No direct benefits were considered since the amount of rainwater harvested was accounted for by a reduction in the costs of purchasing water.

In the cost–benefit analyses, the difference between installing rooftop harvesting as compared to conventional water use (without rooftop harvesting) was calculated. In conventional water use, no investment and maintenance costs were involved. For these scenarios, the costs of using tap water and purchasing water from other sources were solely accounted for. The cost–benefit analyses were calculated at the household level. Two scenarios were considered: one scenario with 100% construction costs and one scenario with 50% construction costs, since part of the residential buildings may have already had water tanks or cisterns installed in the West Bank.

Production costs for water use were calculated based on the percentage of households connected to the water grid and the quantity of water used (Table 2). Data were collected regarding the percentage of households connected to the water grid [4], allowing for us to calculate the percentage of water demand from the water grid and from other sources, such as water trucks (Table 2). Tap water was mostly provided by the Israelian water company Mekorot, and to a smaller extent, derived from spring discharge and water pumped from Palestinian wells. The average water tariff for tap water is 1.2 EUR/m^3. In less well-connected areas—mostly situated in rural areas—households purchase water from other sources, such as water trucks, at high water tariffs of 4 EUR/m3 on average [47]. The reduced amount of water that needed to be purchased was calculated based on governorate-specific numbers about the amount of rainwater that can be harvested. It was assumed that the remaining part of the total water demand was purchased from the water source with the lowest tariff (i.e., tap water). It should be noted that this is a conservative assumption as there is evidence that households do purchase water from trucks and rural areas rely on truck water to a large extent.

Table 2. Household connection to the water grid and water use in the West Bank.

Region	Governorates	Water Use from Water Grid (%) [1]	Water Obtained from Other Sources (%) [1]	Tap Water Use (m^3/hh/yr)	Other Water Source Use (m^3/hh/yr)
North	Jenin, Tubas, Tulkarm, Nablus, Qalqiliya, Salfit	87.5	12.5	166.7	23.8
Middle	Ramallah and Al-Bireh, Jericho, Jerusalem	97.8	2.2	186.3	4.2
South	Bethlehem, Hebron	83.1	16.9	158.3	32.2

Note(s): [1] Based on data for 2011 [4].

Investment and maintenance costs of the installation of rooftop harvesting were calculated. Investment costs included the costs for the construction of a cistern, purchasing and installing a pump (to pump water from the rooftop to the water reservoir), excavation costs (for installing the pump) and PVC piping (to lead the water from the rooftop to the reservoir). Maintenance costs included annual rooftop and reservoir cleaning.

Since the size of the water reservoir that needs to be constructed greatly influences construction costs, the optimal reservoir size was calculated for each governorate using the SamSamWater Rainwater Harvesting tool [44]. This tool calculates the optimal water reservoir size based on the average water use by households and the monthly amount of rainwater that can be harvested based on average monthly rainfall. Optimal storage capacities for the 11 governorates were classified into typical reservoir size classes (Table 3). Construction costs for these reservoir size classes were calculated and used to calculate governorate-specific construction costs.

Table 3. Reservoir size classes for rainwater storage capacity for the 11 governorates in the West Bank.

Reservoir Size Classes (m^3)	Governorates
20	Qalqiliya, Hebron
25	Jenin, Nablus
30	Jerusalem, Tubas, Salfit
35	Bethlehem, Jericho
40	Tulkarm, Ramallah and Al-Bireh

3. Results

3.1. Eyebrow Terraces

Olive yield can be increased by 0.24 up to 0.35 tonne/ha in the West Bank with the implementation of eyebrow terraces in existing olive groves and planting new groves on suitable arable land as compared to the business-as-usual scenario (Figure 4 and Table S2). This comes down to an increase in yield of between 10 and 14% over a time period of 20 years for the three different land suitability zones (Figure 4). The maximum yield that can be reached by implementing eyebrow terraces is 2.1 tonne/ha. Although olive yield varies among the three suitability zones for the business-as-usual scenario, yield increases that can be reached with the implementation of eyebrow terracing are overall similar across the three suitability zones (Figure 4).

The crop–water balance models show that the climate in the West Bank is so dry that even after the wet winter season, the increased water harvesting capacity of the soil (due to implementing terracing) only helps to a small extent to improve olive yield. The scenarios in which terracing is implemented are very effective in capturing rainfall, as the amount of effective rainfall is doubled. However, due to the limited storage capacity of the soil, most soil moisture that is additionally harvested with terracing is rapidly lost to drainage to deeper groundwater during the wet months. This leaves little soil moisture during the dry season. Thus, yield differences between the business-as-usual and terracing scenarios are overall not that large (i.e., between 10–14% higher). As such, eyebrow terraces can capture a lot of rainfall, but soil capacity to store it is limited. In contrast, in the scenarios where no terracing is implemented (business-as-usual), there is less effective rainfall, since part of the rainfall is lost to direct runoff and there is no additional run-on. Due to this, there is no surplus of soil moisture and no drainage to deeper groundwater.

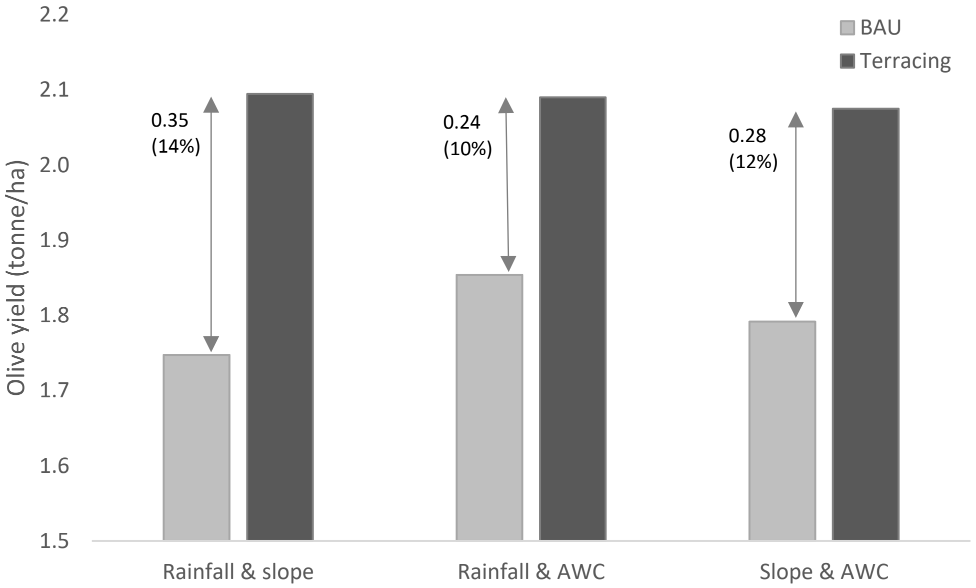


Figure 4. Estimated olive yield (tonne/ha) for the three suitability zones in the West Bank for the business-as-usual (BAU) and terracing scenarios based on results from the crop–water balance models. The arrows indicate the difference in yield between the two scenarios expressed in tonne/ha and as a percentage in-between brackets. AWC stands for available soil water capacity.

3.2. Rooftop Harvesting

On average, 56.9 m^3/hh/yr of rainwater can be harvested from domestic rooftops in the West Bank. The lowest amount of 37.5 m^3/hh/yr can be harvested in Qalqiliya, while the highest amount of 75 m^3/hh/yr can be harvested in Ramallah and Al-Bireh (Figure 5a). In the latter governorate, this is mainly due to the occurrence of relatively large rooftops and a higher amount of rainfall. On average, 30% of household demand can be met with rooftop harvesting, when taking the average household consumption in the West Bank of 191 m^3/hh/yr [45]. As such, rainfall is by far too low to meet household demand with rooftop harvesting alone in the West Bank.

The optimal water reservoir size was calculated based on the monthly amount of rainwater that can be harvested and the average water use by households (Figure 5b). The optimal size ranges from 18 m^3 in Qalqiliya up to 37 m^3 in Ramallah and Al-Bireh. This variation is due to the different amounts of rainfall that can be harvested in each governorate. Variation in optimal reservoir size has implications for the sizes of reservoirs that are ideally constructed for rooftop harvesting in the governorates and the costs incurred in the cost–benefit analyses.

3.3. Cost–Benefit Analysis

3.3.1. Eyebrow Terraces

The cost–benefit analyses of implementing eyebrow terraces in the three suitability zones show that the net results for all three scenarios are positive (Figure 6). This means that the benefits outweigh the costs. Additionally, the internal rates of return show that the annual growth rate of investing in eyebrow terraces is positive.

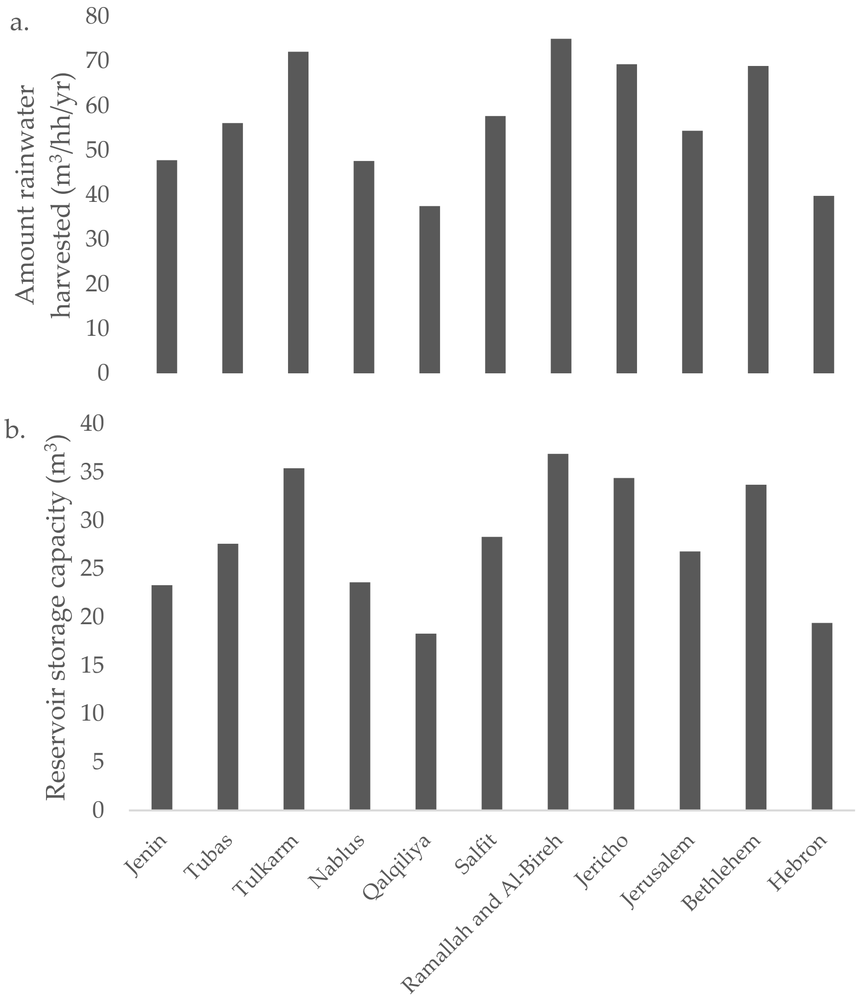
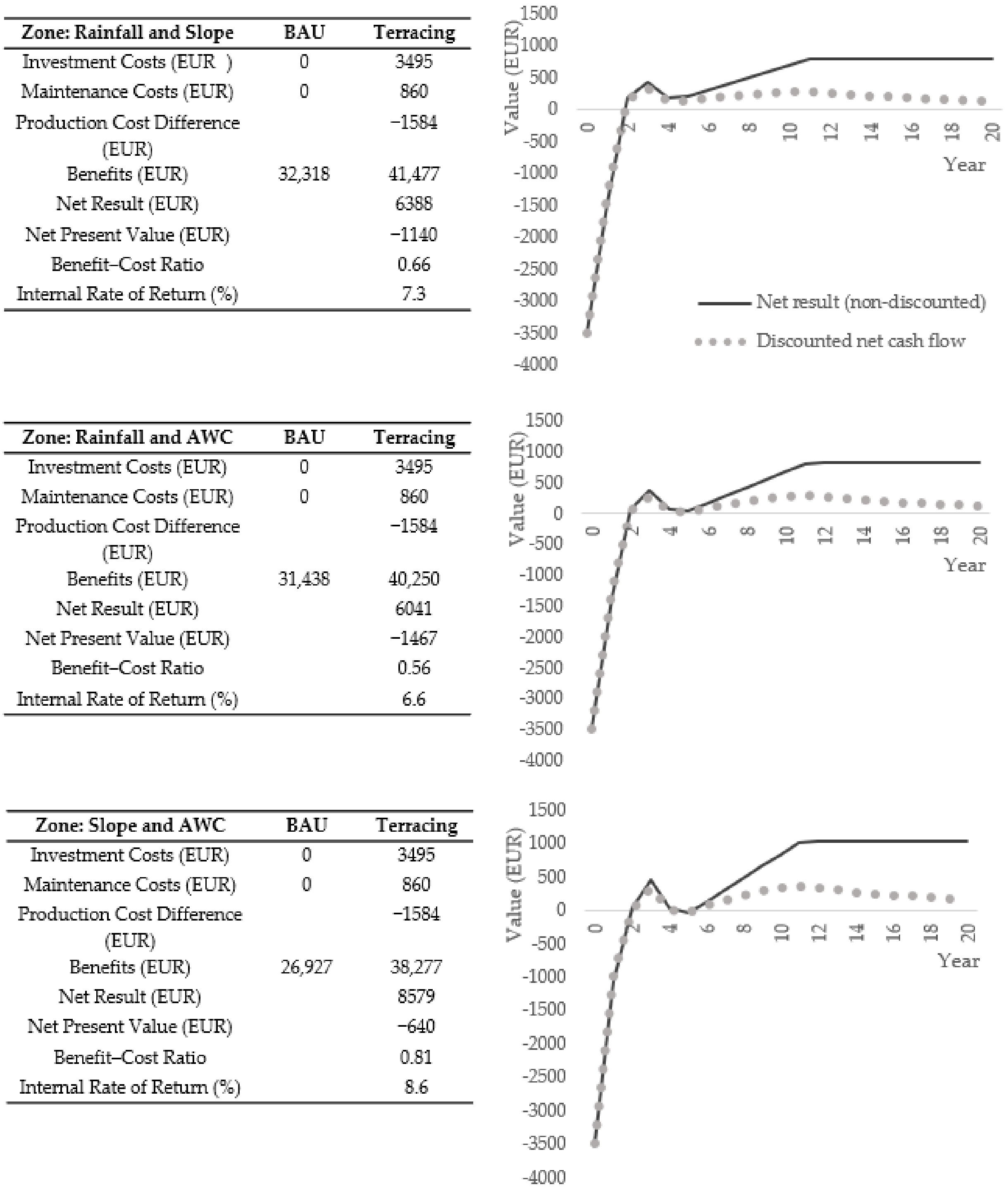


Figure 5. Figure showing (**a**) the amount of rainwater that can be harvested (in m^3/hh/yr) with the installation of domestic rooftop harvesting, and (**b**) the optimal storage capacity of water reservoirs (in m^3) for an average rainfall year in the 11 governorates of the West Bank.

However, when values are discounted (using a discount factor of 10%), the net present values turn out to be negative in all three scenarios. The suitability zone in which slope and AWC determine the suitability for implementing terraces turns out to be the least negative. When a lower discount rate would be used (i.e., $\leq$8.6%, as indicated by the internal rate of return), the implementation of eyebrow terracing would pay off in this scenario. Similarly, the other two scenarios would have a positive NPV, when the discount factor would be set at the level of the internal rates of return.

3.3.2. Rooftop Harvesting

The cost–benefit analyses in the 11 governorates of the West Bank show that investing in installing domestic rooftop harvesting does not pay off in any of the governorates when assuming that for all residential buildings new reservoirs would need to be constructed (i.e., scenario with 100% construction costs; Table 4). However, when assuming that part of the households already has water reservoirs or cisterns installed at their homes and that only in about 50% of the cases new reservoirs need to be constructed (i.e., scenario with 50% construction costs), the net present value becomes less negative and the internal rate of return is positive for the governorates located in the northern and southern governorates, making investing in installing rooftop harvesting more attractive in those regions.



Zone: Rainfall and Slope	BAU	Terracing
Investment Costs (EUR)	0	3495
Maintenance Costs (EUR)	0	860
Production Cost Difference (EUR)		−1584
Benefits (EUR)	32,318	41,477
Net Result (EUR)		6388
Net Present Value (EUR)		−1140
Benefit–Cost Ratio		0.66
Internal Rate of Return (%)		7.3

Zone: Rainfall and AWC	BAU	Terracing
Investment Costs (EUR)	0	3495
Maintenance Costs (EUR)	0	860
Production Cost Difference (EUR)		−1584
Benefits (EUR)	31,438	40,250
Net Result (EUR)		6041
Net Present Value (EUR)		−1467
Benefit–Cost Ratio		0.56
Internal Rate of Return (%)		6.6

Zone: Slope and AWC	BAU	Terracing
Investment Costs (EUR)	0	3495
Maintenance Costs (EUR)	0	860
Production Cost Difference (EUR)		−1584
Benefits (EUR)	26,927	38,277
Net Result (EUR)		8579
Net Present Value (EUR)		−640
Benefit–Cost Ratio		0.81
Internal Rate of Return (%)		8.6

Figure 6. Results of the cost–benefit analysis for implementing eyebrow terraces in the three suitability zones in the West Bank for the business-as-usual (BAU) and terracing scenarios. Net results are not discounted, while net present values are discounted using a 10% discount rate. AWC stands for available soil water capacity and EUR values are reported for the year 2018.

Table 4. Cost–benefit analysis results for installing domestic rooftop harvesting in the 11 governorates of the West Bank, showing scenarios with 100% and 50% construction costs.

Region	**Governorate**	**100% Construction Costs**			**50% Construction Costs**		
		Net Result (EUR) [1]	**NPV (EUR)** [2]	**IRR (%)** [2]	**Net Result (EUR)** [1]	**NPV (EUR)** [2]	**IRR (%)** [2]
North	Jenin	−421	−983	−3.2	204	−358	2.3
	Tubas	−472	−1148	−3.0	278	−398	2.7
	Tulkarm	−588	−1485	−2.9	412	−485	3.1
	Nablus	−426	−985	−3.2	199	−360	2.3
	Qalqiliya	−418	−838	−4.0	82	−338	1.2
	Salfit	−433	−1132	−2.7	317	−382	3.1
Middle	Ramallah and Al-Bireh	−1615	−1922	−10.7	−615	−922	−6.4
	Jericho	−1502	−1731	−11.8	−627	−856	−7.7
	Jerusalem	−1610	−1632	−23.1	−860	−883	−20.2
South	Bethlehem	57	−1067	0.3	932	−192	7.1
	Hebron	108	−614	0.9	608	−114	7.3

Note(s): [1] Net result is the cost minus benefits, which is not discounted over time. [2] NPV is net present value, IRR is internal rate of return; both are estimated using a 10% discount rate.

In the southern region of the West Bank in particular, the net result of investing in rooftop harvesting is the most positive, demonstrating that the benefits outweigh the costs in both scenarios of 100% and 50% reservoir construction costs. Even though this region has the lowest rainfall, domestic rooftop harvesting can be of interest since households are the least well-connected to the water grid (i.e., 83.1%; see Table 2). However, when discounting values at a 10% rate over a 20-year period, the net present values become slightly negative for this region.

In contrast, in the middle region of West Bank, the net results and net present values are deeply negative, showing that investing in installing rooftop harvesting would not pay off, even when assuming that water reservoirs would need to be built only in 50% of the cases. In this region, the connection to the water grid is the best (i.e., 97.8%). Because of this, there is a low reliance on having to purchase expensive water from other sources with high water tariffs (e.g., water trucks). As such, rooftop harvesting does not pay off in this region (Table 4).

Together, the results of the cost–benefit analyses show that when using a discount rate of 10%, it does not pay off to install domestic rooftop harvesting in all governorates of the West Bank. Additionally, when assuming that new water reservoirs would have to be constructed only in about 50% of the cases (instead of in 100% of the cases), investing in rooftop harvesting does not pay off in the middle region, but does become more attractive for the northern and southern regions of the West Bank.

4. Discussion

This study aimed to investigate the economic feasibility of the implementation of the two most commonly practiced rainwater harvesting applications in a rural and urban setting in the West Bank of Palestine. Eyebrow terracing in olive cultivation and domestic rooftop harvesting in urban areas were investigated. We found that—although eyebrow terracing enlarges soil moisture availability for olive trees and thereby increases olive yield by 10 up to 14%—construction costs are too high to make implementation cost-effective. Similarly, we found that rooftop harvesting can harvest, on average, about 30% of the annual domestic water demand and is worthwhile in the northern and southern governorates in particular. Yet, also in this case, construction costs are generally too high to be cost-effective for households to implement. As such, construction costs may obstruct the implementation and upscaling of rainwater harvesting in rural and urban areas of the West Bank.

The height of the initial investment costs to install rainwater harvesting structures forms a considerable barrier to the adoption of rainwater harvesting. Similar findings for high construction costs have been found for both urban and rural applications in other low-income countries in previous studies. They found that adoption by farmers may be limited due to high initial investment costs in Kenya and Tanzania [8,48]. Similarly, initial investment costs were the main limiting factor for upscaling urban rooftop harvesting in a case study in Namibia [49].

Such high investment costs could be reduced, for example, by the means of mechanization, collective investment or including the building of rooftop harvesting infrastructure and cisterns during the construction or renovation phase of residential buildings. This would allow for the benefit/cost ratio to increase and would make the implementation of rainwater harvesting more attractive. This is demonstrated by the scenario with 50% construction costs for domestic rooftop harvesting: the internal rates of return become positive for the northern and southern governorates. These governorates are characterized by being the most arid or the least well-connected to the water grid. This also shows that rooftop harvesting is mostly of interest to those regions in the West Bank that are very arid or not (well-)connected to the water grid.

The cost-effectiveness of the rainwater harvesting techniques investigated in this study may turn out more positive in practice due to several reasons. Firstly, the construction costs for terracing estimated in this study seem relatively high when compared to other international case studies [50]. This may indicate that they might have been estimated too high. Secondly, we used a conservative assumption for calculating the costs of purchasing water for estimating the production costs of the business-as-usual scenario of rooftop harvesting. We assumed that the cheapest source of water would be bought (i.e., tap water), while people may be forced in practice to purchase water from other, more expensive water sources. There is evidence that people buy water from trucks and that especially people in rural areas depend largely on truck water [27]. Thirdly, our analysis is spatially explicit, but analyses were made for average conditions. When cost-effectiveness can be analyzed at a finer spatial scale or for a specific area, specific locations may turn out (more) positive. Future research could further investigate this. If investment costs turn out lower in practice, the implementation of these rainwater harvesting techniques can be of interest for other arid regions in the Mediterranean and elsewhere, since these regions will have to cope with increasing water security due to climate change similar to Palestine.

Despite the high investment costs, we found that considerable benefits can be obtained with both types of rainwater harvesting. By using domestic rooftop harvesting, we found that 30% of the annual domestic water demand could be met. This seems quite substantial, given that a similar study about rooftop harvesting on residential buildings in Jordan found that only 8% of the annual domestic water demand could be met on average [23].

We also found that olive production can be increased to some extent when eyebrow terracing is used, leading to increased water security and an improved livelihood. However, also a lot of harvested rainwater is lost to deep drainage due to the limited storage capacity of the soil. Because of that, terracing had only a limited impact on increasing olive yield. Therefore, it may be interesting to investigate whether harvested rainwater can be stored elsewhere, for example, by diversion to a water storage reservoir or cistern. Stored water could be used for the irrigation of olive trees in the dry season or maybe even throughout the dry season, which can lead to a higher olive yield. Previous studies also show that farm revenue can be considerably increased using rainwater harvesting techniques (e.g., [7,51]).

Overall, however, these benefits could not outweigh the high initial investment costs. Given that initial investment costs are too high for households to afford, construction costs are identified as the most important barrier to the widespread adoption of rainwater harvesting in the West Bank. Here, a role for the government may be to lower these types of costs by providing financial aid.

At the same time, societal benefits of the implementation of rainwater harvesting have not been accounted for in this study, even though these may have been substantial.

Implementation of rainwater harvesting can offer multiple societal benefits—i.e., ecosystem services—such as improved water regulation, reduced soil erosion and improved flood mitigation. Cost–benefit analyses of the implementation of rainwater harvesting in farming systems in arid regions of Jordan and Tunisia found that including environmental benefits increased the internal rates of return significantly and made rainwater harvesting a compelling case for public investment [52,53].

Such societal benefits have not been accounted for, as this study only included costs and benefits at the household level and not costs and benefits at the level of the community or society as a whole. Yet, it is expected that the implementation of rainwater harvesting will offer multiple societal benefits in the West Bank, particularly when it is applied at a large scale.

An important societal benefit is that water security would be increased in the West Bank, making it less dependent on Israel for its water supply. Another important benefit is that the resilience of farmers and households locally would be increased, which is of relevance in view of increasing water uncertainty due to climate change and the political situation. Other positive offsite benefits can include increasing the recharge of shallow groundwater and prolonged soil moisture availability downhill. This may have positive impacts on agricultural production and natural vegetation growth downslope and in the valleys, prolonged streamflow into the dry period and reduction in flood risk downstream. When these societal benefits would be considered as well, the cost-effectiveness of the two studied rainwater harvesting techniques would most likely become positive.

Given that investment costs are too high for widespread adoption, but the extensive implementation could offer multiple societal benefits, there is a role for the government of Palestine. Additionally, given the importance to take adaptation measures for the large, expected impact of climate change in the region, the government could consider developing a strategic program to promote the widespread adoption of rainwater harvesting systems. A simple mechanism for public investment, such as subsidies, may already provide the incentive for households to consider rainwater harvesting.

5. Conclusions

This study has aimed to investigate whether the implementation of two rainwater harvesting techniques—one in a rural and one in an urban context—can be economically feasible for households in the West Bank of Palestine. Eyebrow terracing in olive cultivation and domestic rooftop harvesting in urban areas has been investigated. Although eyebrow terracing enlarges soil moisture availability for olive trees (and thereby increases olive yield by about 10–14%), the costs of constructing terracing are too high for them to be cost-effective. Similarly, domestic rooftop harvesting increases water availability for domestic use, but construction costs of installing water reservoirs are too high to be economically feasible. This obstructs a more widespread adoption of rainwater harvesting, which is urgently needed given the large impacts of climate change in the region. Providing subsidies for rainwater harvesting could help to make adoption more attractive for households. This will help to increase water security in the West Bank alongside providing multiple other societal benefits, such as increasing the resilience of households and farmers.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/w15061023/s1, Table S1: three suitability types for implementation of eyebrow terraces with olive trees analyzed in this study; Figure S1. Curve number map of the West Bank; Table S2: estimated olive yield for the three suitability zones in the West Bank (see Figure 3) for the business-as-usual (BAU) and terracing scenarios based on results from the crop–water balance models.

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