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Conceptualizing and assessing the effects of installation and operation of photovoltaic power plants on major hydrologic budget constituents

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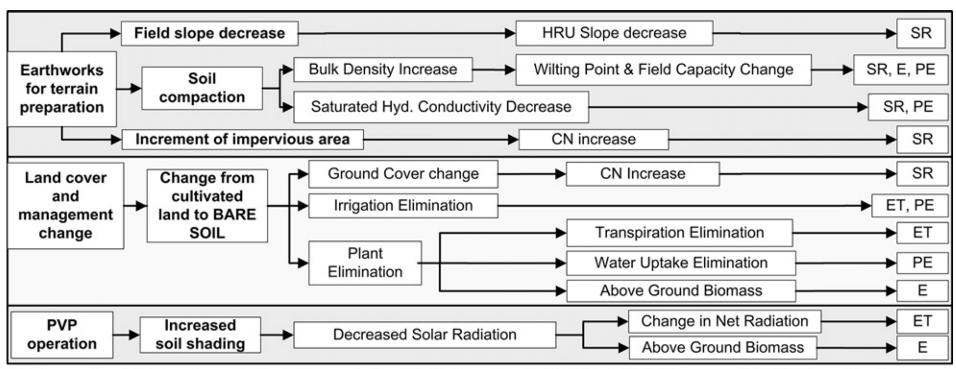
HIGHLIGHTS

- Photovoltaic power plants effects on major hydrologic budget constituents are identified, conceptualized and simulated with SWAT model.
- Spatially, the effects are analyzed in basin and local (sub-basin) scale.
- The long-term effects of land use change from agricultural to photovoltaic power plants were investigated by applying downscaled climate projection data from a Regional Climate Model driven by 5 different General Circulation Models.

GRAPHICAL ABSTRACT



E=Evaporation, ET=Evapotranspiration, PE=Percolation, SR=Surface Runoff, HRU=Hydrologic Response Unit, CN=Curve Number

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ABSTRACT

This study addresses the effects of land use change from agricultural to photovoltaic parks (PVPs) on the hydrology of an area. Although many environmental effects have been identified and analyzed, only minor attention has been given to the hydrologic effects of the installation and operation of PVPs. The effects of current PVP installation and operation practices on major hydrologic budget constituents (surface runoff, evapotranspiration and percolation) were identified, conceptualized, quantified and simulated using SWAT model. Vosvozis river basin located in north Greece was selected as a test site. Additionally, long-term effects were simulated using dynamically downscaled climate projections by a Regional Climate Model (RCM) driven by 5 different General Circulation Models (GCMs) for the period 2011–2100. Results indicate that surface runoff and percolation potential are significantly increased at the local scale and have to be considered during PVP siting, especially when sensitive and protected ecosystems are involved.

1. Introduction

As global greenhouse gas emissions cause an increasing concern on human community regarding climate change, alternative energy sources are substituting for the use of fossil fuel. Solar power plants are among those energy sources which are considered to be environmentally friendly, in terms of emission reduction of greenhouse gases

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(Pehnt, 2006) and other hazardous substances, such as mercury, cadmium or even particulates. However, there are other environmental impacts which have not yet been investigated. Turney and Fthenakis (2011) conducted a thorough review on the environmental effects related to the large scale solar power plants and pointed out that hydrology is one of the fields in which impact study is needed. Photovoltaic parks (PVPs) require large land portions to be covered with solar panels, ranging between 20 and 40 m^2/kW_{peak}, which absorb a high amount of the incoming solar radiation; therefore, they reduce the earth's albedo. Nemet (2009) conducted a study on the radiative forcing due to the installation of widespread PVPs. He concluded that the overall radiative forcing from substitution of PV for fossil fuels is much larger than the one caused by the local reduction of earth's albedo. Moreover, the installation of a PVP causes changes to the physical nature of soil, by changing the preexisting vegetation and by converting to impervious a significant portion of the land occupied for this purpose in order to construct concrete footings for the solar panels to be mounted onto. Turney and Fthenakis (2011) list many interventions related to the installation and operation of PVPs that alter the hydrology of an area, such as: alteration of ground slopes if necessary to less than 5%, periodical mowing of vegetation, installation of inverters, transformers and collector boxes, trenching for electrical and communications cables, construction of access roads, maintenance vehicles moving in the area, and water consumption for washing the panels. Nevertheless, their effects on the hydrology of an area occupied by photovoltaic installations have not yet been investigated.

Climate change is expected to significantly affect hydrological processes, especially in semi-arid and arid regions (IPCC, 2007) and Mediterranean region (Erol and Randhir, 2012). De Paola et al. (2014) analyzed the Intensity–Duration–Frequency rainfall curves for three cities in Africa and concluded that a rise of frequency of extreme events is expected and therefore flood risk is increasing. Luo et al. (2013) simulated climate change impacts on hydrology and water quality in northern Coastal Ranges and western Sierra Nevada, USA using SWAT model and concluded that the sensitivity of both hydrologic cycle and water quality to the projected climate change is high.

Within the present work, it is attempted to identify and analyze the effects of installation and operation of PVPs in the major hydrologic components. Furthermore, a generalized conceptualization of those effects is proposed with a view to a wider application in other climate and land uses change studies. Finally, the hydrologic effects are quantified and simulated in a medium sized basin in northern Greece, i.e., Vosvozis river basin (Fig. 1). For this purpose the widely applied hydrologic model SWAT (Neitsch et al., 2011) was calibrated and verified for the period 2008–2012 and various scenarios of impacts extent and land occupation by PVPs were tested. Moreover, dynamically downscaled projected climate data driven by 5 GCMs under SRES-A1B scenario were used as input to the developed model in order to assess the

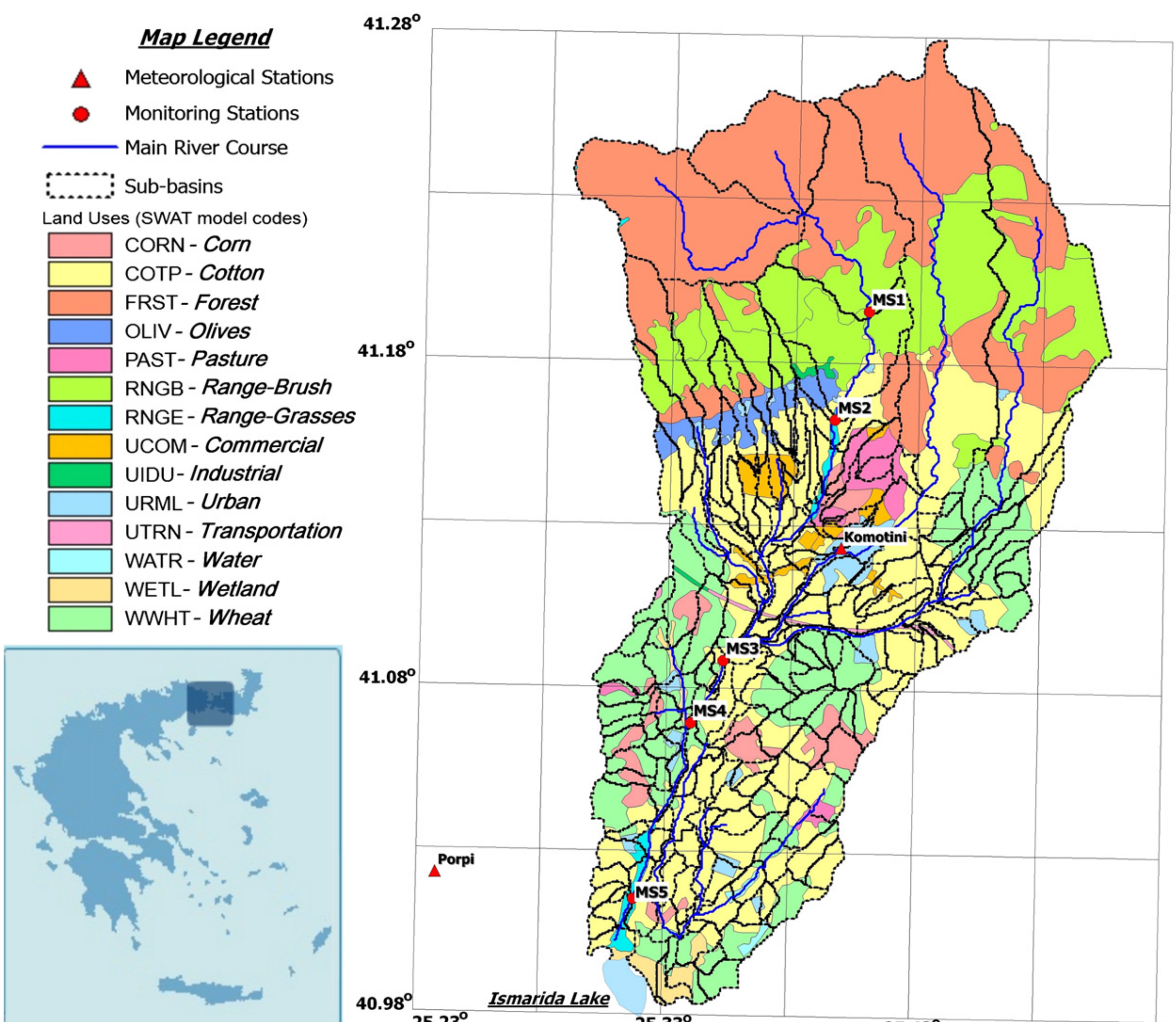

Fig. 1. Location and land use map of the study area.

long-term effects of PVPs on the hydrology of the test site for the period 2011–2100.

2. Materials and methods

2.1. Study area description

Vosvozis river basin in Thrace (Northern Greece) (Fig. 1) constitutes a typical Mediterranean watershed, especially suitable for the installation of PV systems due to the abundance of sunlight, its rural character and the presence of a large proportion of plain land. The catchment size is 340 km^2, extending from the Greek–Bulgarian borders down to the Thracian sea. Vosvozis river discharges into Ismarida Lake, which is an important ecosystem, protected by the Ramsar Treaty, it is designated as Natura 2000 area and it is part of the National Park of Eastern Macedonia and Thrace. Ismarida Lake is an ecosystem where complex interactions among surface waters, groundwaters and sea waters are taking place. Previous research in the area has proved the hydraulic connection of Ismarida Lake and Vosvozis river with the groundwater system. Gemitzi and Stefanopoulos (2011) and Gemitzi et al. (2013) have shown that Ismarida Lake recharges the groundwater system and therefore it should be considered as a groundwater dependent ecosystem. Therefore, any changes on land uses in Vosvozis catchment area are expected to affect Ismarida Lake and the associated aquifer system.

The climate of the area is characterized as Mediterranean with dry hot summers and mild winters. The average annual precipitation is 628 mm and the average annual temperature is 15 °C. The area is characterized by intense agriculture, cattle breeding and urban land uses. The main cultivations are corn, cotton and wheat, as illustrated in Fig. 1. Water is used mainly for irrigation and urban supply. During the last years, several legislative frameworks have been established in Greece which aims to promote the development of renewable energy sources, including photovoltaic power systems. One of the most recent legislative regulations with regard to renewable energy sources is the Law 3851/10 (Official Government Gazette of Greece, 2010), which motivates farmers to install small scale PVPs in agricultural areas, thus promoting land use change and activity modification from agricultural to energy production.

2.2. Model development

2.2.1. Data set and model parameterization

The SWAT model (SWAT2009 version) (Neitsch et al., 2011) was used for the purposes of this study. SWAT model has been widely used for the assessment of climate and land use change effects at the catchment hydrologic regime (Wu et al., 2012; Kim et al., 2013; Luo et al., 2013). SWAT model basic data requirements include topography, land use, soil and weather data. It is calibrated and validated using simulated against observed river discharge data. Thus, five monitoring stations were established in Vosvozis river basin (Fig. 1), in which river flow measurements were performed on a weekly or biweekly basis for the period October 2008 to April 2012. River flow was determined by in-stream wading measurements using a Hydrological Services Pty OSS-B1 current meter. The monitoring process resulted in 580 river flow measurements in total for the five monitoring stations.

Land use distribution for the study basin was defined using a hybrid approach of CORINE data and general crop pattern data derived from Apostolakis (2009). The appropriate SWAT land cover/plant codes were assigned to each land use and a reclassified land use map was produced (Fig. 1), which was used as input to SWAT model. Soil data were obtained by the local authorities and were enriched with recent soil data from Misopolinos (2009), which were incorporated into SWAT soil database.

Digital Elevation Model (DEM) quality can strongly influence the hydrologic simulation results (Defourny et al., 1999). For the mountainous area, DEM was constructed by digitization of the 1:50,000 scale topographic map of the Hellenic Military Geographical Service. For the lowland area, where low slopes are observed, that were not sufficiently represented by the 1:50,000 scale topographic map, 1:5000 topographic maps of the Hellenic Military Geographical Service were digitized. The resolution of the final DEM was 50 × 50 m. Due to the fact that some parameters included in land use change scenarios, such as solar radiation, are assigned at the sub-basin level and not at the Hydrologic Response Unit (HRU) level, the agricultural part of Vosvozis river basin was densely subdivided into small sub-basins in order to be able to develop low PVP coverage scenarios. This does not affect the validity of model performance, as indicated by the results provided by Cho et al. (2010), showing that watershed subdivision did not affect streamflow prediction stability. Vosvozis river basin was subdivided into 211 sub-basins and 265 Hydrologic Response Units (HRUs). Weather data were collected from two meteorological stations shown in Fig. 1, including daily values of precipitation, maximum/minimum temperature, wind speed, solar radiation and relative humidity for the period October 2008 to April 2012.

Two methods are available within SWAT model for surface runoff simulation: the SCS runoff method (USDA-SCS, 1972) and the Green & Ampt infiltration method (Green and Ampt, 1911). Despite the fact that infiltration is directly simulated in Green & Ampt method, it requires sub-daily meteorological data. Hydrologic simulation in a sub-daily time step is not the case for the current study and therefore the widely applied SCS method was used for the purposes of this study. The parameter that controls surface runoff potential in SCS method is the curve number (CN) which ranges between 30 and 100. Lower CN values indicate low runoff potential, while higher values correspond to increasing runoff potential.

SWAT model interface offers several methods for the calculation of potential evapotranspiration. As solar radiation changes are crucial for the purposes of this study, a method which incorporates solar radiation in evapotranspiration calculations should be used. Between Penman–Monteith (Monteith, 1965) and Priestley and Taylor (1972) methods, the former was chosen, as the latter tends to underestimate potential evapotranspiration in semi-arid and arid areas (Neitsch et al., 2011).

2.2.2. Model calibration/verification

Calibration and validation processes are critical for model reliability, as there are parameters, which are difficult to be measured or estimated, thus increasing the degree of uncertainty in simulation. Model calibration could be either manual or automatic. As there are no continuous streamflow time series available, manual calibration was used for the purposes of this study.

Model calibration was based on daily streamflow data for the period October 2008 to October 2010. Several statistical methods and indices have been proposed and assessed for hydrological model evaluation. Legates and McCabe (1999) indicate that, not only correlation-based criteria, but also summary statistics and absolute error criteria have to be used in order to maintain a sufficient hydrological model evaluation. Krause et al. (2005) investigated the performance of several criteria used for the assessment of hydrological models and concluded that, unlike R^2, weighted R^2 (wR^2) is capable to reveal systematic model errors. They also found that the most sensitive criteria to low flow conditions area the logarithmic Nash–Sutcliffe Efficiency (Nash and Sutcliffe, 1970) (lnNSE) and the modified NSE. Moriasi et al. (2007) reviewed several model performance evaluation criteria used in a wide range of watershed models applications. They concluded that NSE, percent bias (PBIAS) and the ratio of the root mean square error to the standard deviation of measured data (RSR), in combination with graphical methods, should be used for model performance evaluation.

According to the above, the SWAT model application within this study was initially evaluated through a visual inspection of calibration results in the form of scattergrams, in which simulated streamflows are plotted versus observed ones and a linear regression line is fitted to (regression line gradient b and coefficient of determination R^2 are also calculated). Then wR^2, NSE, lnNSE, PBIAS, RSR and mean absolute error (MAE) were calculated. The same evaluation criteria were used for model validation assessment with streamflow data for the period November 2010 to April 2012.

2.3. PVP installation and operation effect identification and conceptualization

Based on the current practices applied in PVP siting, installation and operation, three interventions performed in a PVP terrain, which can potentially affect the local hydrology, were recognized. Hydrologic cycle components within a watershed are interacting in a complex way. Therefore, within the present work it is attempted to conceptualize the assessment process by identifying and assigning the PVP installation and operation effects that directly affect the fundamental hydrologic budget components. Indirectly, almost every hydrological component will be affected, as they are in constant interaction. Moreover, SWAT model parameters that describe the specific impact of the affected hydrological process were identified and properly adjusted in order to develop short-term and long-term impact scenarios. The three interventions identified and the subsequent conceptualization of their effects in the major hydrologic budget components are presented in Fig. 2 and described in detail below, while the corresponding equation relating the affected hydrologic budget components to SWAT model parameters is presented in Section A1 of Supplementary Material.

2.3.1. Earthworks for terrain preparation and PV mounting

The first intervention includes the earthworks for field flattening and related equipment installation (PV mounting systems, cables, inverters etc.). In general, low slope areas (<5%) are preferable for the construction of PVPs due to the fact that they are easier approached and the optimum orientation of photovoltaic panels is easier to be obtained, while less earthworks are required. Nevertheless, PVPs can be constructed in relatively high slope terrains. Any changes made in the slope of the PVP terrain will directly affect surface runoff potential. When applying SCS method for surface runoff simulation within SWAT model, CN is properly adjusted according to the slope of the corresponding HRU. Therefore, any changes in the slope of the HRU in which PVP is constructed will affect CN and subsequently surface runoff.

Depending on the case, earthworks may be required in order to eliminate the geomorphological anomalies of the installation terrain. Due to the fact that earthworks and related equipment installation are conducted using heavy machinery, soil compaction is likely to be observed, which refers to the packing effect of mechanical forces on soils (Ozgoz et al., 2006). Alaoui et al. (2011), in their review article, indicated that in most studies investigating the effects of soil compaction, bulk density (BD) was found to be increased in the upper soil layer, while the decrement in pore volumes of compacted upper soil layer, resulted in significantly lower saturated hydraulic conductivity (KSAT) values. The degree to which those soil hydraulic properties are affected by soil compaction depends on several factors, including soil type, moisture content and mechanical force amount load. Despite the fact that during the cultivation process, tractors and harvesting machines contribute to soil compaction, soil compaction effects are relieved by processes such as freezing/thawing, wetting/drying and tillage (Hakansson, 2005). Thus, the extent of recovering for PVP compacted soils is expected to be lower, since these soils are not tilled. Any change in BD affects wilting point and subsequently field capacity of the soil layer. Field capacity is related to retention parameter used in daily CN

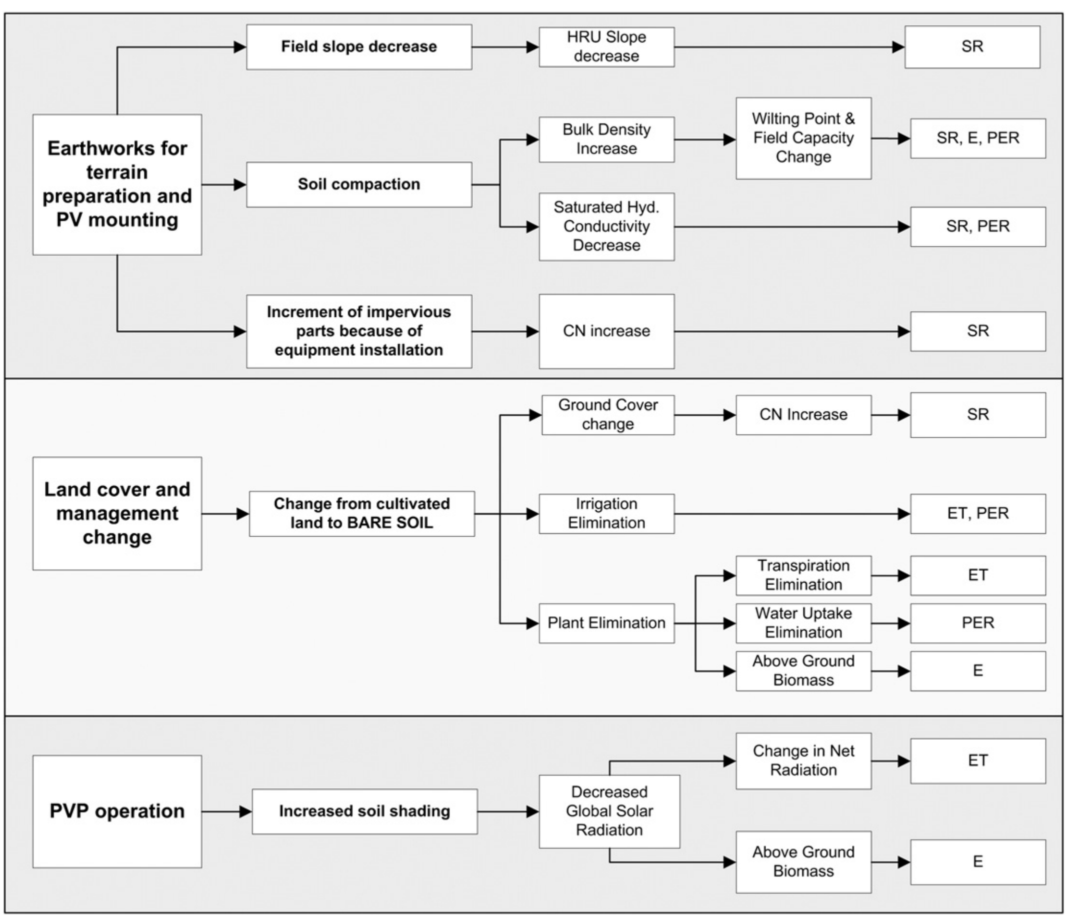

Fig. 2. Conceptualization scheme of PVP installation and operation impacts on major hydrologic components. (E = evaporation, ET = evapotranspiration, PER = percolation, SR = surface runoff, HRU = hydrologic response unit, CN = curve number).

calculation, when the daily CN is calculated as a function of water content and therefore surface runoff is affected. Moreover, soil water evaporation is affected, as field capacity constitutes the threshold water content value below which the evaporative demand of a soil layer decreases. Finally, percolation is affected by soil compaction, as field capacity and KSAT are related to travel time for percolation.

When concrete footings are constructed for PV panel mounting purposes and little prefab buildings are installed, a part of the PVP terrain is substituted by impervious areas. This will directly increase the potential of surface runoff, which is reflected in the modeling process by CN increment in SWAT model.

2.3.2. Land cover and management operations change from agricultural to PVP

The second significant intervention expecting to affect the hydrologic regime of an area is the land use change from agricultural to energy production. Cultivation includes several processes that directly affect the hydrologic regime of the agricultural field, such as plant growth and irrigation, which are eliminated when agricultural land is converted to PVP. Surface runoff is directly related to land cover. Peng and Wang (2012) measured surface runoff for six different land use covers, including forestland, cropland and pastureland using the large runoff field method. Their results indicated that the annual surface runoff can vary significantly with regard to land use type. The effects of land cover change from agricultural to energy production in surface runoff are reflected by changes in CN values, which are higher for bare soil when compared to CN values for the dominant crops of the study area (cotton, wheat and corn). These variations of CN values indicate a significant potential of land use change to affect surface runoff.

Depending on climate conditions and crop type, irrigation could constitute a significant component of the hydrologic budget. When agricultural irrigated land is substituted by PVPs, changes are expected for all the components of the hydrologic budget as irrigation ceases. The most significant change however, is expected to be observed in evapotranspiration due to changes in both transpiration and evaporation processes.

2.3.3. PVP operation

One of the fundamental principles concerning PVP construction is the orientation of photovoltaic panels in the way that they provide the maximum absorption of solar radiation. Within a PVP, several factors have to be taken into account for the definition of energy budget, as there are shaded surfaces of PVP terrain located under the PV panels and unshaded surfaces existing between the PV arrays, which serve to avoid PV panels shading from each other. Concerning the shaded surfaces of a PVP, from the total short-wave radiation, only short-wave diffuse radiation received from the ground should be taken into account. Therefore, significant changes are expected to be observed in ground's energy budget, which will affect evapotranspiration, as according to Penman–Monteith equation, evapotranspiration is directly related to solar radiation.

Studies investigating the energy budget and heat fluxes within a PVP are absent. Therefore, the ground energy balance was simulated with Autodesk Ecotect Analysis software for a typical PVP in order to estimate the shading effects of fixed mounting systems in solar radiation amounts reaching the ground. Despite the fact that Autodesk Ecotect software is mainly used for building energy analysis, for the purposes of this study, it was used in order to identify the extent of decrease in incident (direct and diffuse) solar radiation approaching the ground surface of a PVP. The incident solar radiation was simulated for a hypothetical PVP of 100 kWp, which is constructed in a zero slope terrain. Fixed mounting systems were assumed, whose characteristics are similar to those used in the study of Bakos (2009). South orientation of PV arrays was assumed with an inclination of 25° in order to maintain maximum electricity production during the year, while the appropriate row-to-row PV panel spacing was estimated to 6 m according to Macomber et al. (1981), in order to avoid shading effects of adjacent rows. More details can be found in Section A2 of Supplementary Material.

2.4. PVP installation and operation impact scenarios development

The conceptualization of PVP installation and operation impacts on the hydrologic regime revealed a large amount of parameters influenced, while the degree of influence for some parameters, such as BD, KSAT and solar radiation (SLR) is highly uncertain. For this reason, three scenarios were developed based on intensity and extent of interventions. The first scenario, referred as low impact scenario, incorporates mild interventions, both during PVP construction and operation. According to low impact scenario, earthworks are limited as there is no need for field flattening and mounting systems are installed through pile driving and consequently, there is no need for concrete footing. Therefore, no changes in field slope are anticipated, while soil compaction is expected to be recovered because of drying/wetting and freezing/thawing processes; thus, bulk density and saturated hydraulic conductivity do not change. Agricultural land is substituted with bare soil, while the mounting system type and installation height are expected to cause a low decrease (20%) in solar radiation amount reaching the ground.

The second scenario, referred as medium impact scenario, involves medium interventions during the construction and operation of a PVP. Despite the fact that there is no need for concrete footing for PV mounting, earthworks are more intensive for field flattening, resulting in soil compaction that cannot be recovered by the drying/wetting and freezing/thawing processes. So, bulk density increases by 15%, while saturated hydraulic conductivity decreases by 50%. Similar to the previous scenario, agricultural land is substituted with bare soil, but mounting system setting and installation height cause higher reduction in solar radiation (40%).

The last scenario, referred as high impact scenario, incorporates serious interventions during PVP installation, as well as, during operation. Extensive earthworks are required for field flattening and mounting systems are installed in concrete footing. The extensive earthworks resulted in substitution of agricultural land with bare soil, significant increase in bulk density (30%) and decrease in saturated hydraulic conductivity (the original values were multiplied by 0.1). Moreover, PV mounting systems are closely installed to each other and the installation height is low, resulting in significant decrease in solar radiation reaching the ground (60%). Those three scenarios were tested for 1% and 5% coverage of the study basin. Each coverage, either 1% or 5%, was spatially distributed in five different ways in the catchment site, with PVP replacing different parts of the agricultural area, as illustrated in Fig. 3.

In order to predict the long-term impacts of the above mentioned land-use change scenarios, climate scenarios for the future have to be used as climate input to the SWAT model. For the purposes of the present study, data from the Rossby Centre regional climate model, RCA3 (Samuelsson et al., 2011) were used, which were driven by the following 5 Global Circulation Models (GCMs): a) CCSM3, b) CNRM, c) ECHAM5-r3, d) HADCM3-Q0 and e) IPSL. Nikulin et al. (2011) provided technical details and an evaluation of these regional scenarios and the driving GCMs. Despite the fact that the application of Regional Climate Models (RCMs) offers a much higher spatial resolution in meteorological variables simulation when compared to GCMs, a systematic bias is typically noticed in the hydro-meteorological variables produced by the RCM. This bias originates from either the driving GCM or parameterizations in RCMs (Kotlarski et al., 2005; Kay et al., 2006; Graham et al., 2007). Therefore, the primary hydrological variables such as precipitation and temperature need to be adjusted to get realistic time series for use in local impact studies (Graham et al., 2007; Yang et al., 2010).

In this work, Distribution-Based Scaling (DBS) approach was used in order to further correct RCM precipitation and minimum and maximum temperature for impact model applications. Details about DBS can be found in Yang et al. (2010). The DBS approach aims to maximize

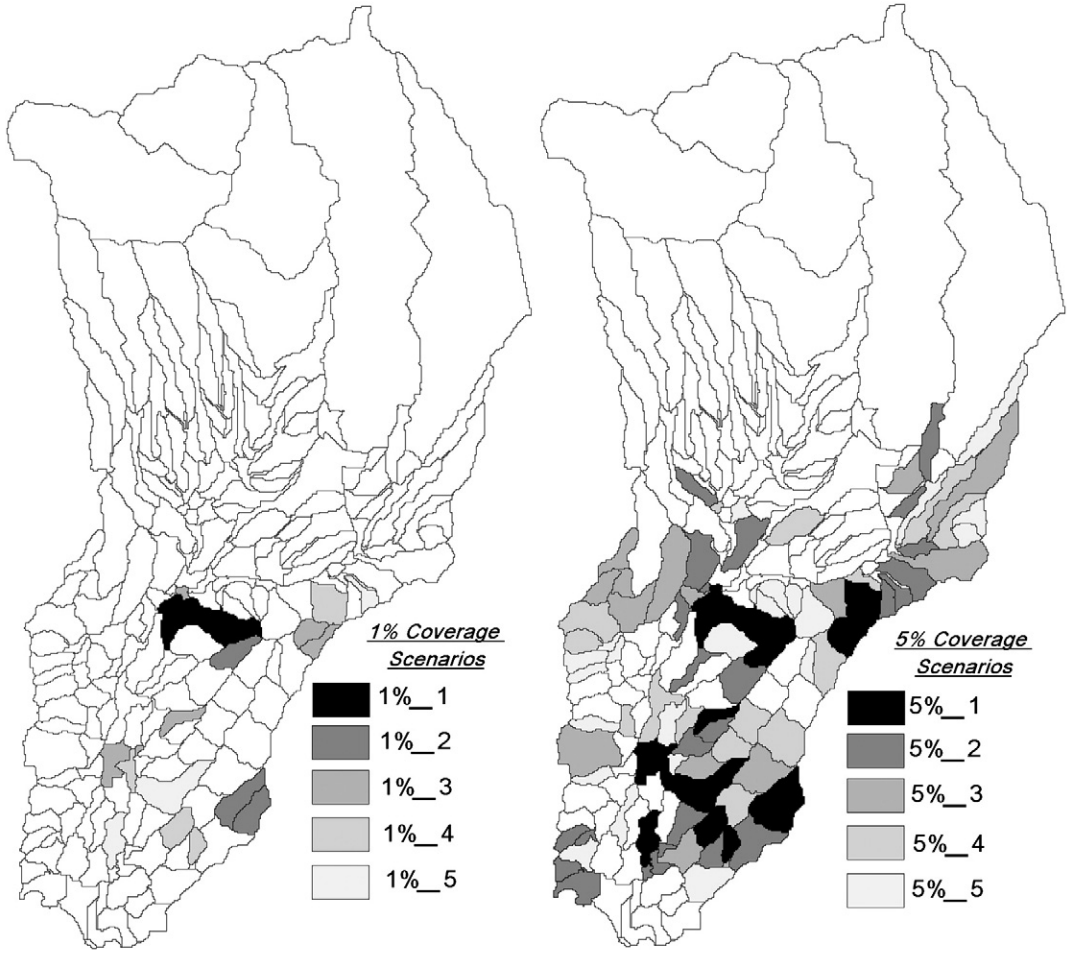

Fig. 3. Spatial distribution of scenarios with 1% and 5% coverage of agricultural land with PVPs.

utilization of RCM outputs to get more realistic input data for hydrological studies. With the DBS approach, statistical properties such as daily mean, standard deviation of temperature as well as distribution and frequency of precipitation days are much improved compared to direct RCM output. Relative humidity, solar radiation and wind speed RCM data were corrected using the widely used linear scaling approach, according to which daily RCM data are corrected by calculating a monthly correction factor for each parameter.

3. Results and discussion

3.1. Global radiation simulation results

The simulation results indicated a significant decrease of incident solar radiation reaching the ground surface of the hypothetical PVP, in relation to the incident solar radiation reaching the ground surface of the same terrain, when it is not covered by PVs. The decrease of average daily radiation in monthly basis ranges between 40% and 47.6% for panel inclination 25°, row-to-row spacing distance of 6 m (Fig. 4, line 25°, 6 m), while on the annual basis the decrease is 43.4%. Lower decreases were observed during summer months, while higher insolation decreases were observed during winter months, which depend mainly on differences of the sun path.

In order to test the influence of PV panel arrays density in insolation, the row-to-row spacing was decreased to 4 m. Moreover, the influence of PV panel inclination on insolation was tested by increasing inclination from 25° to 30° for both row-to-row spacing distances of 4 and 6 m. Thus, three more insolation simulations were performed and their results are presented in Fig. 4. Row-to-row spacing strongly influences the insolation reaching ground surface of a PVP, as decreasing row-to-row spacing from 6 m to 4 m was found to further decrease insolation by 7.3 to 13.5% for 25° inclination and by 6.3 to 13.1% for 30° inclination. With regard to PV panel inclination, the increment from 25° to 30° presented lower insolation decrease during the whole year when row-to-row spacing is 6 m, while insolation was decreased during May and summer months when row-to-row spacing is 4 m and remained almost stable for the other months of the year. Significant changes in energy budget have also been reported in studies investigating the effects of PV panel installation on roofs. Scherba et al. (2011), concluded that adding PV panels to a black roof reduced the daily sensible heat flux by 11%, while for PV-covered white and green roofs the daily sensible heat flux reduction was up to about 50%.

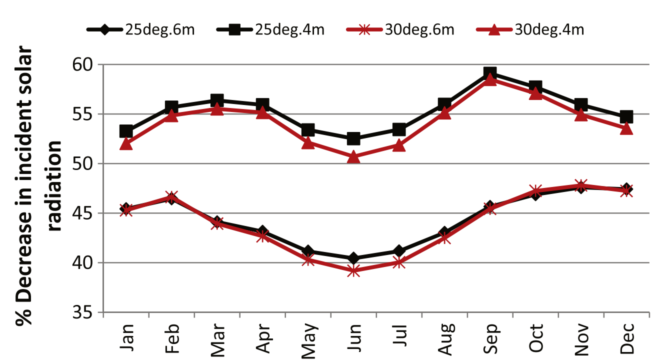

Fig. 4. Monthly decrease of ground surface incident solar radiation for several combinations of PV panels inclination and row-to-row spacing.

3.2. SWAT model calibration and validation

The statistical assessment results of SWAT model calibration and validation in Vosvozis river watershed are presented in Table 1, while the corresponding scattergrams of observed versus simulated streamflow are presented in Section A3 of Supplementary Material. Moriasi et al. (2007) indicate that SWAT model calibration for streamflow is satisfactory when NSE > 0.50, RSR < 0.70 and −25% < PBIAS < 25%. Based on this, both calibration and validation results were satisfactory, as indicated in Table 1, according to which NSE ranged from 0.86 to 0.97 for calibration and from 0.82 to 0.90 for validation, while the corresponding ranges for RSR was 0.19–0.38 for calibration and 0.04–0.387 for validation and for PBIAS is −6.12%–3.14% for calibration and −2.68%–9.13% for validation. The most widely used model performance assessment index (R^2) ranged between 0.87 and 0.98, thus indicating satisfactory model performance. lnNSE variation range was much lower than NSE variation range. Due to the fact that lnNSE is sensitive to low flow conditions, it is indicated that model response in low river flows observed during summer (less than 0.1 m^3/s) was worse than the overall model response. This does not significantly affect model performance, as those low river flows are not contributing significantly to the water budget. Except from MS1, the regression line gradient *b* in all monitoring stations is higher than 1, indicating that the model overestimated river flows. This overestimation (or underestimation for MS1) does not significantly affect model performance as wR^2 values in which *b* is incorporated, were satisfactory. As expected, calibration results are better than validation results, but validation results were also satisfactory.

3.3. Short-term land use change scenarios results

The short-term (2008–2012) effects of land use change from agricultural to PVP as described in the scenarios presented above were investigated at the basin scale, in order to assess the effects of 1% and 5% coverage of agricultural areas with PVP, and also at the sub-basin scale, in order to assess the local effects of land use change. The results for basin scale are presented in Fig. 5, while the corresponding results for sub-basin scale are presented in Fig. 6. The general trend observed both in basin and sub-basin scale is that surface runoff and percolation increase, while evapotranspiration decreases. These trends became more intense, as land use change impact increases from low to medium and high impact scenarios. Also, as impact intensity increased, a small increment in surface runoff was observed, while further decrement of evapotranspiration mostly contributed to increment of percolation. This fact indicates that after the allocation of precipitation water in surface runoff, more water is available to enter and remain in the soil profile, as evaporation decreases because of the shadowing effects.

The highest impact of land use change at the basin scale was presented for evapotranspiration, while the lowest impact was presented for percolation, both for 1% and 5% coverage. The decrement of soil permeability, as well as transpiration elimination, is a key process affecting the major hydrologic budget constituents, as illustrated by the significant increase in surface runoff and the significant decrease in evapotranspiration, even from the low impact scenario.

The coverage of 1% basin area with PVPs does not significantly affect the hydrologic budget of the basin, as surface runoff changes ranged between 0.9 and 1.27 mm, while the corresponding ranges for evapotranspiration and percolation were −2.3 to −5.2 mm and 0.17 to 0.52 mm, respectively (Fig. 5). Significantly higher, but not important at the basin scale was the impact for 5% basin coverage with PVPs (Fig. 5). The wide range of variation of the major hydrologic constituents change illustrated both at the basin and sub-basin scale indicates that the spatial distribution of PVP coverage and the corresponding spatial variability in soil profile composition and properties are key parameters for the assessment of land use change from agricultural to PVPs. This is more obvious in the box-plots presenting the variation of change at the sub-basin scale for 5% coverage (Fig. 6). Especially for evapotranspiration and percolation, the variation range exceeded 100 mm and 300 mm, respectively.

At the sub-basin scale, the results illustrated a significant potential for surface runoff to be locally increased, even in low impact scenario, by more than 100 mm on the median, which subsequently increases the local flood risk. One could expect that surface runoff should not be increased due to the fact that the major part of the study area is cultivated with summer crops (cotton and corn), which are not active during winter, while during summer, their water needs are satisfied by irrigation. However, the fact that crop water requirements during the summer cultivation period are satisfied not only from irrigation but also from soil water implies that water in the soil profile at the end of the cultivation period is significantly decreased and has to be replenished before surface runoff is generated. For the same reason, an increasing trend was presented for percolation and subsequently for groundwater recharge (Fig. 6). Especially for the Mediterranean region, this is a favorable impact, as groundwater constitutes the most significant resource for the satisfaction of water needs and its role is important for the regional and local economies (Aureli et al., 2008). Furthermore, due to the fact that agrochemicals used for crop cultivation purposes will no longer be applied when land use changes from agricultural to PVPs, lower groundwater pollution risk is expected.

When irrigation of an agricultural field is made from groundwater, the groundwater availability in the aquifer is expected to be increased due to irrigation elimination. However, some amounts of water are required during PVP operation for PV panels washing. The water consumption for PV panel washing is highly uncertain, as it varies by site and developer and washing rates are not well documented. Based on Aspen Environmental Group studies (2011a, 2011b) and industry knowledge an estimate of 0–18.93 × 10^{-3} m^3/MWh is reported by US-DOE (2012). Even when considering the highest consumption rate of 18.93 × 10^{-3} m^3/MWh, it is negligible when compared to water consumption for irrigation in semi-arid areas. For a PVP like the one presented by Bakos (2009) of 60 kWp, which is estimated to produce 74 MWh/y and covers an area ranging between 1200 and 2400 m^2, the

Table 1
Statistical assessment results of SWAT model calibration and validation using river discharge data from the 5 monitoring stations located in Vosvozis river basin. (NSE = Nash–Sutcliffe efficiency, lnNSE = logarithmic NSE, b = regression line gradient, R^2 = coefficient of determination, wR^2 = weighted R^2, PBIAS = percent bias, RMSE = root mean squared error, RSR = RMSE–observations standard deviation ratio).

	Calibration					Validation				
	MS1	MS2	MS3	MS4	MS5	MS1	MS2	MS3	MS4	MS5
NSE	0.86	0.90	0.94	0.96	0.97	0.86	0.90	0.83	0.88	0.82
lnNSE	0.70	0.66	0.57	0.81	0.74	0.62	0.67	0.64	0.63	0.78
b	0.96	1.03	1.00	1.05	1.06	0.94	0.99	1.00	0.99	1.03
R^2	0.87	0.91	0.95	0.97	0.98	0.88	0.91	0.86	0.90	0.86
wR^2	0.83	0.89	0.95	0.93	0.92	0.83	0.90	0.86	0.89	0.83
PBIAS (%)	3.14	−6.15	0.97	0.53	−3.88	9.31	0.40	2.45	1.23	−2.68
RMSE (m^3/s)	0.13	0.14	0.22	0.17	0.18	0.07	0.07	0.20	0.17	0.19
RSR	0.38	0.32	0.24	0.19	0.19	0.33	0.29	0.04	0.04	0.39

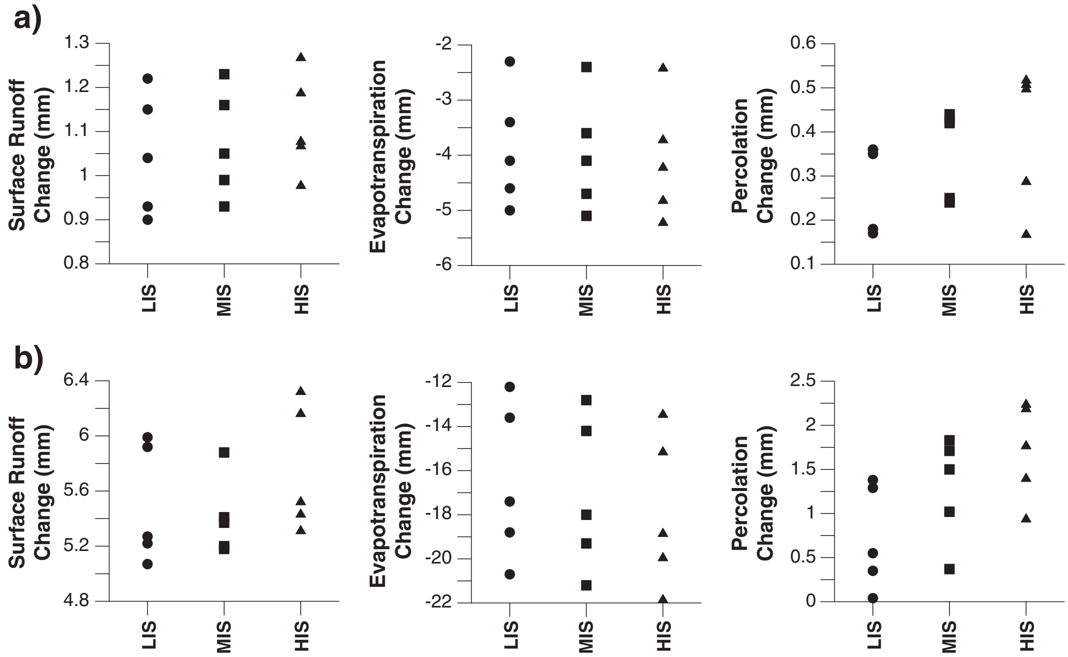

Fig. 5. Basin scale effects of land use change from agricultural to PVP on annual surface runoff, evapotranspiration and percolation for a) 1% PVP coverage and b) 5% basin coverage with PVPs for the period 2008–2012. LIS, MIS and HIS correspond to low, medium and high impact scenarios, respectively.

maximum water consumption is 1.4 m^3 or 0.58–1.16 mm per year. This water amount is low compared to water needs of crops like corn and cotton, which require more than 500 mm H_2O per growing season, mostly provided by irrigation in the Mediterranean region.

3.4. Long-term land use change scenarios results

Before the presentation and assessment of long-term effects of land use change from agricultural to PVP, future trends of precipitation and temperature resulted from the bias-correction process are analyzed and compared to historical data for the period 1954–2010 from Porpi meteorological station (Fig. 1) and are representative of the lowland climate conditions. In terms of precipitation projection, except from downscaled IPSL and downscaled HADCM3 projected data which demonstrate increased average annual precipitation (5% and 13%, respectively) for the period 2011–2100 compared to period 1954–2010, all other projections indicated a decrease of average annual precipitation, ranging between 4 and 10%. IPSL projection indicated periods in which precipitation is well above the historical annual average, while there was no significant drought period signal observed. According to

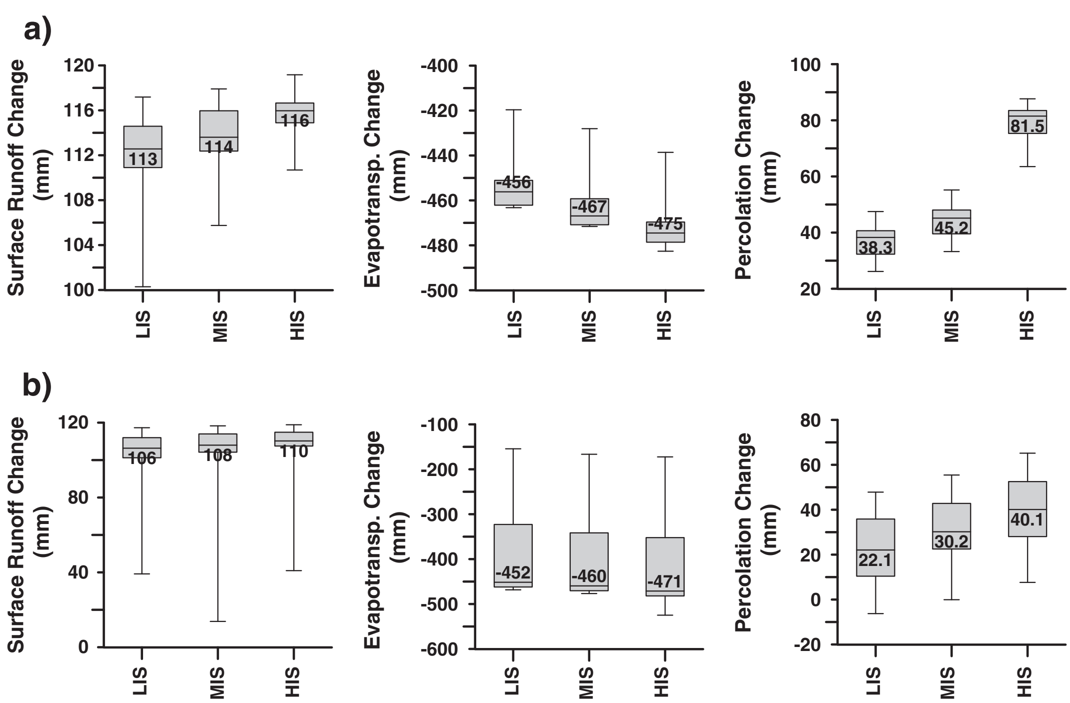

Fig. 6. Sub-basin scale effects of land use change from agricultural to PVP on annual surface runoff, evapotranspiration and percolation for a) 1% PVP coverage and b) 5% basin coverage with PVPs for the period 2008–2012. LIS, MIS and HIS correspond to low, medium and high impact scenarios, respectively.

downscaled CCSM3 data, annual precipitation demonstrated small variation for the period 2011–2070, while for the period 2070–2100, it was significantly decreased. For the same periods, annual precipitation according to downscaled HADCM3 projection was presented increasing and decreasing, respectively. Downscaled ECHAM5 projected precipitation data indicate two significant drought periods, the intensity and duration of which are similar or higher to the drought period observed during 1981–1994. In the same way, downscaled CNRM precipitation data indicated 3 significant drought periods and the strongest decreasing precipitation trend of all projections. Precipitation projection from downscaled CNRM, CCSM and ECHAM data are presented to be more realistic when compared to precipitation data variation for the period 1954–2010. Both annual maximum dry and wet spells demonstrate an increasing trend for all projections, compared to historical period. This fact indicates that after the extended dry spells, extended wet spells are expected to be observed. Also, extreme precipitation event frequency is expected to be increased. Concerning temperature, all projections demonstrated increasing trend, as illustrated in Fig. 7, and average temperature for the study area is presented to be increased from 3.5 °C (downscaled CCSM3 projection) to more than 5 °C (downscaled HADCM3 projection). In terms of solar radiation, it was found to be almost stable, while relative humidity indicated a decreasing trend which is more intense for downscaled HADCM3 projection. Finally, wind speed indicated increasing trend for all downscaled climate projections, except from IPSL, which indicated decreasing trend.

PVP coverage combinations 1_5 and 5_2 presented in Fig. 3 were chosen in order to assess the long-term effects of 1% and 5% land use change from agricultural to PVP, respectively. Those PVP coverage combinations were found to have the highest overall impact among the several PVP coverage distributions tested in short-term scenarios. At the basin scale, long- term impacts of land use change from agricultural to PVP presented in Fig. 8 are comparable to the corresponding results of short-term impacts both for 1% and 5% coverage, except from percolation, whose change was found to be negative under the low impact scenario, both for 1% and 5% coverage. In terms of surface runoff, the strongest increasing trend was observed for IPSL climate projection, thus reflecting the effects of higher precipitation simulated by this model, compared to the other four models. In contrast, the weakest increasing trend was observed for CNRM climate projection, which is consistent to the lowest average precipitation simulated by this model for the period 2011–2100. Concerning evapotranspiration, the strongest decreasing trend was observed for CCSM climate projection, whereas the weakest decreasing trend was observed for IPSL and HADCM climate projections. CCSM climate projection indicates the lowest temperature increase among the 5 climate projections and therefore the lowest temperature stress for the cultivated crops in the basin. This fact results in higher transpiration amounts and consequently higher evapotranspiration values simulated with CCSM climate projection data, which further produced higher change in evapotranspiration (Fig. 8), when transpiration was eliminated. Taking into account the findings of Nemet (2009), according to which PVPs may cover up to 0.39% of land by 2100 in case of high-diffusion of PVPs, the effects of PVP installation and operation are expected to be insignificant at the basin scale.

The results of long-term assessment land use change from agricultural to PVP at the sub-basin scale are illustrated in Fig. 9. The effects of temperature stress in evapotranspiration mentioned above are reflected in evapotranspiration change at the sub-basin scale, indicating higher evapotranspiration change for CCSM projection compared to evapotranspiration change simulated with the other climate projections, while the most wide inter-quartile range is presented for IPSL projection, reflecting the significantly different precipitation variation pattern compared to the other climate projections. The evapotranspiration change simulated for 1% coverage was about 15 to 20 mm higher than evapotranspiration change simulated for 5% coverage, thus indicating the importance of local soil profile properties and composition.

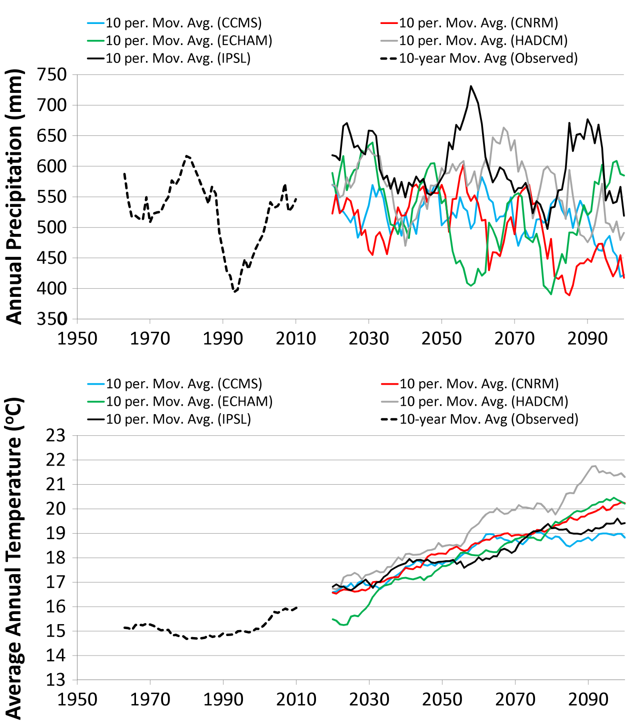

Fig. 7. 10-year moving average of historical (1954–2010) and projected (2011–2100) annual total precipitation and annual average temperature in Porpi (Fig. 1).

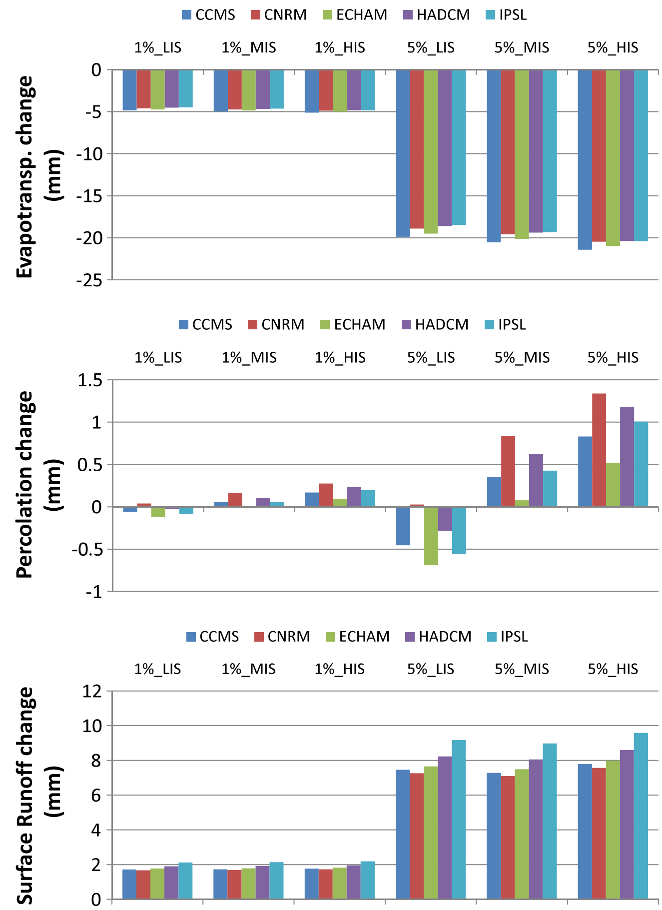

Fig. 8. Basin scale effects of land use change from agricultural to PVP on annual surface runoff, evapotranspiration and percolation for 1% and 5% PVP coverage during the period 2011–2100. LIS, MIS and HIS correspond to low, medium and high impact scenarios, respectively.

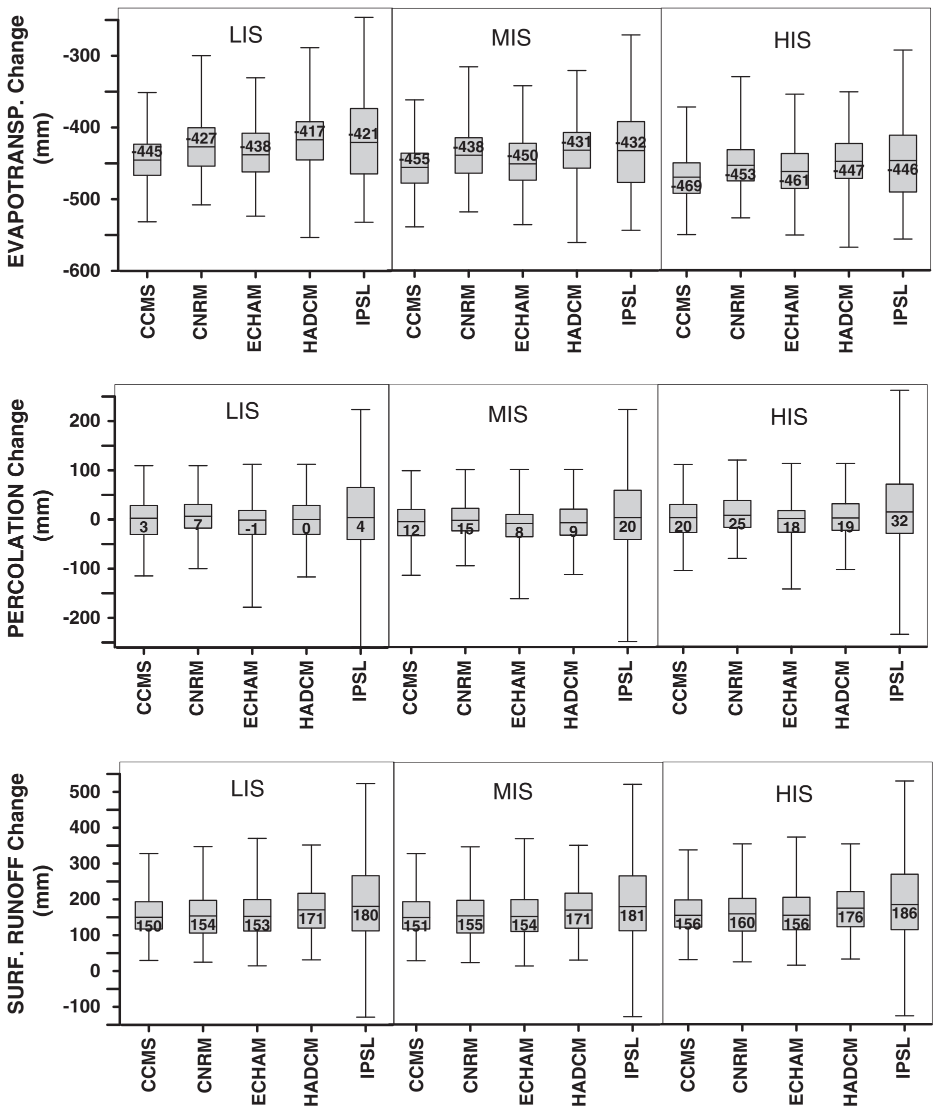

Fig. 9. Sub-basin scale effects of land use change from agricultural to PVP in annual surface runoff, evapotranspiration and percolation for 1% PVP coverage during the period 2011–2100. LIS, MIS and HIS correspond to low, medium and high impact scenarios, respectively.

Evapotranspiration was found to be further decreased from low to high impact scenarios, both for 1% and 5% coverage and all climate projections. For 5% coverage the decrement of evapotranspiration between the impact scenarios was found to be higher, demonstrating once again the effects of local conditions.

The clear increasing trend observed for percolation in the short-term assessment results for both 1% and 5% coverage presented in Fig. 6 was not observed in long-term assessment of land use change from agricultural to PVP, especially under low impact scenario. Median percolation change for ECHAM and HADCM climate projections under low impact scenario and both 1% and 5% coverage was negative, while interquartile range for all projections included both negative and positive percolation change values. The variation trend of percolation became clearer for medium and high impact scenarios, as interquartile range of percolation change included almost only positive values, but median percolation change increase was significantly smaller when compared to the corresponding results from short-term assessment. It is indicated that local soil water balance, part of which is percolation, may vary significantly according to local soil profile composition and properties and therefore resulted in high variation of percolation. Higher percolation increase was observed for IPSL climate projection, while lowest percolation increase was observed for ECHAM climate projection results.

Runoff potential presented a significant increasing trend at the sub-basin scale, as indicated by the significant increase in surface runoff for all climate projections (Figs. 9, 10). Higher runoff increase was indicated for IPSL projection, reflecting the higher projected precipitation amounts compared to the other four projections. Also, a wider interquartile range was presented for surface runoff change under this climate projection, indicating higher precipitation variability and extremes. Overall, surface runoff increase at the sub-basin level was significantly higher for the long-term assessment compared to the results of short-term assessment presented in Fig. 6. When comparing medium and high impact scenarios to low impact scenario, surface runoff was not significantly increased, indicating that further decrease of soil permeability by further increasing the corresponding CN did not significantly affect surface runoff.

4. Conclusions

Taking into account the anticipated climate change effects, the present work demonstrated that the effects of land use change from agricultural to PVPs do not significantly affect surface runoff, evapotranspiration and percolation at the basin scale, even for large coverage of the basin with PVPs. However, the effects of land use change from agricultural to

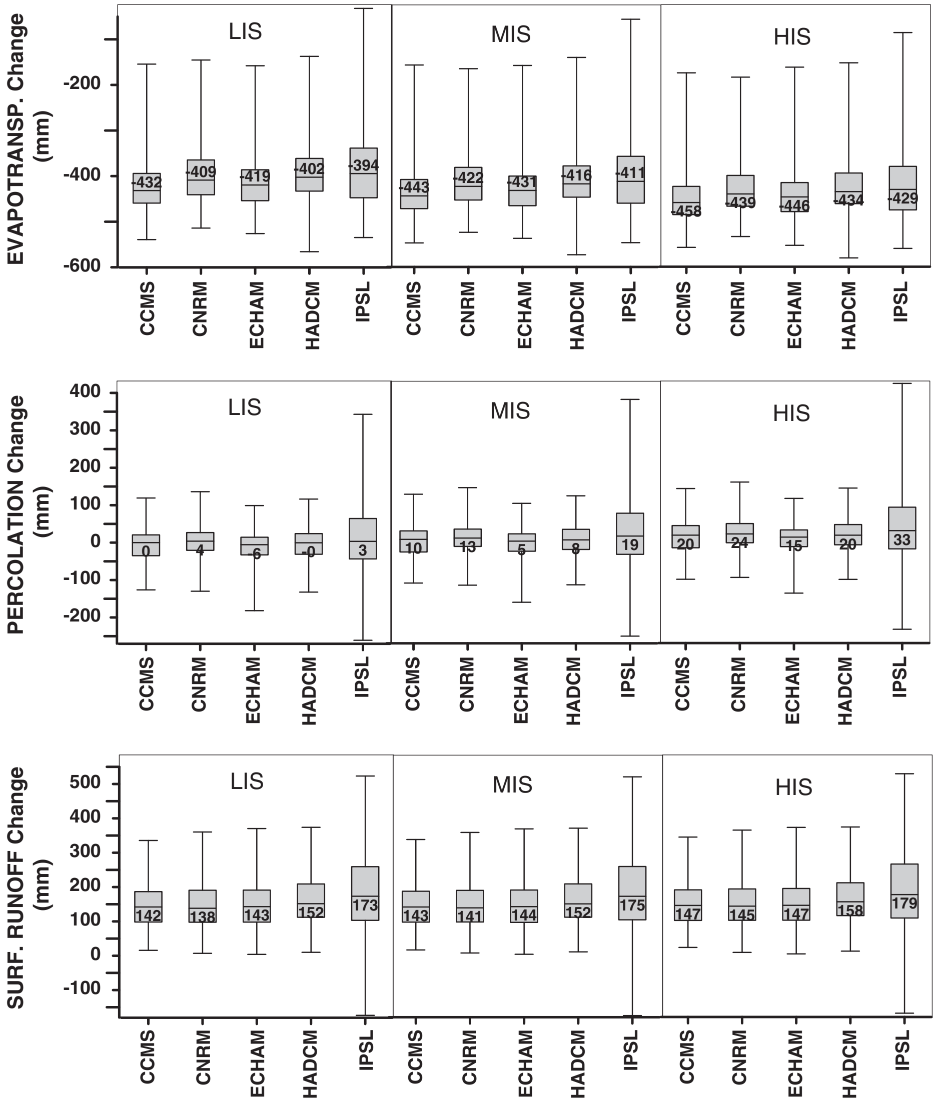

Fig. 10. Sub-basin scale effects of land use change from agricultural to PVP on annual surface runoff, evapotranspiration and percolation for 5% PVP coverage during the period 2011–2100. LIS, MIS and HIS correspond to low, medium and high impact scenarios, respectively.

PVPs were presented to be potentially significant at the local (sub-basin) scale, depending on the local hydrological conditions, which have to be addressed by the decision makers when allocating land for such uses. PVPs installation and operation may have both favorable and unfavorable impacts on the local hydrology of an area. A significant potential for surface runoff to be increased was indicated which has to be taken into account when siting PVPs. Therefore, special attention should be paid when allocating land for PVPs in flood prone areas and policy makers should be aware of the fact that increasing PVPs coverage in such areas may result in increased flood risk. On the other hand, the increasing trend of percolation and subsequently of groundwater recharge may be favorable for areas such as Mediterranean region. Moreover, taking into account the fact that PVP installation and operation minimize the use of fertilizers and pesticides involved in agricultural land uses, it may be assessed that a positive effect is to be anticipated both for surface water and groundwater quality.

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Appendix A. Supplementary information

Supplementary information to this article can be found online at http://dx.doi.org/10.1016/j.scitotenv.2014.05.132.

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