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Special Section: Hydrological Observatories

Core Ideas

- Advanced sensor networks gather dense information on hydro-meteorological variables.
- The Alento CZO helps assess the impact of climate and land-use change on ecosystem services.
- Our research supports effective supply-side and demand-side adaptation strategies.

Monitoring Hydrological Processes for Land and Water Resources Management in a Mediterranean Ecosystem: The Alento River Catchment Observatory

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In recent years, the critical zone (CZ) of catchments across the Mediterranean region has been influenced by rapid changes in both climate seasonality and land use–land cover. Rural ecosystems in southern Europe are experiencing prolonged droughts, seriously compromising water resource availability and crop yields while increasing the risk of wildfire occurrence. Rainy seasons are likely to be characterized by intense storms that trigger floods, resulting in increasing damage severity. The negative effects of anthropogenic disturbance on hydrological ecosystem services can be tempered by demand-side adaptation options and appropriate investments to ensure water supply under drought conditions. To shed light on some of the scientific challenges related to these issues, a critical zone observatory (CZO) has been established in the Alento River catchment. Although sampling campaigns and monitoring investigations have been performed in this area for >25 yr, a more systematic research program was recently started to take comprehensive measurements in representative subcatchments of the study area. These sites are instrumented with advanced ground-based sensor network platforms that provide hydro-meteorological variables and fluxes in the groundwater–soil–vegetation–atmosphere system. Hydrological models of different complexity exploit the dense information gathered to assess the impact of land use and climate changes on key functions and services of the CZO in the Alento River catchment.

Abbreviations: ARC, Alento River catchment; CZ, critical zone; CZO, critical zone observatory; LARC, Lower Alento River catchment; PDR, Piano della Rocca; UARC, Upper Alento River catchment.

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Land and water management practices have long been primarily controlled by socioeconomic factors, and the exploitation of both renewable and nonrenewable natural resources has provided enormous benefits (ecosystem functions and services) to society (Pascual et al., 2017). However, such practices have also engendered negative and sometimes irreversible effects on the environment. The European Union is currently facing a significant demand for natural resources (water, soil, forests, fossil fuels, minerals, rare earth elements, etc.) and is thus seeking to combine socioeconomic growth with sustainable and "smart" management of nonrenewable resources to guarantee adequate provision of ecosystem services for future generations (European Commission, 2017; Maes and Jacobs, 2017). A major challenge for the coming decades will be preventing a scarcity of freshwater, which represents a key natural resource and one of the most precious goods on a global basis. Agricultural and forest ecosystems in Europe, especially those distributed across the Mediterranean Belt, are experiencing an excessive demand for water due to competition among different uses (agricultural, recreational, and industrial uses, hydroelectric power generation, and drinking water supply), which could lead to future conflict, especially in water-stressed regions (Munia et al., 2016). To react and adapt to stress situations, especially those relative to the water sector, there is a growing need for supply-side policies and infrastructures that require relatively high investment costs. However, the implementation of such measures becomes an effective policy if the impact that various human disturbances exert on the hydrological ecosystem functions in a catchment can be reliably assessed (Guswa et al., 2014). Supply-water infrastructures can be integrated with demand-side adaptation strategies to reduce the consumption of freshwater by promoting, for example, water-use efficiency in irrigation and recycling and/or treating of household, industrial, and agricultural wastewater, as well as preventing contaminant transport to groundwater (Sposito, 2013).

The Alento River catchment (ARC; in southern Italy, 411 km^2) represents an interesting case study partly because of the presence of an integrated system of storage dams, the largest being the Piano della Rocca multipurpose earthen dam (PDR dam in Fig. 1) constructed to regulate water for irrigation, hydropower generation, flood control, and drinking purposes. In certain respects, this earth dam partitions the ARC into a lower (LARC) and an upper (UARC) part, the former being mainly devoted to farming and tourism, while the latter is a mosaic habitat mainly covered by shrubland and woodland. In the aftermath of World War II, land use and land cover in the UARC was subject to rapid changes due to a massive migration of people toward the urban–industrialized lowland areas (Nasta et al., 2017). On the one hand, rural abandonment in the UARC induced a significant increase in forest cover and a consequent reduction in arable and pasture lands. Under more frequent and severe drought conditions, scarce forest maintenance has increased the risk of forest fires (Ursino and Romano, 2014). On the other hand, the LARC has preserved its arable acreage but has experienced urban sprawl, especially in proximity to and along the coastline due to the increase in tourist facilities and hence freshwater demand during the summer season.

The decision-makers and stakeholders concerned are now starting to ask the following questions about future benefits and constraints deriving from the observed land-use changes or from plausible changes in climate seasonality:

- How will the storage capacity of the water reservoir in the UARC vary with time in view of projected climate and land-use changes to continue meeting short- and medium-term requirements from households, agriculture, tourism, and hydropower generation?

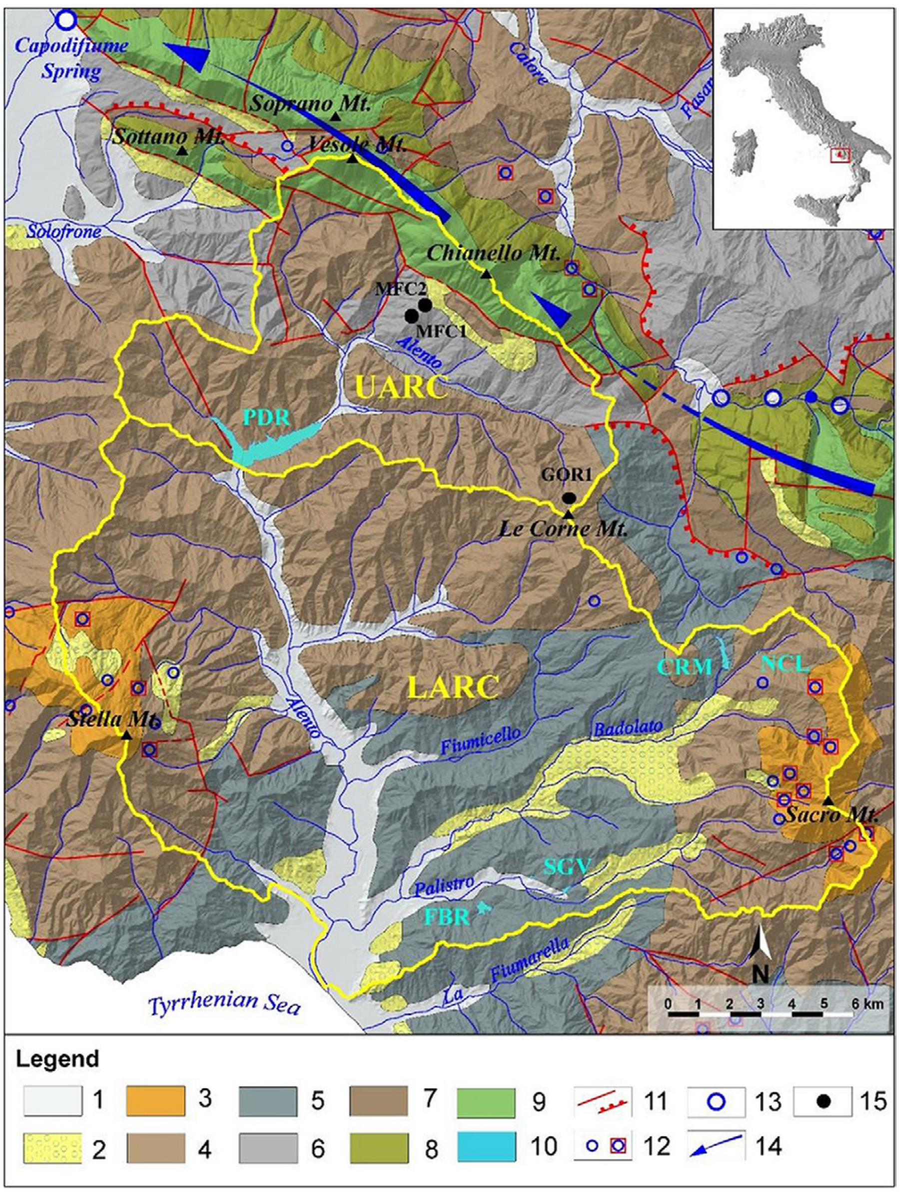

Fig. 1. Hydrogeological map of the Upper (UARC) and Lower (LARC) Alento River Catchments (modified from De Vita et al., 2018). Hydrogeological complexes: (1) alluvial-coastal (Quaternary); (2) epiclastic continental (Quaternary); (3) turbidite arenaceous-conglomeratic (Miocene); (4) turbidite arenaceous-calcarenitic-pelitic (Miocene); (5) turbidite calcareous-pelitic (Oligocene–Miocene); (6) clayey-calcareous (Cretaceous–Miocene); (7) pelitic-calcareous (Miocene); (8) transitional calcarenitic-marly (Paleocene); and (9) carbonate (Cretaceous). Other symbols include: (10) reservoirs managed by the Velia Bureau of Land Reclamation (PDR, Piano della Rocca; CRM, Carmine; NCL, Nocellito; SGV, San Giovanni; FBR, Fabbrica); (11) faults and thrusts; (12) untapped and tapped springs (flow rate $Q < 0.1\ m^3\ s^{-1}$); (13) untapped springs ($0.1\ m^3\ s^{-1} < Q < 3.0\ m^3 s^{-1}$); (14) main groundwater flow paths within carbonate aquifers; and (15) experimental subcatchments.

- What are the most effective demand-side adaptation options to be promoted in the LARC?
- What is the optimal land resource management to ensure adequate water availability to all sectors and reduce fire risk during the expected prolonged dry season but at the same time alleviate natural hazards such as flooding and soil erosion during the wet season?

Motivations

Advanced process-based models can offer scenario-based projections, but a trade-off between model efficiency and reliable performance largely depends on highly detailed data availability. Hydro-meteorological variables and fluxes need to be systematically monitored using state-of-the-art measurement technologies and data management tools within the continuum of the groundwater–soil–vegetation–atmosphere (Vereecken et al., 2015). Therefore, a science-driven terrestrial observatory was recently established in the ARC, which will be referred to as the Alento Critical Zone Observatory (CZO; Bales et al., 2011; Ochsner et al., 2013; Brooks et al., 2015; Guo and Lin, 2016). The research program offers a unique opportunity to couple the high-quality data sets with hydrological modeling tasks to evaluate the impact of land-use and land-cover changes and variations in climatic seasonality on the hydrologic ecosystem functions under different environmental and socioeconomic conditions. This approach would also serve to improve decision support systems and to optimize the plausible selection of adaptation and management strategies.

To date, we present the following objectives:

- to couple near-real-time monitoring of hydro-meteorological variables and fluxes with catchment-scale modeling tools of different complexities
- to gauge the impact of anthropogenic disturbance and propose appropriate supply-side and demand-side adaptation options with the main aim of developing innovative solutions for cost-efficient management of land and water resources in a typical Mediterranean ecosystem.

By using scenario-based projections, research in the UARC will be mainly devoted to gaining a better understanding of the impact of natural and anthropogenic disturbance (changes in land use and climate seasonality) on future water and sediment yields. This information will serve to select the most suitable water-supply strategies to offset projected droughts. Recently we established experimental subcatchments located in the Upper Alento that mainly reflect different hydrogeological conditions and land uses: arable land on low-permeability argillaceous bedrock (Sites MFC1 and MFC2); forest land on medium-permeability arenaceous bedrock (Site GOR1).

Investigations in the LARC will be mainly focused on demand-side adaptation options to enhance water quality and irrigation efficiency. Moreover, in 2011 the LARC was designated by the Regional Environmental Protection Agency as a nitrate vulnerable zone, and investigations have started (i) to assess space–time variations in the connectivity between groundwater and surface water, (ii) to identify the sources of potential nitrate contamination in the shallow aquifer, and (iii) to analyze nutrient dynamics and retention in riverbed sediments at key river reaches to evaluate the importance of the hyporheic and riparian zones in nutrient recycling processes.

General Setting

The ARC is situated in the southern Italian region of Campania and lies within the renowned Cilento area, with a total drainage area of about 411 km^2 and a perimeter of approximately 145 km (see Fig. 1). The ARC is included as a representative site within the UNESCO-HELP program and falls partly within the Cilento, Vallo di Diano and Alburni National Park, a UNESCO Man and the Biosphere (MAB) Programme site established in 1991 and the largest national park in Italy, with an area slightly exceeding 1800 km^2.

This catchment is not affected by snowmelt processes. The headwaters originate from the slopes of Mt. Le Corne (894 m asl, in the municipality of Stio), and the main river has a total length of about 37.4 km, running initially in a northwest direction and then southeast until it flows into the Tyrrhenian Sea. The ARC is set on terrigenous geologic formations from pre- (Cretaceous) to syn-orogenetic (Upper Miocene) series, commonly referred to as Cilento flysch, made up of argillaceous and arenaceous rocks, with low to medium hydraulic permeabilities (Bureau of Reclamation, 1985; De Vita et al., 2018). A carbonate platform series (Lower Cretaceous–Paleocene) crops out in a limited part of the upper ARC and forms the Mt. Vesole–Chianiello–Rupa della Conca mountain ridge. The latter is a small part of the Mt. Cervati-Vesole regional karst aquifer, whose underground basin extends beyond the ARC watershed. Due to the relatively high permeability caused by intense fracturing and karst phenomena, this aquifer has negligible runoff but high groundwater recharge and circulation (Allocca et al., 2015), flowing out into the great Capodifiume spring (with a mean discharge of about 3 $m^3\ s^{-1}$), located outside the ARC at the westernmost point of the carbonate ridge (Fig. 1). Quaternary deposits comprising alluvial, detrital, and colluvial deposits discontinuously mantle the above-mentioned types of bedrock (De Vita et al., 2018).

More information about the pedological characteristics of the study area is available for the UARC, where more numerous and detailed vadose zone investigations have been performed. Soil surveys have shown that a different combination of factors led in UARC to the formation of different subgroups of Entisols, Inceptisols, Vertisols, Alfisols, and Andisols (according to Soil Survey Staff, 1999) that can coexist within the same system or subsystem. Soil observations to describe the soil profile were performed by digging pits in 37 different locations, and this survey, together with information about geology, geomorphology, land use, and other landscape features, was used to delineate a soil landscape map for the UARC. The soil landscape map showing only the main units is illustrated in Nasta et al. (2017) and has not been included again here for the sake of brevity.

A hydraulic system of five dams supplies water for irrigation, flood control, hydropower generation, and domestic use (Fig. 1). The main barrage is the PDR earthen dam that has been operating since 1995 and can be viewed as a sort of hinge that not only physically connects the two parts of the ARC, namely the UARC (102-km^2 drainage area) and the LARC (309-km^2 drainage area) but also holds together various monitoring and modeling activities (see Fig. 1). For this artificial reservoir, a bathymetric survey and sediment coring were performed in October 2007.

Detailed investigations concerning the hydrogeology and vadose zone hydrology have been performed for many years in the ARC (Celico et al., 1992, 1993; Casciello et al., 1995; Nasta et al., 2009, 2013, 2017, 2018; Stellato et al., 2016; Perri et al., 2017). More hydrologically oriented investigations have been performed in three experimental sites (MFC1, MFC2, and GOR1) located in the UARC upstream of the PDR reservoir. It is worth mentioning that GOR1 was selected as the forested headwater catchment to contribute to an investigation performed along European transects to elucidate the physical and chemical compositions of stream-water elements bound to natural nanoparticles and fine colloids (Gottselig et al., 2017).

Land use in the UARC has been affected by a progressive demographic decline starting from the Post-War period. The initial situation depicted in a land-use map of 1955 shows a dominance of subsistence agriculture (about 76%) (Nasta et al., 2017). Various socioeconomic stressors have prompted massive migration from the UARC to urban areas and have consequently led to forest re-expansion, with a forest cover of about 73% in 2006 (see pie charts in Fig. 2). In contrast, the demographic decline in the LARC has been somewhat tempered by more favorable socioeconomic conditions sustained by tourism near the coastal zone.

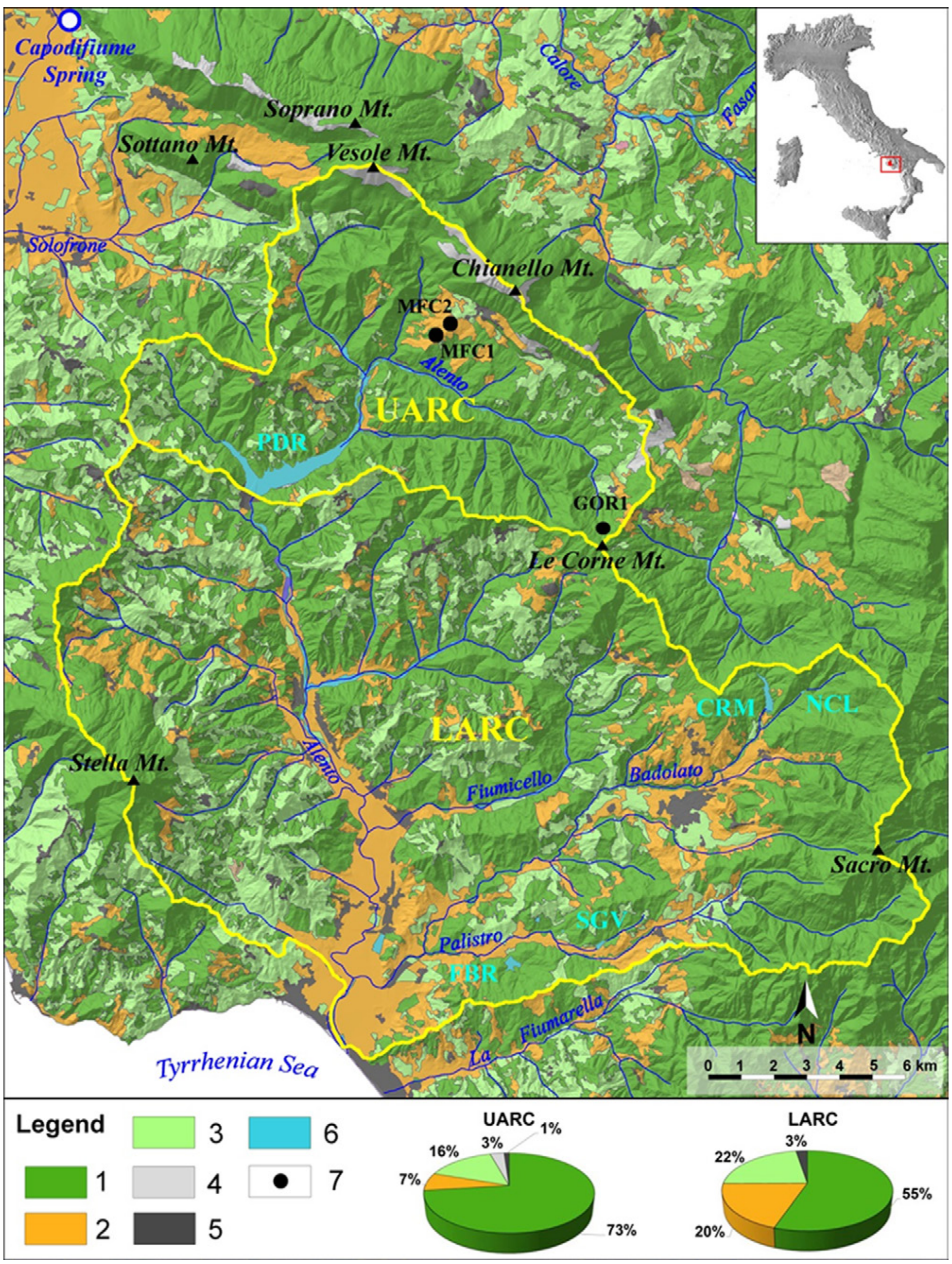

Fig. 2. Land use map of the Upper (UARC) and Lower (LARC) Alento River Catchments: (1) forest and shrubs; (2) arable land; (3) orchards; (4) outcrops of bare rocks; (5) urban fabric; (6) freshwater reservoirs managed by the Velia Bureau of Land Reclamation (PDR, Piano della Rocca; CRM, Carmine; NCL, Nocellito; SGV, San Giovanni; FBR, Fabbrica); and (7) experimental subcatchments.

Smallholder agriculture (arable land and orchards accounted for 42% of land cover in 2006) has been sustained by mechanization, road infrastructure, availability of groundwater stocks, and recently water storage (supplied by the dam network) for irrigation purposes. The increase in tourism along the coastline has favored local economic growth at the cost of urban sprawl. Most of the urban fabric along the coastline is not considered in the pie chart in Fig. 2 because it is located outside the Alento catchment, but this external urban area consumes water supplied by the dam network.

Basic Long-Term Observations

Meteorological and hydrological observations in Campania have been performed since 1915 by the former Italian Hydrologic Service, whose precipitation monitoring network consisted initially of 80 traditional rain-gauge stations. In October 2002, the local office of the Italian Civil Protection took over as the monitoring agency, and the current real-time telemetric hydro-meteorological network consisting of 136 weather stations is equipped with a total of 216 sensors, including rainfall (112), streamflow (50), and air temperature (54) sensors. Moreover, four weather radars operate in Campania, one of which is located in the town of Salento, close to the Alento River area. The Civil Defense Office network is complemented with a network of 68 weather stations managed by the Campania Regional Authority and specifically devoted to the forest-fire service, as well as a network of 37 weather stations, again managed by the Regional Authority but specifically devoted to the agro-meteorological service. The datasets from these networks of weather stations are extremely useful for assessing the seasonal trends of precipitation and carrying out analyses of drought, rainfall erosivity, and fire risk.

For the entire ARC, eight rainfall stations and four air thermometric stations provide more direct and useful information on the basic hydrological variables. The climate belongs to sub-humid Mediterranean mountains (Csa climate; Peel et al., 2007), with a sharp distinction between a cold-wet season (spanning about October–March) and a hot-dry season (about April–September). As commonly occurs in the case of a Mediterranean climate, an effective reference period when computing the hydrologic budget is the 12-mo hydrologic year, which is conventionally taken from 1 October of a given year through 30 September of the following year. The longest operating hydrometric measurements are taken at the main river gauge station located at Casalvelino Scalo that has been operating since 1965. Seven additional stream gauging stations have more recently been located along various tributaries of the Alento River and are managed by the Velia Bureau of Land Reclamation.

Dedicated Campaigns and Experiments

Main Field Campaigns in the Upper Catchment

The first field campaigns were performed in the UARC to delineate the soil-landscape units and to carry out soil hydraulic characterization studies by digging sparse pedological pits and sampling soil cores in each soil horizon of the soil profiles. More detailed surveys were then performed to measure soil physicochemical (oven-dry bulk density, organic C content, particle-size distribution, texture) and hydraulic (water retention and hydraulic conductivity functions) properties on soil cores collected in the topsoil of six hillslope transects that run along different soil-landscape units (Nasta et al., 2009). In the same transect locations, near-surface soil moisture was measured with a portable time domain reflectometer during 10 campaigns from October 2004 to January 2005 (Romano, 2014). Daily discharge data at the UARC outlet are retrieved from the water balance of the dam reservoir, based on daily storage and volume uptake datasets provided by the dam manager (Nasta et al., 2017).

Main Field Campaigns in the Lower Catchments

In the framework of a project funded by the Coordinated Research Activity of the International Atomic Energy Agency (CRP-IAEA), four sampling campaigns were performed from July 2014 to June 2016 in the LARC. The piezometric reconstruction was obtained by measuring groundwater levels at 43 domestic and agricultural wells (10–15 m deep). At each sampling location, variables such as temperature, pH, alkalinity, and electrical conductivity were measured in situ, whereas water samples were analyzed to determine the major ion concentrations, δD and δ^{18}O, δ^{15}N, and δ^{18}O of dissolved nitrates, and radon specific activity. The multidisciplinary approach adopted yielded the following outcomes (Stellato et al., 2016): (i) a gaining river condition was identified in the northern part of the alluvial plain by means of a combination of the hydrogeological (water table morphology), physical, chemical (temperature and electrical conductivity), and isotopic (^{222}Rn, δD, and δ^{18}O) datasets; (ii) rapid recharge from seasonal precipitation originating from evaporated and re-evaporated air masses was detected by studying the δD and δ^{18}O data relationship; and (iii) up to now, no nitrate pollution (nitrate threshold: 50 mg L^{-1}) was detected in the study area.

Dedicated Observations

The MFC1 Subcatchment

An intensive monitoring program was conducted from April 2006 to December 2009 in the MFC1 subcatchment of approximately 5.0 ha, located near the village of Monteforte Cilento (Nasta et al., 2013, 2018). This experimental area belongs to five landholdings with olive orchards, arable land (wheat), and grassland. A schematic drawing of the monitoring locations is illustrated in Fig. 3. Low-cost capacitance water-level probes (Odyssey, Dataflow Systems Ltd.) were placed in a 90° V-notch weir at the outlet of the ephemeral stream and in four shallow stone-cased wells (each well is identified by a three-digit number) to measure the depth to the groundwater table. Records of water height at the V-notch weir were converted into volumetric flow rate ($m^3\ s^{-1}$) or surface runoff flux (usually mm d^{-1}). An automatic weather station has been operational since April 2006 to

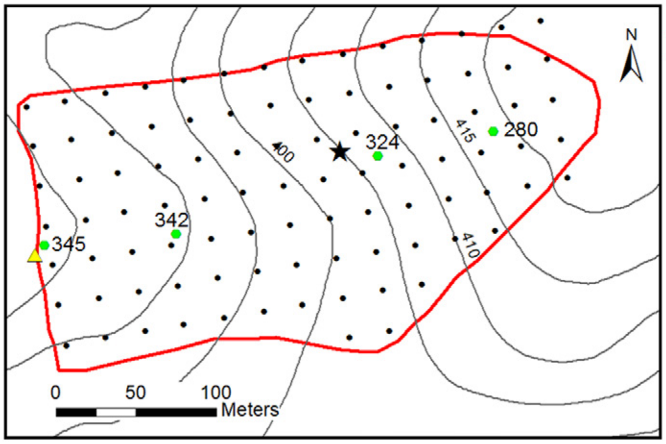

Fig. 3. Map of the MFC1 subcatchment showing the catchment boundary, isolines, and positions of the V-notch weir, stone-cased wells, weather station, and 94-point regular grid with sampling points for near-surface soil moisture measurements.

record the following meteorological variables: rainfall with an aerodynamic rain-gauge at 1-min intervals, along with air temperature and relative humidity, wind speed and direction, and solar radiation using a four-component (pyranometers and pyrgeometers) net radiometer at 15-min intervals. Reference evapotranspiration (mm d^{-1}) was computed with the Penman–Monteith equation (Allen et al., 1998). Near-surface (0–15 cm) soil moisture (θ, $m^3\ m^{-3}$) was measured at MFC1 by using a portable TDR100 time domain reflectometer on a regular square grid of 92 points during 13 sampling campaigns from September 2006 to April 2008. Figure 4 shows daily values of rainfall, reference evapotranspiration, surface runoff, and soil moisture. The bottom plot of this figure presents water-level data recorded at the selected four stone-cased wells expressed as heights above the data set at the MFC1 outlet. The temporal patterns of precipitation and reference evapotranspiration evidence the marked climate seasonality. Results from these investigations have been discussed in previous studies (Nasta et al., 2013, 2018), whereas analyses are currently underway to simulate the water budget in MFC1 by using the Richards-based three-dimensional HydroGeoSphere model (Davison et al., 2018).

Long-Term Observations at MFC2 and GOR1 Subcatchments

Subcatchment MFC2 is situated near MFC1 and represents a typical agricultural area with cherry trees (*Prunus* sp.) and walnut trees (*Juglans* sp.) planted for wood production. Another subcatchment, called GOR1, is instead located close to the rural village of Gorga and reflects the forest land use with mixed chestnut (*Castanea* sp.) and oak (*Quercus* sp.) woods. Apart from their different land-use and land-cover features, the MFC2 and GOR1 test sites are also representative of two different hydrogeological features.

Subcatchments MFC1 and MFC2 are set on a regolith (matrix of silt and clay and a subordinate fraction of sand and gravel) above a turbidite argillaceous bedrock, with relatively low permeability (Bureau of Reclamation, 1985; De Vita et al., 2018). Auger hole infiltration and slug tests were performed in MFC2 to characterize the low-permeability regolith zone. These tests also highlighted the existence of an uppermost soil layer with greater saturated hydraulic conductivity (K_s) values, primarily due to macroporosity and shrinking cracks (K_s ranges from 1×10^{-2} to

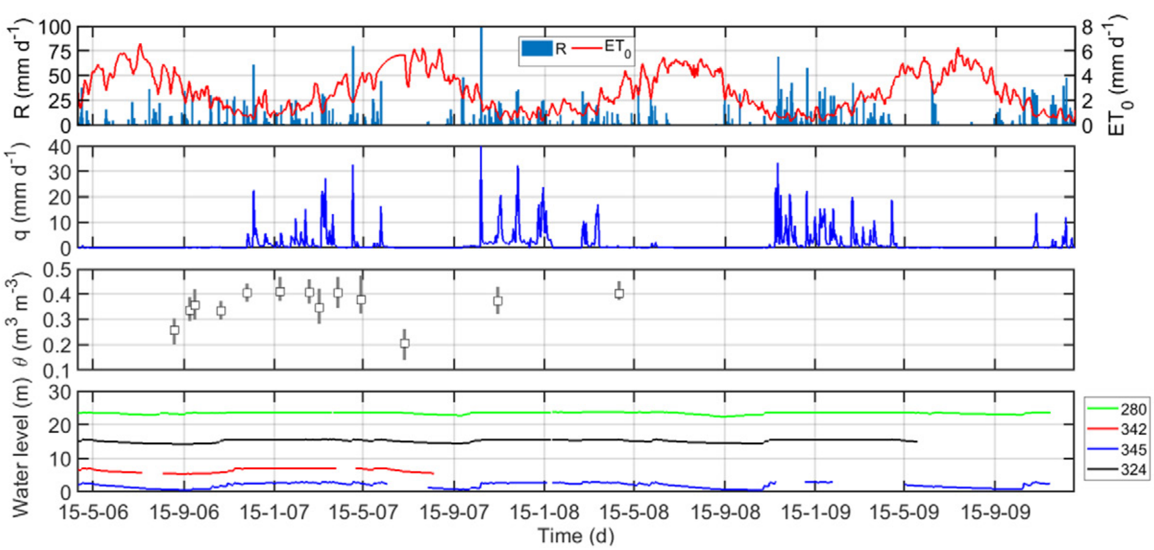

Fig. 4. Daily values of rainfall (R), reference potential evapotranspiration (ET_0), surface runoff (q), spatial median near-surface soil moisture (θ; the vertical bar represents the interquartile range), and water level of the four wells (280, 324, 342, and 345) recorded at the MFC1 subcatchment from April 2006 to December 2009.

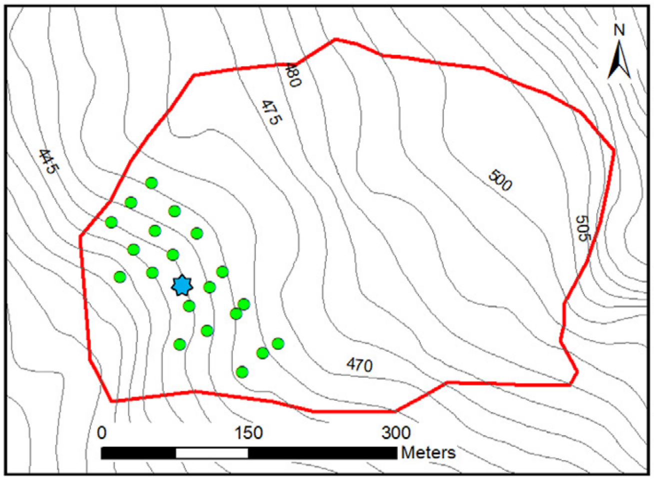

Fig. 5. Map of the MFC2 subcatchment showing catchment boundary, isolines, and positions of the cosmic ray neutron probe (CRNP) and SoilNet sensor units.

1×10^{-3} cm s^{-1} in the first 0.30 m of soil depth and then decreasing rapidly to 1×10^{-5} and 1×10^{-6} cm s^{-1} at about the 1.0-m soil depth). By contrast, the GOR1 subcatchment has a bedrock made up of turbidite sandstones, with medium permeability and mantled by a regolith zone characterized by sand–silt mixtures. In this area, the auger hole infiltration tests determined K_s values varying along the soil profile from approximately 1×10^{-2} cm s^{-1} in the first 80 cm, up to 5×10^{-4} cm s^{-1} at 2 m, and then to 1×10^{-4} cm s^{-1} down to 5 m of soil depth.

An automatic weather station has been operational in GOR1 since March 2016 and is similar to the one in service for the MFC1–MFC2 area. The ephemeral stream at GOR1 drains an area of approximately 37.9 ha, and the discharge is monitored continuously using a water height pressure transducer positioned close to the outlet of a long circular road culvert (UTM WGS84 33T, 519832 m E, 4462834 m N). Recently, this culvert was conveniently modified to monitor low values of streamflow. Instead, the outlet section of the ephemeral stream at MFC2 (UTM WGS84 33T, 515479 m E, 4468216 m N) drains an area of approximately 16.0 ha and a stream-gauging station at the outlet will soon be installed to monitor discharge continuously using an ultrasonic sensor.

Vadose zone variables and fluxes have been collected in each of these subcatchments systematically since March 2016 through a wireless sensor network and a cosmic-ray neutron probe. Each wireless sensor network (SoilNet, Forschungszentrum Jülich, Germany; Bogena et al., 2010) comprises an array of 20 underground measuring nodes that are distributed in space to account for the local geomorphological and pedological features. At soil depths of 0.15 and 0.30 m at each node, we embedded the following sensors: the GS3 sensor (Decagon Devices) measures soil moisture (θ, m^3 m^{-3}), soil temperature (°C), and apparent electrical conductivity (mS m^{-1}) simultaneously, whereas the MPS-6 sensor (Decagon Devices) measures soil matric pressure head, ψ (m H_2O). At each node of the network, the GS3 and MPS-6 sensors provide soil water retention data points, θ(ψ), at the two investigated soil depths, whereas the MPS-6 sensors provide information about the total hydraulic gradients. With a view to ensuring the best and most effective communication among the various wireless sensor network units, the physical layout is of the aboveground-to-aboveground type, i.e., the transmitter and receiver are both located above the soil surface. The positions of the sensors at MFC2 and GOR1 are shown in Fig. 5 and 6, respectively. Figure 7 illustrates an example of the monitoring outcomes, with daily records of state variables and water fluxes acquired at Box no. 03 in MFC2. We report rainfall and reference evapotranspiration as meteorological forcing data together with soil moisture and matric pressure head values measured at the two soil depths of 0.15 and 0.30 m. We also consider battery voltage to guarantee functionality. In the example of June 2017, the sensors were temporarily blocked for several days before battery replacement.

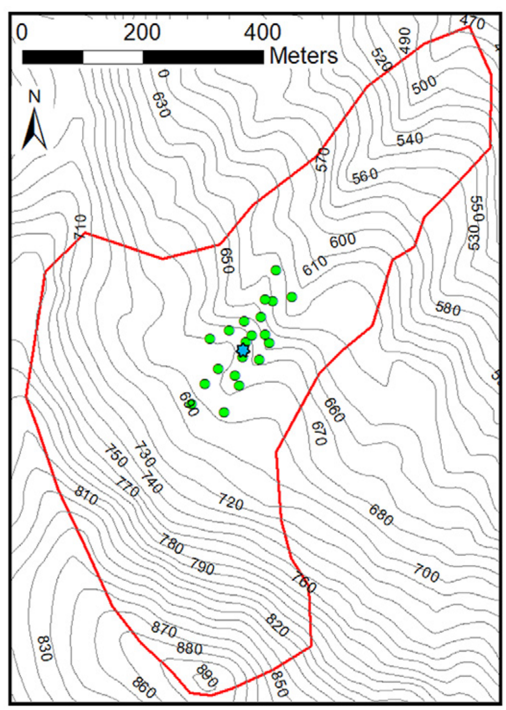

Fig. 6. Map of the GOR1 subcatchment showing catchment boundary, isolines, and positions of the cosmic ray neutron probe (CRNP) and SoilNet sensor units.

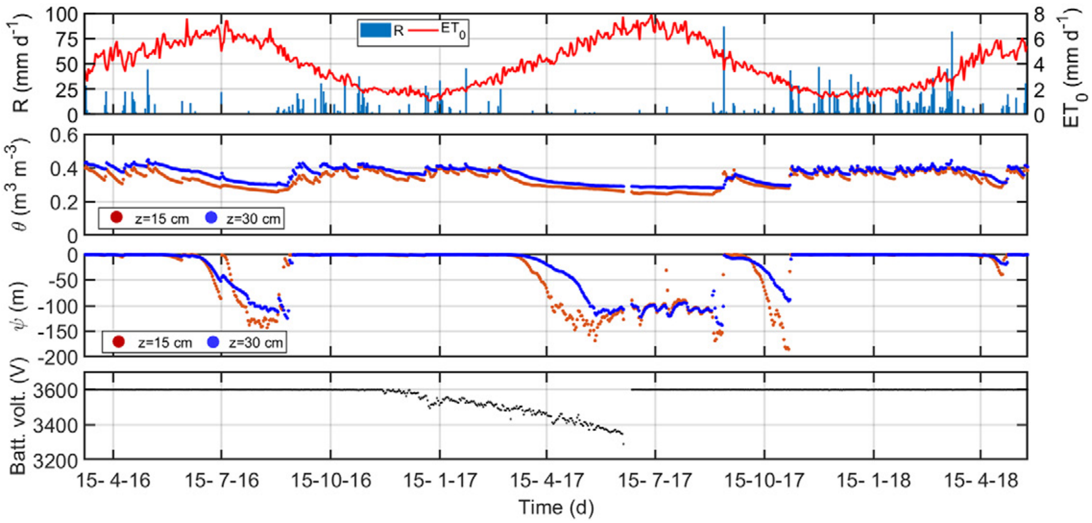

Fig. 7. Daily values of rainfall (R), reference potential evapotranspiration (ET_0), near-surface soil moisture (θ) at the 0.15-m (red dots) and 0.30-m (blue dots) soil depths, soil matric pressure head (ψ) at the 0.15-m (red dots) and 0.30-m (blue dots) soil depths, and battery voltage recorded by one sensor unit (Box no. 03) in the MFC2 catchment from March 2016 to May 2018.

In each of these subcatchments, one cosmic-ray neutron probe complements the SoilNet network, providing area-average soil moisture for a footprint of approximately 15 to 20 ha on the basis of fast neutron intensity measurements (Romano, 2014; Andreasen et al., 2017). To our knowledge, these two cosmic-ray neutron probes are the first installed in a catchment in central or southern Italy and have been operational for about 2 yr.

The plots of Fig. 8 compare the spatial-average near-surface values (at a depth of 0.15 m) of soil temperature, soil water content, and matric pressure head between the two sites. Spatial-average soil temperature is compared with air temperature (black line) at both sites. The highest soil temperature time series is recorded at MFC2, which is located on the south-facing hillslope, which is why evaporation from the soil surface at MFC2 may be higher than at GOR1. Spatial averages of θ and ψ diagnose significant seasonal trends, with soil saturation and desaturation dynamics during the wet and dry seasons, respectively. However, note that the MPS-6 sensor is unable to measure a matric pressure head ψ above −9.0 m of water (equal to a matric pressure of about −90 kPa). Hence precious information on the matric head near saturation conditions in the soil is lacking. We observe similar trends in spatial-average θ characterized by slow drying phases interrupted by wetting pulses. Obviously, the occurrences of rapid wetting processes are frequent when nearly all plants go dormant and soil saturation is around 0.4 $m^3\ m^{-3}$. In contrast, we detect strong differences between MFC2 and GOR1 in spatial-average matric pressure head values,

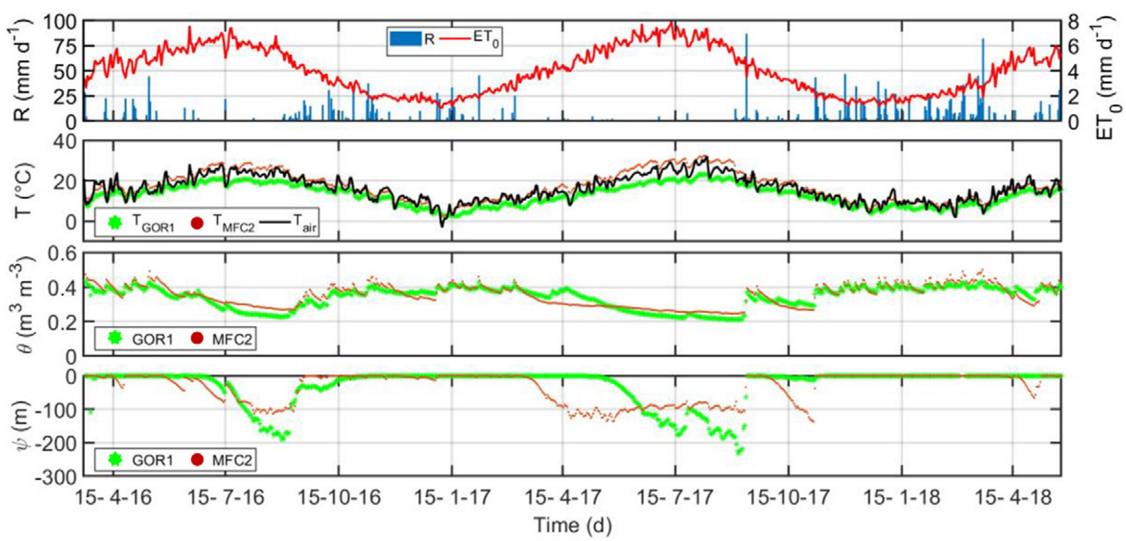

Fig. 8. Daily values of rainfall (R), reference potential evapotranspiration (ET_0), air temperature (T_{air}), spatial-average soil temperature (T), near-surface soil moisture (θ), and soil matric pressure head (ψ) (GOR1 and MFC2 subcatchments are indicated by green and red dots, respectively) from March 2016 to May 2018.

which are regulated by transpiration demand during the growing season. The cherry and walnut trees at MFC2 start transpiring in the early spring, whereas the chestnut trees delay the beginning of their growing season.

Another interesting aspect obtained from the recorded time series is the comparison between 2016 and 2017, the latter being characterized by a severe drought. The low θ values in 2017 extended their duration by several weeks. Closer inspection of daily spatial-average θ values at the depth of 0.15 m reveals interesting preliminary patterns. The plots of Fig. 9 clearly show that the empirical frequency distributions of θ values in both sites have bimodal features, which are in accordance with the findings of Vilasa et al. (2017) based on satellite observations. Identifying bimodal features in soil moisture observations is very useful input information for climate models.

The empirical frequency distribution can be suitably split into the four seasons (Fig. 10). Winter is dominated by wet atmospheric conditions and θ values are organized in normal distributions, similar at both sites. Spring represents a transition period from wet to dry and the response of θ values is slightly different between MFC2 (multimodal with a predominance of drier than average values) and GOR1 (normal with negative skewness). This different response could be dictated by the shift of the growing season, which starts in early spring at MFC2 and in early summer at GOR1. In summer, θ in both sites is exponentially distributed, with a preponderance of low θ values and few occurrences of wet soil conditions produced by episodic rainfall events. Fall represents the transition phase from dry to wet and prompts different responses between the two sites. Soil moisture values at MFC2 are normally distributed with negative skewness (a tendency to preserve drier than average soil moisture in some positions); in contrast, the probability distribution of θ values at GOR1 is bimodal.

The spatial average and spatial standard deviation of soil moisture depicted in Fig. 11 follow a nearly linear relationship that highlights increasing variability when approaching wetter conditions. However, the results of some studies concurred (Molina et al., 2014) and other contrasted (Mittelbach and Seneviratne, 2012; Rosenbaum et al., 2012) with this finding. Martínez García et al. (2014) generated synthetic relationships between the spatial average and spatial standard deviation of soil moisture through ensemble simulations by varying soil hydraulic parameters and climatic conditions. The soil moisture patterns under forest cover have systematically lower spatial variability compared with patterns observed under arable land cover.

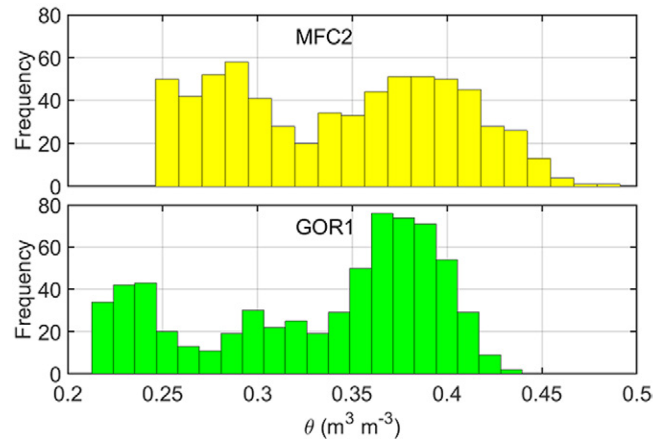

Fig. 9. Frequency distributions of near-surface soil moisture values at the MFC2 and GOR1 subcatchments.

Two networks of stand-pipe piezometers (2.5-cm inner diameter) will soon be installed in both MFC2 (13 piezometers) and GOR1 (six piezometers) by using dynamic penetrometer drilling and equipped with Micro-Diver sensors (Eijkelkamp Inc.) for continuous measurements of the groundwater level. Preliminary measurements showed the occurrence of a shallow groundwater table at MFC2, unlike at GOR1. The observed patterns of groundwater heights above mean sea level match the Mediterranean meteorological regime well, with its prolonged recession limb during summer until early fall, mainly due to dry conditions, and a recharge period starting in late fall (Fig. 12).

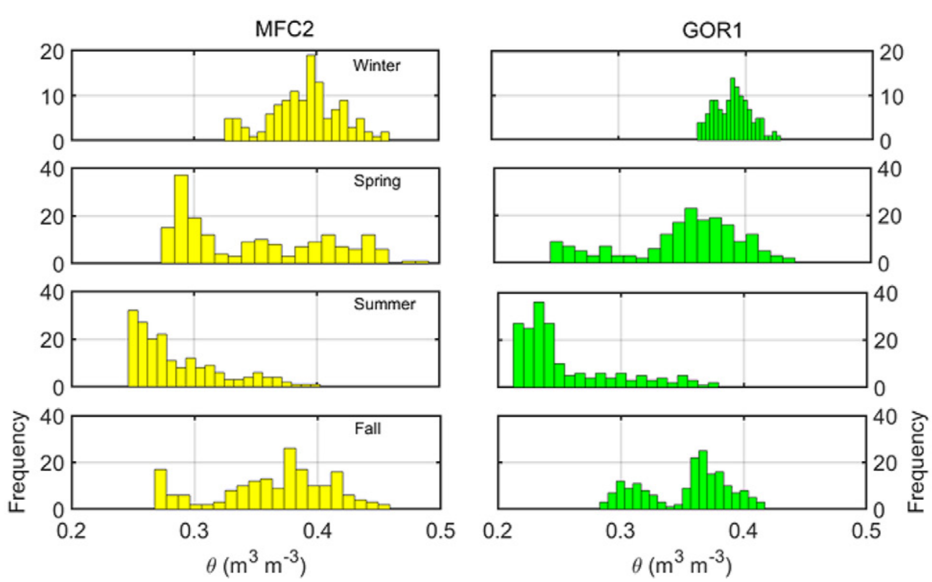

Fig. 10. Seasonal frequency distributions of near-surface soil moisture values at the MFC2 and GOR1 subcatchments.

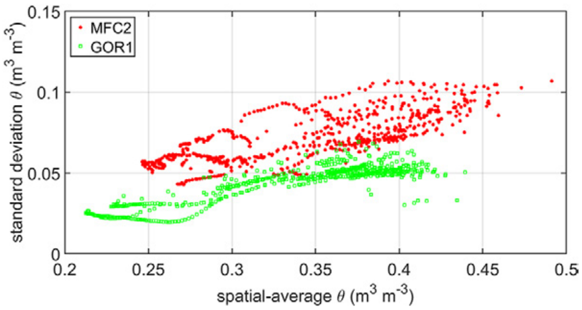

Fig. 11. Relationship between spatial average and spatial standard deviation of near-surface soil moisture (θ) at MFC2 and GOR1 subcatchments.

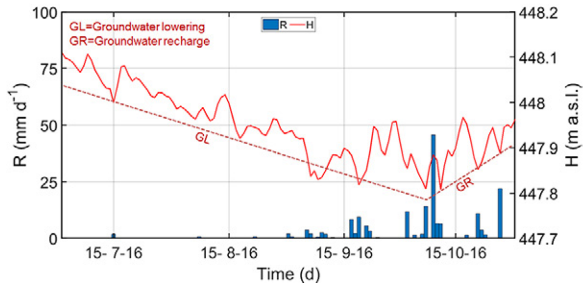

Fig. 12. Daily values of rainfall (blue bars) and water table level (red line) referenced to sea level at the MFC2 subcatchment from July to October 2016.

The GNIP Station at Piano Marra

In June 2016, the Piano Marra meteorological station (Perito village, UTM33 40.26862, 15.147093), managed by the Velia Bureau of Land Reclamation, became part of the Global Network of Isotopes in Precipitation (GNIP, http://www-naweb.iaea.org/napc/ih/IHS_resources_gnip.html) of the IAEA. Rainwater samples are collected on a monthly basis and analyzed for δD and δ^{18}O at CIRCE of the University of Campania "Luigi Vanvitelli" and for tritium at the IAEA Isotope Hydrology Laboratory. Ancillary data (e.g., air temperature and rainfall) collected by GNIP stations belonging to national networks are also supplied to the IAEA and included in a database. The overall objective of the GNIP is a systematic collection of basic spatial data on the isotope content of precipitation across global scales to determine temporal and spatial variations of both environmentally stable isotopes and tritium in rainfall to inform a range of scientific disciplines, including but not limited to hydrology, meteorology and climatology, oceanography and limnology, and studies related to the Earth's water cycle and climate. Recently, the GNIP has played an important new role in facilitating novel isotope research in ecological investigations, food authentication and traceability, as well as forensic issues (Rozanski et al., 1993; Vodila et al., 2011). Figure 13 shows δD vs. δ^{18}O values measured in cumulative rainwater samples collected at the Piano Marra station. The data points are plotted against the Global Meteoric Water Line ($\delta D = \delta^{18}O \times 8 + 10$). The fitting (dotted) line can be considered a first estimate of the Local Meteoric Water Line, which is site specific (Vodila et al., 2011).

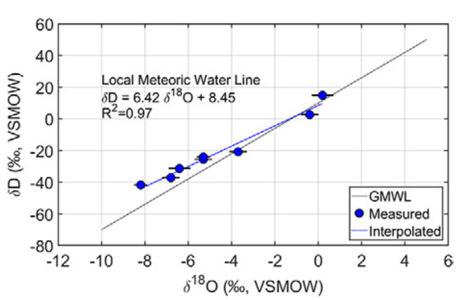

Fig. 13. Plot of δD vs. δ^{18}O measured in cumulative rainwater samples collected monthly from June 2016 to January 2017 at the Global Network of Isotopes in Precipitation (GNIP) station at Piano Marra (Perito, Salerno, Italy) and based on Vienna Standard Mean Ocean Water (VSMOW). The least squares regression line represents the Local Meteoric Water Line. The graph also shows the Global Meteoric Water Line (GMWL; $\delta D = 8 \times \delta^{18}O + 10$).

Data Management and Policy

The Alento CZO, together with the Picassent (Spain) and Thessaly Basin (Greece) observatories, was recently considered part of the TERENO (TERrestrial ENvironmental Observatories) network (Zacharias et al., 2011; Bogena et al., 2012) for dedicated research in the Mediterranean region (Hohlfeld, 2016; http://teodoor.icg.kfa-juelich.de). The acquired environmental data will be available to the scientific community through the TERENO data portal TEODOOR (www.tereno.net). The state-of-the-art sensor network will offer integrated and robust datasets for future project calls within the European Union research funding programs.

The Alento CZO has the potential to be fruitfully integrated with additional advanced instrument clusters by exploiting future funding opportunities so as to enrich the quality and quantity of data availability (Zaslavsky et al., 2011). To this end, MOSAICUS (MOnitoring and modeling Soil–vegetation–atmosphere processes in the Alento river basin for Implementing adaptation strategies to Climate and land USe changes) serves as a sort of recipient of a combination of background studies and various types of projects (funded also by different organizations). Therefore, MOSAICUS manages all of the datasets more efficiently and facilitates data sharing among different research units. To advance in this effort, interactions are of paramount importance with public agencies, small- and medium-sized enterprises, and stakeholders. Among the former bodies, a fruitful collaboration is active with the Velia Bureau of Land Reclamation, which is a public institution undertaking as its prime duty the design, operation, and maintenance of irrigation networks, the reservoir storage system, and the different types of engineering structures for soil and environmental protection.

Future Perspectives

The Mediterranean region has pronounced climate seasonality, a large variety of soils and land uses, and complex situations of confined and unconfined aquifers. Therefore, there is a growing need to identify the dominant hydrological processes with reliable accuracy to transfer knowledge to stakeholders, food chain partners, and land use planners. To date, monitoring programs and field campaigns performed at the Alento CZO have provided interesting insights at fine spatial scales (plot to field to hillslope scales), but the main challenge in the near future is to provide environmental diagnostics at large scales (catchment scale) to serve policy decisions efficiently.

Therefore, more effort will be devoted to integrating past and future findings within a general framework by shedding light on the scale transfer of hydrological processes. Multidisciplinary research will be based on the implementation and operation of state-of-the-art ground-based and airborne-based sensor platforms to develop a "sensors net" approach for "smart" management of land and water resources in a typical ecosystem of the Mediterranean region. For example, remote sensing technologies will be exploited for measuring soil attributes that are used as input to estimate the soil hydraulic properties via pedotransfer functions. This breakthrough will be possible by planning direct measurements of the visible-near infrared through satellite or unmanned aerial system based hyperspectral imagery. Furthermore, our view is that monitoring activities should always be interwoven with advanced modeling approaches so as to better frame the dynamics of the hydrological processes under study and also quantify associated uncertainties (Romano et al., 2012).

In the near future, the MOSAICUS program is expected:

- to contribute to the development of a range of plausible scenarios and the selection of adaptation and management strategies at various scales;
- to provide reliable and cost-effective diagnostic tools (advanced monitoring equipment, upgraded agro-hydrological models, etc.) for better managing fairly dense information and modeling approaches;
- to provide sustainable and environmentally friendly and health-promoting technologies, creating opportunities such as "green" jobs;
- to positively impact the educational and public awareness programs that encourage healthy behaviors and provide information on opportunities for interventions.

With its improved sensing and integrated modeling of the Critical Zone, MOSAICUS will greatly contribute to effectively address the multifaceted challenges in the Mediterranean area like floods, fires, and especially water scarcity conditions often exacerbated by droughts.

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