Evaluating flow regime alterations due to point sources in intermittent rivers: A modelling approach

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Abstract

Hydrological regime alterations may strongly influence river morphology, water quality, and river ecosystem. The present paper aimed to define an integrated modelling framework for analysing the hydrological regime alterations induced by point sources (PSs) discharges in data-limited regions through two case studies: the Canale d'Aiedda (Italy) and Nil wadi (Algeria). Long time series of daily streamflow in un-impacted and impacted (PSs discharges) conditions were generated by applying the Soil and Water Assessment Tool model and the hydrological regime was characterised by using several hydrological indicators. Flow regime alterations due to PSs were assessed with the range of variability approach. Results showed that the PSs induced alterations of some flow regime components (magnitude, duration, and timing). Hydrological regime classification of the river reaches receiving wastewaters from PSs shifted from intermittent to perennial. All the components of the low flow (1-, 3-, 7-, 30-, and 90-day minimum flow, zero-days) and the monthly flow recorded in summer were severely altered. Minor hydrological alterations were assessed for high flow components (1-, 3-, 7-, 30-, and 90-day maximum flow) and mean monthly flow in the wet period. The timing of minimum flow was found to shift later in the year. This study may support river ecologists in the ecological status evaluation.

Introduction

Non-perennial rivers and ephemeral streams (NPRSs) constitute the dominant freshwater types in Mediterranean regions (Datry *et al*., 2017). Unlike perennial rivers, NPRSs are characterised by the absence of streamflow for a certain period of the year over the whole river network or only in part of it.

The spatio-temporal patterns of streamflow within a basin depend on climate, lithology, geology, soil permeability, land cover, watershed size, and shape (Gallart *et al*., 2012; Arthington *et al*., 2014; Costigan *et al*., 2017, Beaufort *et al*., 2019, Zimmer *et al*., 2020). In addition, anthropogenic activities such as dam operations, water abstractions from river and groundwater, land use management (*i.e*., afforestation and deforestation), and point source discharges (PSs) may reduce or increase the river flow (De Girolamo *et al*., 2017) altering the natural flow regime. Hence, perennial rivers may turn into NPRSs, and NPRSs can become perennials depending on hydrological pressures (Hassan and Egozi, 2001; Skoulikidis *et al*., 2011; Datry *et al*., 2014).

The hydrological regime strongly influences ecosystem services (Pastor *et al*., 2022) and several processes such as river morphology, groundwater, and surface water interactions, sediment and nutrient delivery, and water quality (Arthington, 2014; Wohl *et al*., 2015; Gallart *et al*., 2016; Fortesa *et al*., 2021). Many studies have pointed out that NPRSs provide habitats for freshwater species, which result dynamically variable depending on wet-dry cycles (Poff *et al*., 1997; Larned *et al*., 2010; Datry *et al*., 2014; Prat *et al*., 2014). The diversity, spatial arrangement, turnover, and connectivity of these habitats are controlled by the amplitude, frequency, and duration of drying events (Stanley *et al*., 1997; Bunn *et al*., 2006; Bonada *et al*., 2007). Hence, altering the natural flow regime may strongly influence the river ecosystem (Stubbington *et al*., 2020).

Several studies analysed the flow regime alterations due to dam operation or flow diversions (Richter *et al*., 1997; De Girolamo *et al*., 2015b); meanwhile, there are no case studies in the literature that have analysed or quantified the impact of PSs on flow regime in ungauged basins with NPRSs. Nevertheless, the PSs may constitute critical pressures for NPRSs that can severely impact flow regime and water quality due to the limited dilution effect (D'Ambrosio *et al*., 2020).

Flow regime alterations due to human pressures are generally assessed by comparing flow regime components before and after the impacts (Richter *et al*., 1997). At this aim, several hydrological indicators (HIs) were developed (Richter *et al*., 1996) that can describe all the components of the flow regime. HIs are widely used for the eco-hydrological classification of rivers (D'Ambrosio *et al*., 2017), assessing hydrological alterations, and for designing the environmental flow (Richter *et al*., 1997). However, for a river reach, HIs are calculated based on daily streamflow recorded over a long period (*i.e*., 20 years) in order to include the inter-annual variability of streamflow (Richter *et al*., 1997). This may constitute a limitation, especially in the Mediterranean Region, since several basins are ungauged (Pagano *et al*., 2020; Tramblay *et al*., 2021). In addition, the pre-impact rarely has been monitored since the available stream gauges are often located on streams already altered by human activities (Zimmer *et al*., 2020). Indeed, in the past decades, NPRSs were generally excluded from the monitoring plans and environmental policy and management (Nikolaidis *et al*., 2013).

The lack of data can be overtaken using modelling approaches and free and accessible databases for their setup (D'Ambrosio *et al*., 2017). In particular, eco-hydrological models such as the Soil and Water Assessment Tool (SWAT) (Arnold *et al*., 1998) allow to simulate hydrological processes in natural and impacted conditions and to generate long daily streamflow time series that are used for assessing HIs and the hydrological alteration due to human pressures (De Girolamo *et al*., 2015a, 2017). Although the SWAT model was developed for simulating hydrological processes in ungauged river basins (Arnold *et al*., 1998), in NPRSs, the calibration assumes great importance, especially in eco-hydrological studies that focus on the low flow or absence of streamflow. When time series of streamflow are unavailable or data quality is poor (*e.g*., short time series, high rate of missing data), specific strategies have to be adopted to calibrate models. At this aim, easy streamflow monitoring methods (*e.g*., float method) (De Girolamo *et al*., 2022), satellite images, interviews, pictures of the stream (Gallart *et al*., 2016), and smartphone apps (Kampf *et al*., 2018) can be used for monitoring streamflow and identifying the dry period. In addition specific calibration strategies such as a splint-in-space approach or the use of the entire dataset for calibrating the model may be adopted to reduce the uncertainty associated with the model results (D'Ambrosio *et al*., 2020).

This study aimed to define an integrated modelling framework for analysing the hydrological regime alteration induced by PSs discharging into NPRSs in data-limited regions. The methodological approach was tested in the Canale d'Aiedda and Nil wadi basins, located in Italy (Apulia Region) and Algeria (Jijel province). The specific objectives were: i) to generate long period daily streamflow data both in un-impacted and impacted (PSs discharges) conditions by applying the SWAT model; ii) to characterise the hydrological regime by using proper HIs both in un-impacted and impacted conditions; iii) to assess the alteration due to PSs discharging into NPRSs.

The study results provide useful information to river ecologists who have to estimate the ecological status of NPRSs and to river basin managers who have to design a program of measures to reach the goal of good ecological status for all water bodies.

Study areas

Two Mediterranean basins with intermittent river networks were analysed: the Canale d'Aiedda, located in Southern Italy (Puglia Region, Figure 1A), and the Nil wadi, located in North East Algeria, within the territory of the province of Jijel (Figure 1B). In both basins, the river network has an intermittent regime, with most of the headwater reaching dry in summer and permanent in the final stretch of the main river course.

Canale D'Aiedda basin

The Canale d'Aiedda drains an area of 222 km^2 (Figure 1A); however, the total surface area (360 km^2) includes, in the eastern and the northern parts, limestone, sinkholes, and caves which do not contribute to surface runoff (D'Ambrosio *et al*., 2019). Clayey, silty-sandy, and arenitic units are the dominant lithology of the central and the lower parts, which are morphologically depressed and subject to flooding during particularly intense rain events (Guerricchio and Simeone, 2013). The main channel is 29 km long with an average slope of 0.84%. The elevation ranges from 0 to 381 m a.s.l. (Figure 1A). The stream network, predominantly channelised (D'Ambrosio *et al*., 2019), flows into the Mar Piccolo, an inner, semi-enclosed sea basin connected to the open sea (Ionian Sea) through two channels. Close to the outlet, there is an important wetland (Palude la Vela), protected at the European level as it belongs to the 'Mar Piccolo' Site of Community Importance (SIC-IT9130004).

The climate is typically the Mediterranean, with humid winters and hot, dry summers. The average annual precipitation is 621.5 mm year^{-1}, and the average monthly maximum and minimum temperatures are, respectively, 32.1°C for July and 5.4°C for January, according to data from the Grottaglie meteorological station (1920 to 2012) (40°31'12'N; 17°24'0'E). Rainfall is generally concentrated between October and March. The distribution of the precipitation significantly differs between the mountain (855.9 mm) and the plain (576.2 mm) areas. These conditions lead to high spatial variability of the precipitation regime, affecting the basin's hydrology. The hydrological regime is intermittent, characterised by extreme low flow or total absence of flow in summer and high flow in spring and winter (D'Ambrosio *et al*., 2019).

The agricultural land uses are vineyard (36.3%), olive grove (24.5%), and durum wheat in rotation with aromatic herbs and fallow (28.1%). Water abstraction from groundwater is used to irrigate vineyards and olive groves. Breeding farms are limited in the northern part of the study area. Natural land uses are composed of holm oak and coniferous forests (2.7%), Mediterranean maquis (2.4%), and bushes (0.9%). These areas mainly belong to the regional park and forest reserve (*e.g*., Terra Delle Gravine, Bosco Delle Pianelle) (D'Ambrosio *et al*., 2020). Urban areas are limited to medium-sized towns, surrounded by extensive forms of agriculture. Three wastewater treatment plants (WWTPs) - Montemesola (W1), Monteiasi (W2), and San Giorgio Ionico (W3) (Figure 1A; D'Ambrosio *et al*., 2019) discharge their sewage into the river.

To assess the degree of alteration of the hydrological regime and the consequent environmental impact of the WWTPs, a monitoring plan was implemented by installing two automatic gauging stations (MDS Dipper-PT, ©2019 Seba Hydrometrie, Kaufbeuren, Germany) located in two sections of the hydrographic network downstream the PSs (Figure 1A). Specifically, the two measurement stations are station A, 'Canale Cicena' in the municipality of San Giorgio Jonico, and station B, 'Canale d'Aiedda' in the same municipality. More information about the monitoring equipment can be found in D'Ambrosio *et al*. (2019) and De Girolamo *et al*. (2019).

Nil wadi basin

The Nil wadi river has a total drainage area of 304.22 km^2, five sub-basins constitute it: Nil (175.75 km^2), Boukaraa (60.79 km^2), Saayoud (38.60 km^2), Tassift (16.03 km^2), and El-Kennar swamp (13.05 km^2) (Mahdid *et al*., 2015). The basin is constituted by the alluvial filling of an ancient valley dug in the Eocene marls in the West and the metamorphic grounds in the East. On these alluviums, recent dune formations such as that El-Kennar are deposited (Ehrmann, 1928; Baghdad *et al*., 2017). Soils are sandy-clay and marly, sandy and alluvial with pebbles and gravel. The main channel (35 km) has an average slope of 2.98% and shows mostly a natural pattern; it flows in the Mediterranean Sea near El Kennar municipality. The elevation ranges from 0 to 1510 m a.s.l.. This region is one of the rainiest areas of Algeria. It is subject to the Mediterranean climate, which is characterised by hot and dry summers alternated with cold and humid winters. The average annual rainfall, registered by the Achouat meteorological station (1988 to 2015) (36°47'39.4'N, 5°52'41.2'E), is approximately 1000 mm year^{-1}. Rainfall is generally concentrated between October and April, with an average of 796 mm year^{-1}. The remaining months instead have an average rainfall of 206 mm year^{-1}. Maximum and minimum monthly temperatures are 28.1°C (August) and 13.4°C (January), respectively. The Nil wadi basin is dominated by natural land uses (mixed forest alternated with rangeland), which are mainly localised in the upstream parts of the basin and cover 57% of the basin's total area. The sewerage network only covers the main towns and some secondary cities. Wastewater is discharged through septic tanks for the rest of the Nil wadi watershed. Seven urban point sources discharge in the Nil wadi, constituting important hydrological and water quality pressures (Figure 1B).

In recent decades, streamflow has not been monitored. To carry out the present study, streamflow measurements have been conducted since October 2019 using the float method at the river sec-

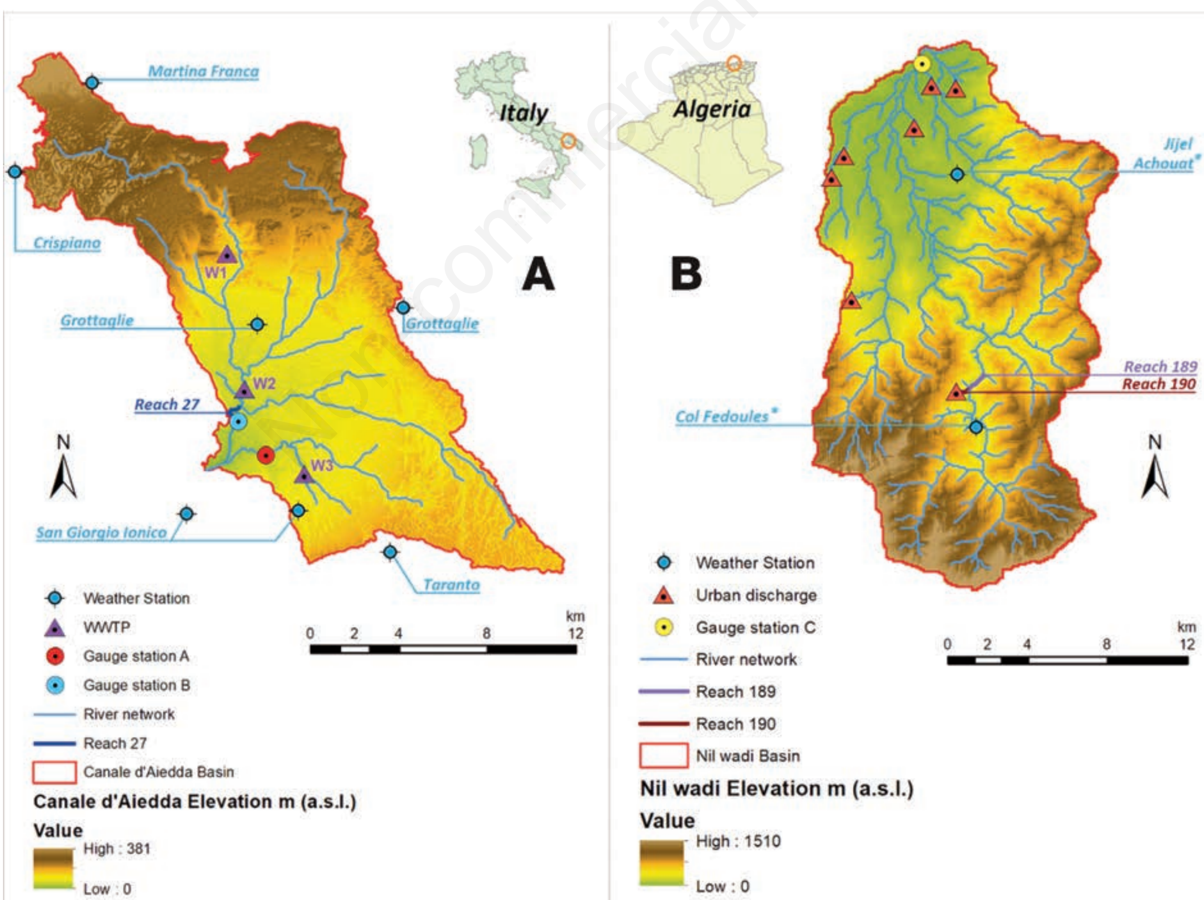

Figure 1. Study areas: A) Canale d'Aiedda (Italy); B) Nil wadi (Algeria).

tion, called hereafter station C, located near El-Kennar city (Figure 1B). This method is simple and has uncertainties of around ±10% (Rantz, 1982). During the monitored period (October 2019 and December 2020), the values of streamflow ranged from 115 m^3s^{-1} (winter) to 0.1 m^3s^{-1} (summer) (Drouiche *et al.*, 2021). The flow measurements were made at the daily time step during rainy episodes and with a different time step between floods (2 to 6 days). More information about the monitoring equipment can be found in Drouiche *et al*. (2021).

Materials and methods

Modelling streamflow

The SWAT is one of the most used semi-distributed hydrological models, developed by the United States Department of Agriculture, Agricultural Research Service (USDA-ARS) (Arnold *et al*., 1998) to simulate streamflow, sediment, and nutrient loads in ungauged river basins (Arnold *et al*., 2012a). Bezak *et al*. (2021) pointed out that SWAT applications involve many scientific fields such as hydrological, soil sciences, forestry, and territorial planning and management.

In the present work, SWAT version 2015 was used to generate time series of un-impacted and impacted daily streamflow (20-years) in the Canale d'Aiedda and Nil wadi basins. First, the impacted conditions of streamflow were simulated, including PSs discharges as inlets into the river network. The un-impacted conditions were simulated, excluding the PS contributions (Figure 2). Finally, the surface runoff was estimated by using the modified Soil Conservation Service-Curve Number method (USDA-SCS, 1972) and the Hargreaves method for evaluating potential evapotranspiration (PET) (Hargreaves, 1975). The latter has proved effective in being applied in geographical regions characterised by a Mediterranean climate. Neitsch *et al*. (2011) and Abdelwahab *et al*. (2018) reported more theoretical information on the SWAT model.

Model configuration

SWAT requires several input data to be correctly implemented, such as land use, soil profile and characteristics, digital elevation model, and weather (Arnold *et al*., 2012a). For the Canale d'Aiedda and the Nil wadi input data were obtained from different sources (Figure 2, Table 1); they were suitably processed and then included in the SWAT geodatabase as reported in D'Ambrosio *et al*. (2019).

The Canale d'Aiedda was subdivided into 40 sub-basins by

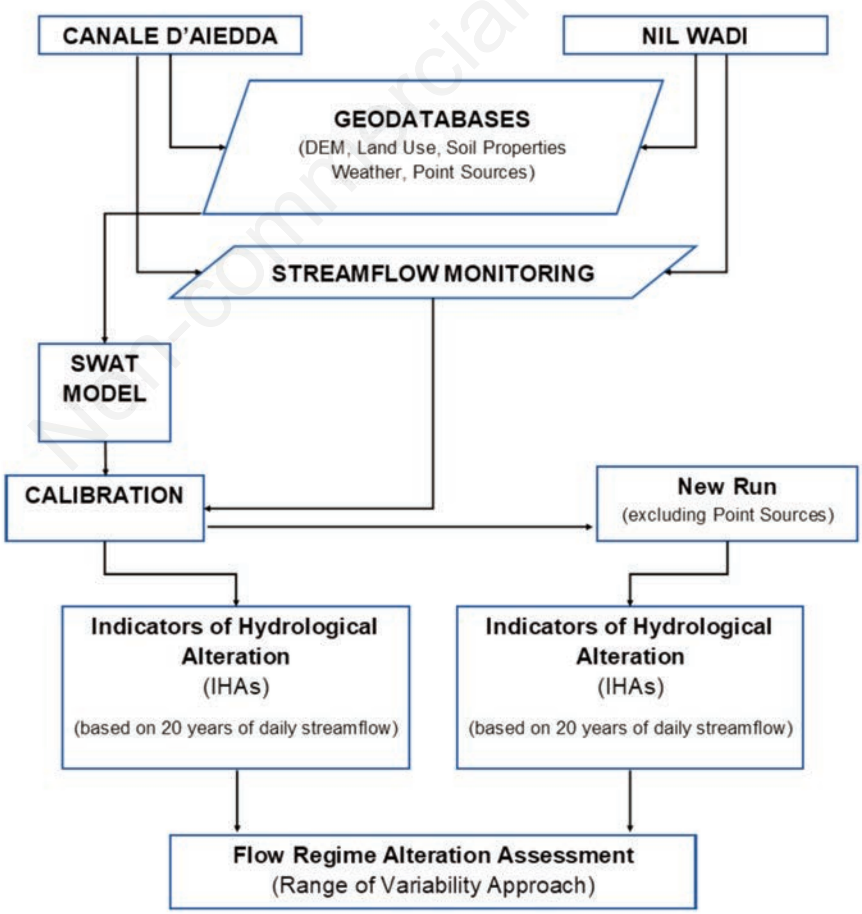

Figure 2. Methodological scheme of the study.

setting a threshold of 350 ha for drainage areas. Subsequently, the basin was further divided into 271 hydrological response units (HRUs) using percentage values of 10%, 10%, and 20% of land use, soil class, and slope, respectively (D'Ambrosio *et al*., 2019). Considering the small patches of land uses, the Nil wadi was subdivided into 298 sub-basins using a threshold of 50 ha. Moreover, 1074 HRUs were obtained using percentage values of 10%, 10%, and 20% of land use, soil class, and slope, respectively. From this operation, 23 land uses, among which vineyard, olive grove, and durum wheat were the main crops, and 12 soil types varying from silty clay to sandy loam characterised the Canale d'Aiedda basin. The Nil wadi was characterised by 12 land uses with a prevalence of forests, greenhouses, orchards, and five soil types ranging from clay to loam. Agricultural practices, including irrigation, were added to the management database for both basins using data retrieved from direct interviews and agricultural census.

SWAT was run at daily time step for the period 1997-2019, with 3 years of warm-up for the Canale d'Aiedda, while for the Nil wadi basin, the SWAT model was run at daily time step for the period 1991-2019, with 3 years of warm-up.

Model calibration

The SWAT model was calibrated for the Canale d'Aiedda basin using daily streamflow data recorded in two gauging stations (Figure 1A). The SWAT-CUP tool was used to carry out the sensitivity analysis and the calibration process through the Sequential Uncertainty Fitting (SUFI-2) algorithm (Abbaspour *et al*., 2015). The automatic procedure available in SWAT-CUP was applied, setting as objective function the Nash and Sutcliffe (1970) Efficiency (NSE) greater than 0.5 (D'Ambrosio *et al*., 2020). Daily streamflow (m^3s^{-1}), continuously measured from August 2017 to December 2019, showed different hydrological conditions (*i.e*., dry and wet). During the first year (from August 2017 to August 2018), only very small floods were recorded; meanwhile, in the second year, several large floods were recorded. Hence, to include the inter-annual variability (dry and wet conditions) in the calibration process and, to improve the robustness of the parameterisation, it was chosen to use the entire dataset for the model calibration (Ricci *et al*., 2018; Arsenault *et al*., 2018). In addition, to improve the calibration at the basin scale, a split-in-space strategy was adopted that considers the variability of the environmental factors among the sub-basins. For this aim, a specific calibration was carried out for each gauging station (A and B, Figure 1A), where streamflow measurements were recorded (D'Ambrosio *et al*., 2020).

In the Nil wadi basin, the limited data availability of measured streamflow available (discrete measurements from October 2019 to October 2020) (De Girolamo *et al*., 2022) did not allow the model validation (Arsenault *et al*., 2018). Therefore, the calibration was carried out manually, changing the most sensitive parameters one at a time. Model performances were evaluated using the coefficient of determination (R^2), NSE, and percent bias (PBIAS %).

The model generally overestimates the extremely low flow in intermittent rivers (De Girolamo *et al*., 2015a, 2015b); therefore, a procedure was defined to improve the extremely low flow simula-

Table 1. SWAT input data for the Canale d'Aiedda and the Nil wadi basins.

Input	Description
Canale d'Aiedda	
Digital Terrain Model (DTM)	Puglia Region, resolution, 8x8 m (http://www.sit.puglia.it)
River network	Hydro-geomorphological map and Regional Technical map (http://www.sit.puglia.it)
Land use map	Land Use Map (UDS) of Puglia Region (http://www.sit.puglia.it), resolution of 100 m. 23 land use classes
Soil database	Agro-ecological Characterisation of the Puglia Region ACLA2 (Regione Puglia, 2001), resolution 250×250 m. European Soil Data Centre (ESDAC) soil database, resolution 500×500 m (Tóth *et al*., 2013); 9 soil profiles
Point sources	Environmental Regional Agency for the Prevention and Protection of the Environment Ground-water (ARPA), wastewater treatment plant discharges monitoring database (http://www.arpa.puglia.it) Acquedotto Pugliese, mean annual volumes of treated sewage for each plant. 3 WWTPs
Meteorological data	Civil protection of Puglia Region (http://www.protezionecivile.puglia.it) and Regional agency for irrigation and forestry activities (ARIF) (https://www.arifpuglia.it). 18 meteorological stations, 7 considered by the model. Daily data: precipitation, solar radiation, wind speed, relative humidity, min. and max. temperature
Agricultural practices	Farmers' and dealers' interviews were used (D'Ambrosio *et al*., 2019)
Nil wadi	
Digital Terrain Model (DTM)	Digital Elevation Model (DEM) of Algeria, The NASA Shuttle Radar Topographic Mission (SRTM) (https://earthexplorer.usgs.gov/ and http://120.27.60.193/SRTM/Africa/), 30×30 m
Land use map	Land Use Map (UDS) of Geological Engineering Laboratory (LGG). UDS of European Space Agency (ESA) - Climate Change Initiative (https://www.esa-landcover-cci.org), resolution 20×20 m. 12 land use classes were identified throughout the basin
Soil database	International Soil Reference and Information Centre (ISRIC) (https://www.isric.org/projects/soil-property-maps-africa-250-m-resolution). Resolution 250×250 m 5 soil profiles
Point sources	Geological Engineering Laboratory (LGG). United Nations Environmental Programme (UNEP) data on wastewater treatment plants discharge. 7 WWTPs
Meteorological data	Geological Engineering Laboratory (LGG), Weather history for the whole world (https://www.historique-meteo.net/), Global Weather Data for SWAT (National Centers for Environmental Prediction) (https://globalweather.tamu.edu). 2 gauging stations. Daily data: precipitation, solar radiation, wind speed, relative humidity, min. and max temperature
Agricultural practices	Geological Engineering Laboratory (LGG) data. Specific data of agronomic books. Satellite image analysis

Table 2. Selected indicators of hydrological alterations (IHAs) that are representative of the non-perennial rivers and streams (NPRSs) hydrologic regime: magnitude, duration, and timing.

Flow regime component	Name	Description
The magnitude of annual water condition	Mean annual flow	Average annual flow (m^3s^{-1})
Magnitude and timing of monthly water condition	January, February, …, December mean flow	The magnitude of monthly flow
Magnitude and duration of annual extreme water conditions	1-day min, 3-day min, 7-day min, 30-day min, 90-day min flow 1-day max, 3-day max, 7-day max, 30-day max, 90-day max flow	Annual minimum flow of 1-3-, 7-, 30-, 90-day duration (over consecutive days) Annual maximum flow of 1-3-, 7-, 30-, 90-day duration (over consecutive days)
Magnitude	Baseflow index	7-day minimum flow/mean flow for the year
Duration	Zero-days	Number of days per year with zero daily flow
Timing of annual extreme water conditions	Date of min Date of max	Julian date of annual minimum flow Julian date of annual maximum flow

Richter *et al*., 1996; The Nature Conservancy, 2009.

tion. First, a zero-flow threshold (actual no flow) was identified for the analysed river reaches. For the Canale d'Aiedda, field surveys were periodically carried out to identify the absence of streamflow along the river network. For the Nil wadi, historical satellite images from 2007 to 2020, available in Google Earth Pro (Google Earth Pro, 7.3.4.8248), were used to identify the periods during which the river network was completely dry. About 50 clear images (*i.e*., without clouds cover) of the river network were extracted, and the presence or the absence of flow was visually analysed.

When the analysed reaches were found dry for both basins, the correspondent simulated streamflow values were extracted, and their average was assumed as the zero-flow threshold. The time series of simulated streamflow were modified by subtracting the zero-flow threshold. When the subtraction gave negative results, the streamflow was set to zero. De Girolamo *et al*. (2022) reported the methodology adopted to identify the zero-flow. In order to simulate the un-impacted flow regime, a new simulation was carried out in both river basins, excluding the contribution of the PSs.

Assessing anthropogenic impacts by means of hydrological indicators

The flow regime alterations due to PSs and WWTPs' discharge were assessed employing a number of HIs having ecological relevance (Richter *et al*., 1996; Poff *et al*., 1997; D'Ambrosio *et al*., 2017). The HIs are able to characterise the hydrological regime in the un-impacted and impacted conditions. In the present study, the HIs describing the magnitude (amount of water flowing per time unit through a fixed position), duration (period associated with a specific flow condition), and timing (regularity with which flows of a defined magnitude occur) were analysed (Table 2). These HIs were chosen based on their representativeness for NPRSs (Olden and Poff, 2003; D'Ambrosio *et al*., 2017). The 'indicators of hydrologic alteration (IHA)' software developed by the US Nature Conservancy was used for this purpose (The Nature Conservancy, 2009).

In order to include the variability of the flow regime, the HIs were computed based on 20-years of daily streamflow (Figure 2) both in un-impacted and impacted conditions (Richter *et al*., 1997).

Table 3. Hydrological alteration classes values.

Hydrological alteration (HA)	Values
Low	<0.33
Moderate	0.34-0.67
High	>0.67

Richter *et al*., 1996; The Nature Conservancy, 2009.

HIs were computed for a river section downstream of the WWTPs for Canale d'Aiedda (Reach 27; Figure 1A) and for two river sections along the Nil wadi (Reach 189, and Reach 190; Figure 1B), which are located downstream of the waste discharge inflow and downstream of the first confluence with the main course of the Nil wadi, respectively.

The hydrological alterations were evaluated using the range of variability approach (RVA; Figure 2) (The Nature Conservancy, 2009). The RVA allows estimating the extent to which flow regimes have been altered (Richter *et al*., 1997). To do this, the full range of variability of each HIs in the un-impacted condition is divided into three classes of equal size, with the boundaries between classes as a number of standard deviation (SD) away from the mean. In this work, it was assumed the 'Low RVA category' (values < Mean-SD), the 'Middle RVA category' (Mean –SD < values < Mean + SD), and the 'high RVA category' (values > Mean + SD). For each class, the hydrological alteration (HA) value is computed with Equation 1.

$$HA = \frac{(impacted\ frequency - un\text{-}impacted\ frequency)}{un\text{-}impacted\ frequency} \quad (1)$$

A positive hydrological alteration value indicated that the frequency of values in the category was increased from the un-impacted to the impacted conditions. The threshold values assumed to identify low, moderate, and high alterations are reported in Table 3.

Results

SWAT model calibration results

The hydrological parameters modified in the calibration at gauges A, B, and C, their initial values, and the best-fitted values are summarised in Table 4. The split-in-space strategy adopted for the Canale d'Aiedda provided two different sets of fitted parameters, referred to as sub-basins upstream gauge A and gauge B, respectively. To ensure the spatial variability of some parameters (*i.e.*, CN2, SOL_Z, and SOL_AWC), their initial value was modified by multiplying the initial value for a fixed coefficient in the SWAT-CUP automatic procedure (Table 4). For the Nil wadi model simulation, all the selected parameters were manually modified to fit the measured streamflow at gauge C (Table 4).

Results of the daily streamflow calibration for the Canale d'Aiedda showed that NSE and R^2 were close to the satisfactory threshold (0.5) for gauge A and good for gauge B (Table 5), assuming the criteria defined by Moriasi *et al*. (2007) that are valid for

Table 4. Calibrated parameters for the best fit simulation at the gauge A and B (Canale d'Aiedda) and gauge C (Nil wadi).

Parameter	Description	Initial values (A, B)	Best fit (A)	Best fit (B)	Initial values (C)	Best fit (C)
EVRCH.bsn	Reach evaporation adjustment factor				1	0.1
TRNSRCH.bsn	Fraction of transmission losses from main channel that enter deep aquifer	0	0.499	0	0.15	
CN2.mgt	Initial SCS curve number for antecedent moisture condition (AMC) II	63.7-89.2	–0.327*,°	–0.316*,°	62-95	68-86*
CH_K2.rte	Effective hydraulic conductivity in main channel alluvium (mm hr^{-1})	0	9.824	6.110	6.5	0
CH_N2.rte	Manning's 'n' value for the tributary channels				0.014	0.3
CH_K1.sub	Effective hydraulic conductivity in tributary channel alluvium (mm hr^{-1})	0	120.012	53.205	0	4
CH_N1.sub	Manning's 'n' value for the tributary channels				0.014	0.3
SOL_Z.sol	Depth from the soil surface to bottom of layer (mm)	400-2000	–0.069*,°	–0.316*,°		
SOL_K.sol	Saturated hydraulic conductivity (mm hr^{-1})	0.065-27.8	0.123*,°	0.196*,°	1.38-19.06	2.9-13.34*
SOL_AWC.sol	Available water capacity of the soil layer (mm H_2O mm $soil^{-1}$)	0.097-0.13	–0.097*,°	0.374*,°	0.09-0.13	0.077-0.091*
GW_DELAY.gw	Groundwater delay time (d)	31	69.926	59.633	31	0
GWQMIN.gw	Threshold water depth in the shallow aquifer required for return flow to occur (mm H_2O)				1000	0.1
GW_REVAP.gw	Groundwater 'revap' coefficient				0.02	1
RCHRG_DP.gw	Deep aquifer percolation fraction.	0.05	0.379	0.945	0.05	0
REVAPMN.gw	Threshold depth of water in the shallow aquifer above which the water movement from the shallow aquifer to the unsaturated zone is allowed	750	448.932	847.346	750	500
ALPHA_BF.gw	Baseflow alpha factor (1/days)				0.048	1
CANMX.hru (GRBN)	Herbage maximum canopy storage (mm)	0	1.738	1.109		
CANMX.hru (OLIV)	Olive maximum canopy storage (mm)	0	2.185	2.969		
EPCO.hru	Plant uptake compensation factor	1	0.379	0.746	0.8	1
ESCO.hru	Soil evaporation compensation factor				0.950	0.01
OV_N.hru	Manning's 'n' value for overland flow				0.14	0.1-0.6
BIOMIX.mgt	Biological mixing efficiency				0.2	0.2

*The initial CN2, SOL_Z, and SOL_AWC values depended on the land use and soil type. The adjustment slope factor was considered (Neitsch *et al*., 2009); °the indicated values refer to the coefficient for which was multiplied by the existing parameter values through the SWAT-CUP 'relative' methodology.

Table 5. Model performances for daily calibration.

Statistical index	Canale d'Aiedda		Nil wadi
	Gauge A	Gauge B	Gauge C
NSE	0.47	0.71	0.35
R^2	0.48	0.72	0.40
PBIAS (%)	–4.21	5.05	24.12

monthly time step simulations (satisfactory: R^2 and NSE ≥0.5; PBIAS ≤ ±0.25). However, the streamflow was overestimated in gauge A (PBIAS –4.21) and underestimated in gauge B (PBIAS +5.05).

Model performances for daily streamflow calibration at the Nil wadi (gauge C) were satisfactory (Table 5) for PBIAS (+24.12), indicating underestimation but lower than the rating suggested by Moriasi *et al*. (2007) for NSE and R^2. However, these results were considered acceptable for regions characterized by a paucity of data (Zema *et al*., 2016). On the other hand, Arnold *et al*. (2012b) recommended adjusting the ratings based on the time step simulation, the quality and quantity of observed data, and depending on the project scope.

The SWAT model correctly simulated the main peaks in the Canale d'Aiedda; meanwhile, the normal flow was underestimated, and the low flow was generally overestimated (Figure 3A). Over the calibration period, the highest measured peak of flow (2.67 m^3s^{-1}) was slightly overestimated by the model (2.85 m^3s^{-1}).

For the Nil wadi basin, SWAT predicted the highest peak of flow recorded over the study period (Qobs=115 m^3s^{-1}; Qsim=118 m^3s^{-1}) but underestimated the normal flows overestimated the low flows (Figure 3B).

For Reach 27, the zero-flow threshold was 0.017 m^3s^{-1}. For the Nil wadi, the zero-flow was equal to 0.00 m^3s^{-1} for the Reach 189 and 0.005 m^3s^{-1} for the Reach 190. Time series of simulated daily streamflow were corrected by subtracting the zero-flow threshold for the impacted and un-impacted conditions before computing the HIs in the three river sections analysed in this work.

The water balance for the Canale d'Aiedda basin estimated by the model showed that the potential evapotranspiration (1186.7 mm) was relatively high compared to the precipitation (621.5 mm). As a result, the estimated surface runoff was 122.70 mm with a total water yield (Surface runoff + baseflow + lateral flow) of 152.24 mm, and the transmission losses were 43.07 mm due to the calcareous nature of the basin.

For the Nil wadi, the average annual rainfall over the study period was 1000.3 mm; 51.81% of the rainfall is lost via evapotranspiration (528.3 mm). Therefore, the average annual surface runoff was estimated at 235.1 mm, corresponding to 23.5% of the rainfall, and the average annual total water yield (surface runoff + baseflow + lateral flow) was 468.27 mm, which was equivalent to 46.81% of the rainfall.

Assessing the anthropogenic impact

The flow duration curves (FDCs) comparison between pre- and post-impacts showed that river reaches receiving inlets from the PS become perennial (Figure 4). In un-impacted conditions, a long absence of flow characterised the river Reach 27 and Reach 190.

The FDC of the Reach 27 (Canale d'Aiedda basin) assumed an extraordinarily sharp shape in extremely high flows (0-5%, Figure 4A) in un-impacted and impacted conditions. The divergence between

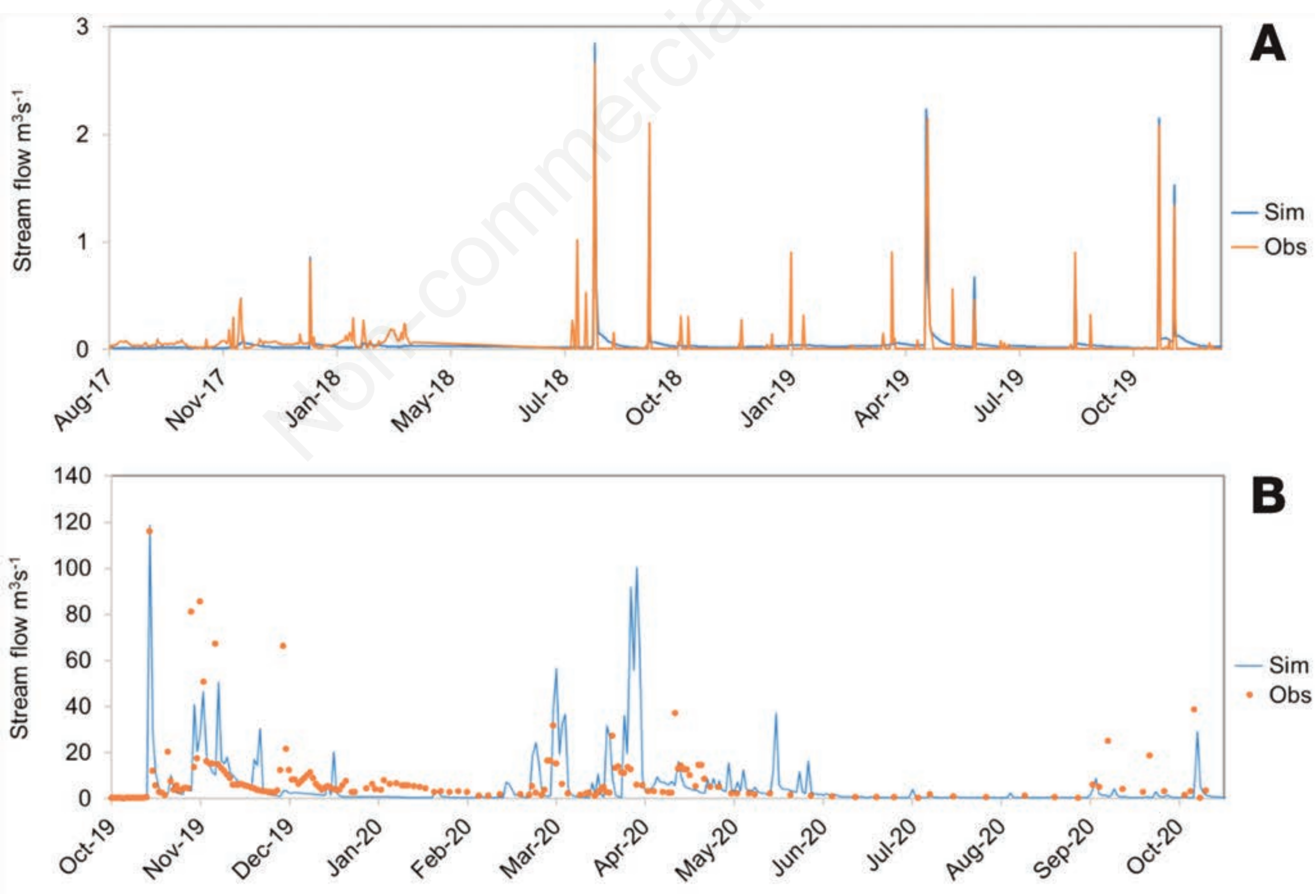

Figure 3. Simulated (Sim) and observed (Obs) streamflow: A) Canale d'Aiedda (Italy) Gauge B; B) Nil wadi (Algeria) Gauge C.

the two FDCs increased in concordance with the exceedance probability, suggesting alterations in flow regime after the impacts occurred in normal and low flow conditions. For impacted conditions, a gentle slope is observed in the FDC in the normal flow (20-40%), and in the low flow conditions, the FDC assumed almost constant values.

The FDCs of Reach 190 (Nil wadi) showed steep slopes in extremely high (0-5%) and high flow conditions (5-20%; Figure 4B). The divergence between the FDCs in un-impacted and impacted conditions increased in normal flow and low flow. The streamflow became constant in low flow conditions suggesting that the highest alteration degree occurred in the low flow components of the flow regime. For Reach 189, the FDCs (in un-impacted and impacted) slightly differed only in the low flow conditions (Figure 4C). This reach drained an area much larger than the Reach 190 (Figure 1B).

In impacted conditions, the mean annual streamflow simulated at Reach 27 and Reach 190 increased (37.5% and 100%, respectively); meanwhile, a negligible variation was simulated for Reach 189 (1.2%) (Table 6). The analysis of the flow regime components showed that the mean magnitude and duration of the high flow (1-, 3-, 7-day maximum flow, m^3s^{-1}) did not significantly change (Table 6) for the Reach 27 (1%-4%) and the Reach 190 (3%-10%), and it was negligible for the reach 189. Similarly, mean values of the 30-and 90-day maximum flow (m^3s^{-1}) increased at the Reach 27 (8%-15%) and the Reach 190 (22% to 41%); meanwhile, no significant

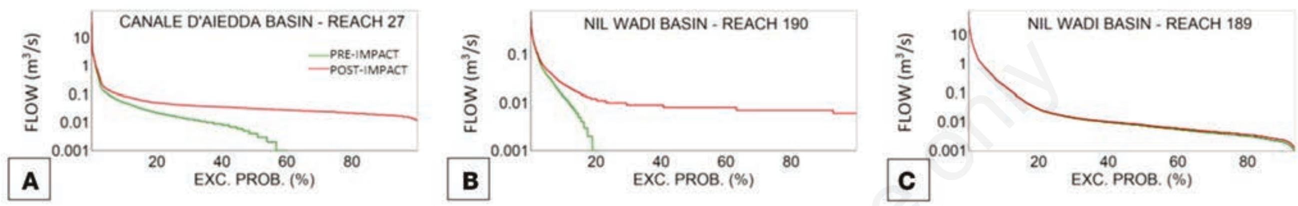

Figure 4. Flow duration curves concerning un-impacted (pre-impact) and impacted (post-impact) conditions. A) Canale d'Aiedda Reach 27; B) Nil wadi, Reach 190; C) Nil wadi, Reach 189.

Table 6. Mean annual values of the hydrological indicators (IHAs) estimated over 20-years in un-impacted and impacted (including point source discharges) conditions in the Canale D'Aiedda and Nil wadi basins and their rate of variation (% for magnitude and duration; days for timing). For the IHAs equal to 0 in un-impacted conditions, variation (%) was not determined (ND).

Group	Hydrological indicators	Canale D'Aiedda Reach 27			Nil wadi Reach 190			Nil wadi Reach 189		
		Unimpacted	Impacted	Var. (%) or days	Unimpacted	Impacted	Var. (%) or days	Unimpacted	Impacted	Var. (%) or days
Magnitude	Annual mean flows	0.080	0.110	37.5	0.010	0.020	100	0.820	0.830	1.2
	January mean flows	0.108	0.142	31.5	0.014	0.023	64.3	1.424	1.434	0.7
	February mean flows	0.040	0.071	77.5	0.021	0.030	42.9	1.987	1.997	0.5
	March mean flows	0.160	0.193	20.6	0.017	0.027	58.8	1.678	1.689	0.7
	April mean flows	0.016	0.045	181.3	0.016	0.025	56.2	1.542	1.552	0.7
	May mean flows	0.016	0.044	175	0.004	0.012	200	0.526	0.536	1.9
	June mean flows	0.008	0.034	325	0.001	0.009	800	0.288	0.299	3.8
	July mean flows	0.003	0.027	800	0.001	0.009	800	0.242	0.253	4.5
	August mean flows	0.017	0.042	147.1	0.000	0.008	ND	0.187	0.197	5.3
	September mean flows	0.162	0.194	19.8	0.001	0.009	800	0.269	0.280	4.1
	October mean flows	0.201	0.233	15.9	0.002	0.009	350	0.283	0.294	3.9
	November mean flows	0.141	0.174	23.4	0.007	0.015	114.3	0.706	0.717	1.6
	December mean flows	0.081	0.115	41.9	0.008	0.016	100	0.834	0.844	1.2
Magnitude and duration	1-day minimum flow	0.000	0.018	ND	0.000	0.007	ND	0.129	0.139	7.8
	3-day minimum flow	0.000	0.018	ND	0.000	0.007	ND	0.130	0.140	7.7
	7-day minimum flow	0.000	0.019	ND	0.000	0.007	ND	0.132	0.143	8.3
	30-day minimum flow	0.000	0.021	ND	0.000	0.007	ND	0.143	0.153	6.9
	90-day minimum flow	0.003	0.026	767.6	0.000	0.008	ND	0.170	0.180	5.9
	1-day maximum flow	14.490	14.640	1.1	0.341	0.351	2.9	26.130	26.150	0.1
	3-day maximum flow	5.512	5.641	2.3	0.177	0.188	6.2	14.080	14.100	0.2
	7-day maximum flow	2.584	2.687	3.9	0.101	0.111	9.9	8.333	8.344	0.1
	30-day maximum flow	0.693	0.748	7.9	0.045	0.055	22.2	3.999	4.010	0.3
	90-day maximum flow	0.255	0.294	15.2	0.022	0.031	40.9	2.048	2.058	0.5
	Number of zero days	146	0	-100	288	0	–100	0	0	ND
	Base flow index	0.001	0.241	24000	0.000	0.467	ND	0.185	0.198	7
Timing	Date of minimum	99	239	+140 days	17	158	+141 days	311	327	+16 days
	Date of maximum	197	207	+10 days	42	42	0 days	42	42	+0 days

changes were simulated at the Reach 189 (Table 6).

The HIs describing the magnitude of monthly flow for the dry months (*i.e.*, June, July, and August mean flows, m^3s^{-1}) and the magnitude and duration of minimum flow (1-day, 3-day, 7-day, 30-day, and 90-day minimum flow, m^3s^{-1}) resulted altered in the river reaches receiving the PS discharges (Table 6). In particular, for the Reach 27 (Canale d'Aiedda), the mean value of the 30-day minimum flow varied from 0.000 to 0.007 m^3s^{-1} in un-impacted conditions and from 0.012 to 0.032 in impacted conditions (Figure 5A). For the Reach 190 (Nil wadi), the mean value of the 30-day minimum flow was equal to 0.000 over the whole study period in the absence of PSs, while it ranged from 0.006 to 0.008 m^3s^{-1} after the impacts (Figure 5B). All the HIs showed minor changes (Table 6, Figure 5C) for the downstream river reach (Reach 189).

PSs discharges severely altered the duration of the dry period (Number of zero days). Indeed, in impacted conditions, the mean value of the zero-days was 0 throughout the study period (2000-2019) in Reach 27 and Reach 190 (Figure 5D and E). Whilst, in un-impacted conditions, zero-days ranged between 0 and 310 for Reach 27 and between 228 and 339 for Reach 190. Alterations of the timing of the extremely low flow (date of min) were detected for the Reach 27 and Reach 190, the date of minimum occurred later in the year. No significant change in the mean annual value of zero-flow and in the timing of extremely high flow (date of max) was assessed the at Reach 189 (Figure 5F).

The HIs describing the magnitude of monthly streamflow showed significant alterations from April to August for the Reach 27 and from May to November for the Reach 190 (Table 6, Figure 6). Alterations in mean monthly flow during the wet months (Table 6, Figure 6) were also detected for Reach 27 (16%-78%) and Reach 190 (43%-100%). However, the alterations in the magnitude of monthly streamflow were negligible for Reach 189.

The annual values of the HIs in pre- and post-impact for the three river reaches analysed in the present work are reported in the

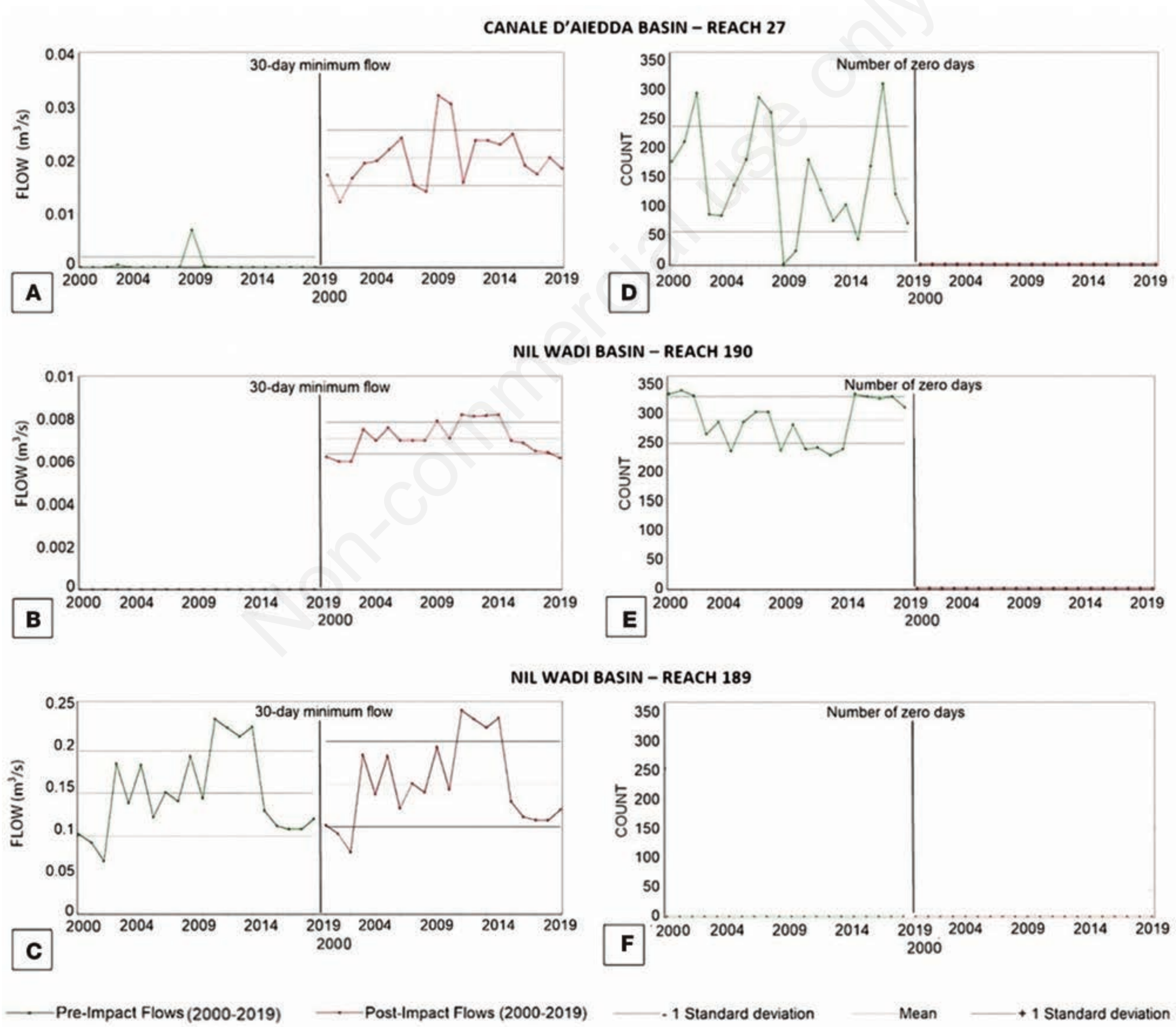

Figure 5. Hydrological indicators for the pre-impact (left of the vertical line) and post-impact (point sources) conditions (right of the vertical line): 30-day minimum flow and Number of zero-days for Canale d'Aiedda basin - Reach 27 (A, D), Nil wadi basin - Reach 190 (B, E), and Nil wadi basin - Reach 189 (C, F).

Supplementary Material (27, S1; 189, S2; 190, S3).

For the Reach 27, the RVA showed high and positive hydrological alteration values of the following HIs: 1-, 3-, 7-, 30-, 90-minimum flow, and mean monthly flow (January, February, April, May, June, and July), date of min in the high RVA category, and of the number of zero-days in the low category (Figure 7A). For the reach 190, high alteration values (high RVA category) were detected in all the mean monthly flow, 90-day minimum flow, date of min (Figure 7B), and zero-days. For the river Reach, 189 hydrological alteration values were detected for the 1-, 3-, 7-, 30-, 90-minimum flow and for August mean monthly flow for the high RVA category (Figure 7C). The positive hydrological alterations values indicated that the frequency of values in the high category was increased from the pre-impact to the post-impact period. Conversely, negative values for the high RVA category of the zero-days determined in reaches 27 and 190 clearly indicated a reduction of the frequency in that category. The hydrologic alteration values associated with Reach 27 (Figure 7A) and Reach 190 (Figure 7B) resulted in one order of magnitude higher than those detected for Reach 189 (Figure 7C). This result indicated a minor impact of the PSs on river sections located downstream of the first confluence with the main river.

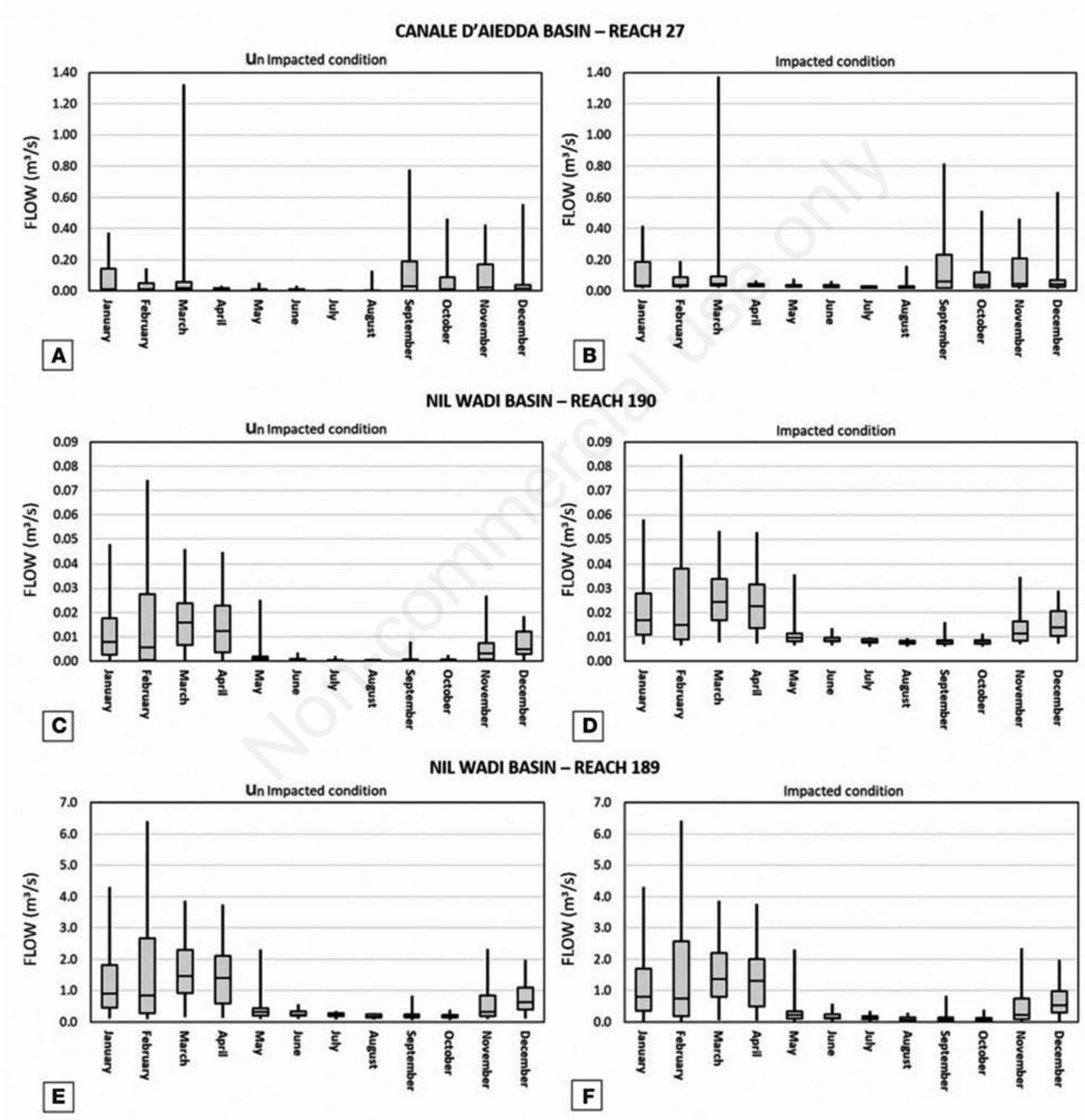

Figure 6. Box plot of monthly flow (m^{3}s^{-1}) in un-impacted and impacted conditions. The horizontal line within the boxplots indicates the median value, the box boundaries indicate the 25th and 75th percentiles, and the whiskers indicate the minimum and 95th percentile.

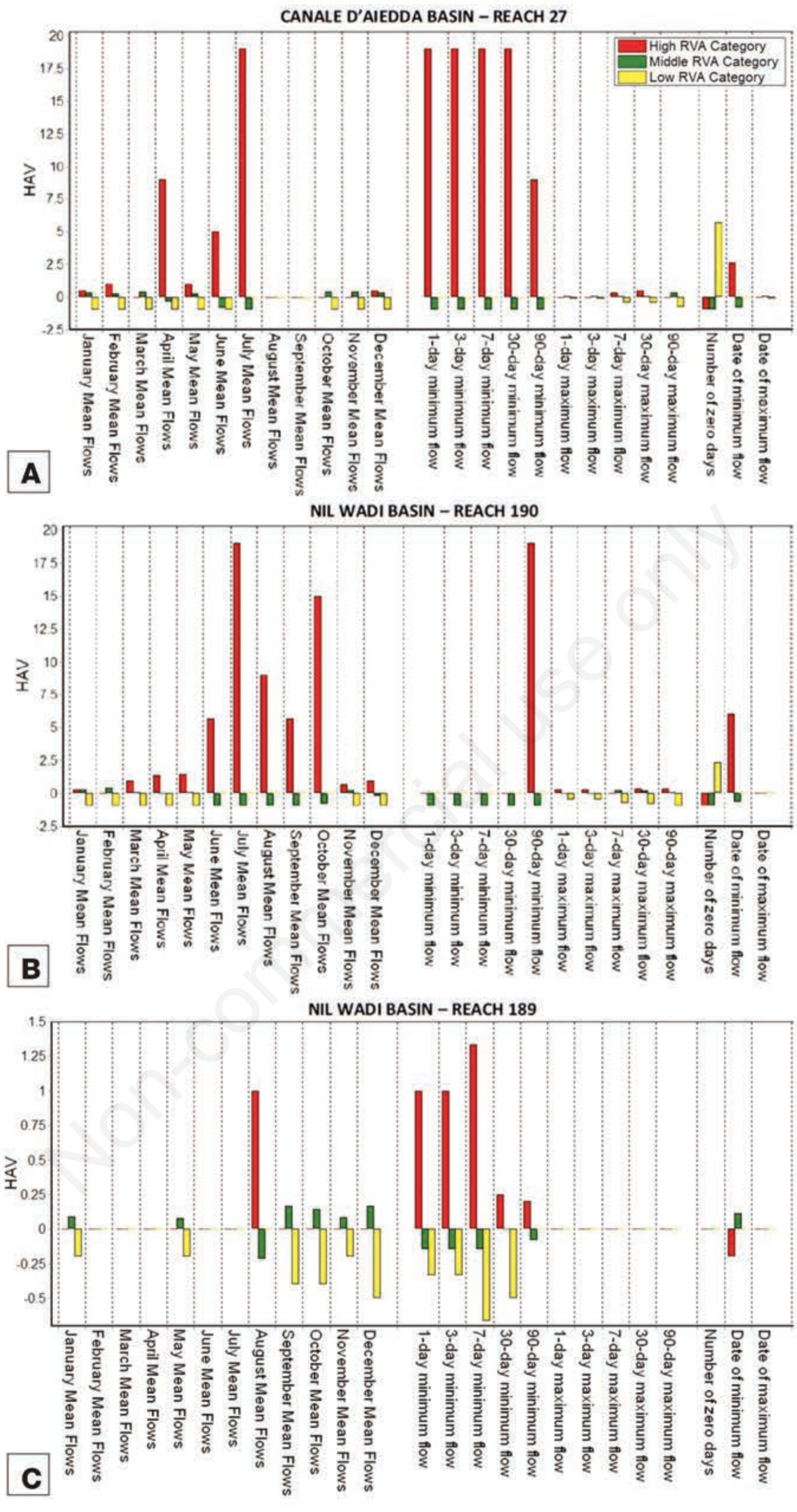

Figure 7. Hydrologic alterations (HA) [(impacted frequency - un-impacted frequency)/ un-impacted frequency] for the IHAs considered in the present study computed for three classes: high RVA category (values >0.67), middle RVA category (values included in the range 0.34-0.67), low RVA category (values <0.33) for the Canale d'Aiedda basin - Reach 27 (A), Nil wadi basin - Reach 190 (B), and Nil wadi basin - Reach 189 (C). Positive HA values (HAV) indicate that the frequency of values in the category has increased from the un-impacted to the impacted conditions; negative values mean that the frequency of values has decreased.

Discussion

Modelling streamflow

Hydrological models are fundamental tools in river management and environmental studies (Gassman *et al*., 2014). The free available regional and global databases allow applying models also in areas characterised by data scarcity like the Mediterranean Region (Panagos *et al*., 2015; Abbaspour *et al*., 2019; Brouziyne *et al*., 2021). However, regional databases are often characterised by a low resolution that can lead to large model uncertainty and low model performance (Pluntke *et al*., 2014; Moges *et al*., 2021). Moreover, merging data with different resolutions and derived from diverse sources may also increase uncertainty (Ricci *et al*., 2022). Despite these limits, this study demonstrated that global databases such as Global Weather Data for SWAT and International Soil Reference and Information Centre (ISRIC) were fundamental for simulating hydrological flow alterations in data-limited regions.

For the Canale d'Aiedda streamflow simulations, the model showed better performances for gauge B than gauge A. This discrepancy could depend on the different characteristics of the two drainage areas upstream of the two gauges. Indeed, gauge A drains a small area characterised by lower daily flow than gauge B (D'Ambrosio *et al*., 2019). In addition, one of the most sensitive parameters that control the fraction of transmission losses from the main channel (TRNSRCH.bsn) can only be adjusted at the basin scale (Arnold *et al*., 2012a; 2012b). Hence, the average value adopted in the simulations was overestimated for the sub-basins upstream gauge A and slightly underestimated gauge B.

For the Nil wadi basin (gauge C), the SWAT model performances were unsatisfactory except for the PBIAS. In this basin, most of the data used for the model setup were derived from a merge of data recorded in the area with global datasets (Table 1). The weather stations (*i.e*., location and their number in a river basin) assume a key role in Mediterranean basins, where the rainfall events are generally localised in small areas; therefore if the weather stations are not well spatially distributed within the basin, it could be difficult to calibrate the model (Galván *et al*., 2014; De Girolamo *et al*., 2017). For the Nil wadi basin, only two weather stations were available; one covered the downstream areas and the other the upstream areas (De Girolamo *et al*., 2022). The measured data (rainfall and temperature, 2019-2020) were combined with data from the global weather database (https://globalweather.tamu.edu) to create a longer time series (20-years). The number of gauging stations, their location, and the origin of data (*i.e*., radar) may have influenced the model's performances (Abdelwahab *et al*., 2016; Ehlers *et al*., 2019; Ricci *et al*., 2022). Streamflow measurements could be an additional cause of the low performance. Indeed, only discrete values of streamflow measurements were available for calibrating the model (Nil wadi, gauge C), and the measurements were taken by using the float method, which could have overestimated the extremely low flow provides discrete measurements of streamflow (Harrelson *et al*., 1994; Dobriyal *et al*., 2017; Hundt *et al*., 2019; De Girolamo *et al*., 2022).

The model validation is usually carried out to ensure parameter transferability (Arsenault *et al*., 2018). Unfortunately, it is generally difficult to perform both the model calibration and validation in regions with limited data availability. To carry out this study, since the Nil wadi is an ungauged basin, an inexpensive monitoring program was implemented covering one-year observations in a river section, based on the available economic resources. For example, in the Canale D'Aiedda basin, about two years of daily streamflow were available in two river sections. Considering that the calibration period should include both wet and dry weather conditions (Arnold *et al*., 2012b), it was chosen to use the entire datasets for calibrating the model; therefore, the validation is missed in this study. On the one hand, this choice assured the most robust calibration possible (Arsenault *et al*., 2018), but, on the other hand, the uncertainty associated with the model results due to the missed validation process could be significant. However, the low flow calibration, which is the most critical phase in NPRSs, was carried out with particular caution. As reported in De Girolamo *et al*. (2022), surveys and images from Google Earth were used to integrate the available data and identify the zero-flow thresholds corresponding to the actual zero flow.

Despite the limits described above, this work showed that the SWAT model could simulate hydrology with acceptable results in basins with limited data availability.

Flow regime alterations

Several river ecologists pointed out that NPRSs are prevalent waterways globally (Messager *et al*., 2021) and play an essential role in maintaining biodiversity (Myers *et al*., 2000; Datry *et al*., 2014). River ecologists also recognised that hydrological regime alteration is one of the dominant factors that affect the changes in composition and health of aquatic species (Roy *et al*., 2005; Konrad *et al*., 2008; Sabater and Tockner, 2009; Poff & Zimmerman, 2010; Kupferberg *et al*., 2012). Depending on the degree of hydrological alteration, the risk of unexpected ecological changes may significantly increase (Poff and Zimmerman, 2010).

Several studies analysed flow regime alterations due to water diversions or dam operations (Richter *et al*., 1997; De Girolamo *et al*., 2015b), mainly with the final aim of designing or revising the environmental flow (Mezger *et al*., 2021). A few studies have analysed the effects of PSs on NPRSs, and in those studies, the authors investigated the impact in terms of water quality. D'Ambrosio *et al*. (2020) highlighted that PSs harm water quality, especially in the dry season, due to the limited dilution effect that characterises the intermittent rivers. Hassan and Egozi (2001) analysed the impact of wastewater treatment plant discharge on the channel morphology of some ephemeral streams; they found that changes in vegetation within the channel and changes in the composition of the bed surface material were the major impacts. However, no studies were found in the literature that analysed the hydrological alterations due to PSs.

In the case studies analysed in the present paper, the PSs induced alterations in the flow regime components such as magnitude, duration, and timing. The river's flow regime receives wastewaters from PSs (Reach 27 in the Canale d'Aiedda and Reach 190 in the Nil wadi basin) shifted from intermittent to perennial. The mean annual value of zero-days in un-impacted conditions was 146 and 288 in the Canale d'Aiedda and Nil wadi, respectively, became zero in impacted conditions. All the components of the low flow, such as 1-, 3-, 7-, 30-, and 90-day minimum, and the monthly flow recorded in summer and autumn were severely altered. The date of minimum flow was found to shift later in the year.

The hydrologic alteration values estimated with the RVA for the receiving PSs inlets (Reach 27 and Reach 190) resulted in one order of magnitude higher than the hydrological alterations detected for the river reach downstream of the first confluence with the main river (Reach 189). However, further studies are needed to investigate the impact on water quality. Indeed, wastewater from PSs may influence water temperature, oxygen level, and nutrient concentrations in the receiving river reach.

The flow regime components, which were altered, have an ecological function. Hence, several implications are expected for river ecology (Poff *et al*., 1997). Indeed, the alterations of the flow permanence will impact the structure of communities, habitat, river morphology, and the riparian cover of the river systems. The alterations of the magnitude of streamflow on a monthly basis will influence species diversity and abundance, riparian cover, species richness, and the possibility of establishing non-native species (Konrad *et al*., 2008). The alteration of the duration and timing of extreme conditions may influence non-native species to become dominant (Richter *et al*., 1998).

Conclusions

In the present paper, a methodological approach for analysing the impact of PSs on the flow regime of intermittent rivers under data-limited conditions was presented through two case studies: the Canale d'Aiedda River basin and Nil wadi basin.

Results demonstrated that the flow regime alteration could be assessed in basins under data-limited by coupling a hydrological model and field activities. In the case studies, free regional databases integrated with field data may allow the implementation of hydrological models. However, a significant uncertainty may affect model results. In the case studies presented in this work, the SWAT model overestimated the low flow. The dry period and the low flow are crucial points when evaluating the flow regime alterations due to PSs in intermittent rivers. To improve simulated streamflow in the low flow and dry conditions, a zero-flow threshold was identified through field observations and images from Google Earth and was used to revise the daily time series of streamflow. Results showed that the PSs induced alterations in the magnitude, duration, and timing of the flow regime. The flow regime of the river reaches receiving wastewaters from PSs (Reach 27 in the Canale D'Aiedda basin and Reach 190 in the Nil wadi) shifted from intermittent to perennial. All the low flow components, such as 1-, 3-, 7-, 30-, and 90- day minimum, and the monthly flow recorded in summer were severely altered. Minor hydrological alterations were assessed for the river reaches downstream the confluence with the main river in the Nil wadi basin. These results may support river ecologists in the ecological status evaluation. However, further studies are needed to assess the implications of flow regime alterations on water quality and the river ecosystem.

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