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RESEARCH ARTICLE

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Can meteorological model forecasts initialize hydrological simulations rather than observed data in ungauged basins?

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Abstract

Floods are among natural disasters which cause the largest damages worldwide each year, inducing fatalities of human lives, destruction of infrastructure and economical losses. Consequently, forecasting this type of events through hydro-meteorological models is still of great importance from a civil protection point of view since it allows to reduce hydrological risk by means of early warning systems. Nevertheless, hydrological model initialization in ungauged basins, where there is lack of direct measurements of meteorological information, is a known issue affecting the entire prediction chain. The present study evaluates the possibility of using forecasts provided by the meteorological model MOLOCH developed by CNR-ISAC forcing the FEST-WB hydrological model developed by Politecnico di Milano to perform discharge simulations assuming that the forecasting errors are negligible when using the first 24 h of time horizon. The study is carried out in the urban catchments of Milan city, the Seveso-Olona-Lambro (SOL) river basins, located in northern Italy. The main hydro-meteorological variables are analysed by comparing the spatialized and observed meteorological data, provided by an official regional network of weather stations plus a citizen scientists' contribution with the meteorological model forecasts. Moreover, a sensitivity analysis following the well-known one-factor-at-a-time methodology is accomplished with the aim of defining which atmospheric forcing, beyond rainfall, mostly affects flowrate forecasts. Results generally show satisfactory correspondences between forecasts and observed data for the discharge variable at daily scale, although an underestimation of precipitation, particularly for severe events in summer, is present. Therefore, using meteorological forecasts to create daily initial conditions for hydrological model, instead of ground observations, might be a reliable and valuable approach, even if some considerations should be borne in mind when coupling the two models.

KEYWORDS
hydro-meteorological forecasts, initial conditions, MOLOCH model, SOL basins, ungauged basins

1 | INTRODUCTION

Floods are the most frequent catastrophes among natural hazards, and one of the most severe hydro-meteorological events (CRED, 2022): they induce large damages to population and infrastructure and generate financial costs. In 2022, it was estimated that 1.81 billion people are exposed to intense flood risk, leaving one third of them in poverty conditions (Rentschler et al., 2022). From 1970 to 2012, 79% of the weather, climate and water-related disasters worldwide were caused by storms and floods, causing around 1 million deaths and approximately US$ 2 trillion of economic losses (WMO, 2014). Forecasting floods is of great interest in a civil protection framework since it allows to prevent or mitigate hydrological risk with non-structured measures as early warning systems (EWSs). Consequently, hydrological models forced with meteorological variables have been a tool to properly monitor discharges in river basins where high risk of inundations is present (Ceppi et al., 2013; Ranzi et al., 2009; Ravazzani et al., 2016; Verbunt et al., 2006).

Problems affecting discharge predictions arise from different sources, for example, lack of observed hydro-meteorological information, because of poor-quality network of weather and hydrological data stations, or fast response times due to basin characteristics, especially in urbanized areas. Therefore, coupling meteorological and hydrological models or using additional approaches, besides direct measurements to obtain meteorological variables, which influence discharge forecasts, are topics of wide interest. In the last two decades, several studies have been developed about coupling numerical weather prediction and hydrological models to perform discharge forecasts (Bartholmes and Todini, 2005; Gouweleeuw et al., 2005; He et al., 2009; Lombardi et al., 2018; Ye et al., 2016). However, hydro-meteorological phenomena, especially those associated with convective precipitations are difficult to accurately forecast, thus affecting discharge predictions (Wetterhall et al., 2011). The uncertainty propagation along the forecasting chain (Silvestro & Rebora, 2014) and the absence of information in the studied areas are main challenges for the scientific community aiming at improving the performance of discharge forecasts.

It is well known how the lack of rainfall and discharge information are limiting factors for flood forecasting. Reynolds et al. (2020) evaluated the impact of rainfall errors, in terms of volume and duration, on the performance of a calibrated model with limited discharge data. In addition, the lack of hydro-meteorological information affects discharge forecasts as assessed by Seibert and Beven (2009) in defining the amount of discharge measurements needed to properly parametrize a model for providing streamflow. On the other hand, the usefulness of other types of precipitation data, such as remote measurements, were evaluated in Ward et al. (2011) from a water resources perspective over two complex mountainous catchments. Similar procedures have been followed in Chintalapudi et al. (2014) who used different satellite precipitation products to force a physically based distributed hydrological model obtaining different performances in terms of statistical indexes.

Other types of methodologies, such as regionalization, are used to perform discharge forecasts, particularly in ungauged basins. For instance, Yang et al. (2018) tested different methodologies of regionalization about parameters involved in the hydrological modelling in a catchment situated in Norway. More recent studies (e.g., Chawla & Mujumdar, 2020) calculated the performance of different reanalysis datasets, satellite products and the Weather Research Forecasting (WRF) model to represent heavy rainfall over a region in Himalayas, using rain gauge data as reference dataset. This information was used to initialize a hydrological model and to assess its ability to reproduce floods even in ungauged area where reanalyses revealed an unsatisfactory performance; however, the output obtained from the WRF model or TMPA (Multisatellite Precipitation Analysis) datasets could be improved in future to perform flood forecasting in early detection and warning.

In Ines and Hansen (2006), daily rainfall simulations from a general circulation model (GCM) have been transformed by applying a bias-correction method which consists of two steps, frequency and intensity correction.

In the present study, problems regarding the lack of hydro-meteorological information in river basins requiring discharge predictions are tackled. In the framework of coupling meteorological and hydrological models to predict flowrates, the following question is addressed: is it possible to use meteorological forecasts as if they were observed data to perform flood forecasts when direct measurements are missing? In this concern, it is assumed that errors in precipitation forecasts might be negligible when treating the first 24 h of meteorological forecasts, in order to generate flowrate predictions in ungauged river basins where few (if any at all) ground meteorological measurements are available.

To pursue this scope, a verification of the high-resolution MOLOCH meteorological forecasts, which is used as driven-input into the FEST-WB hydrological model instead of observations for discharge forecasting, is firstly performed, considering an 8-year period between 2013 and 2020. The Seveso-Olona-Lambro (SOL) river basins located in the Milan urban area in northern Italy have been chosen as testbed, since a great amount of observed weather data are available from the official network operated by the Regional Environmental Protection Agency (ARPA Lombardy) and from the citizen-scientist network managed by the Meteonetwork (MNW) association; hence, a good and reliable assessment can be executed.

The present study is structured as follows: the area of study is described in Section 2 together with the main characteristics of the SOL river basins. Section 3 deals with tools and methods concerning the meteorological and hydrological models and their coupling and with observed and forecast meteorological variables and their treatment. Section 4 describes the main results, and the comparison between observed and forecast hydro-meteorological variables, as well as the sensitivity analysis are deeply discussed.

2 | AREA OF STUDY

The area of interest includes the hydrological catchments of the rivers Seveso, Olona and Lambro, located in the north of Milan city in the Lombardy region of Italy, characterized by a pronounced seasonality in the meteorological regime. According to the analysed data from the ARPA Lombardy and MNW weather stations in the period 2003–2020 (Chaves González, 2021), precipitation shows a bimodal behaviour with two peaks: one with larger amounts in autumn and the other in spring. January is the month with the lowest value (57.4 mm), while November presents the highest (158.8 mm). Maximum hourly precipitations are attained in summer, mainly due to convective storms. The yearly mean rainfall value aggregated over the SOL catchments is around 1200 mm with an increasing trend of 14.2 mm/year along the available 18 years. Concerning temperatures, January is the coldest month with a mean value of 2.9°C, and July is the warmest one with 24.0°C, while a yearly average equal to 13.2°C is observed with temperatures spanning from 12 to 14°C with an increasing trend of 0.08°C/year.

From hydrological point of view, the Olona basin covers the western part of the studied region with a surface of 911 km^2: most of the basin (99%) is within the Italian borders with a small portion of watershed located in Switzerland. Seveso is the central basin with a surface of 277 km^2, of which 100 km^2 belong to urban areas with the closure section at via Ornato where the river has its maximum capacity of about 35 m^3/s before the subsurface channel network of Milan commences. The eastern catchment is the Lambro River basin, characterized by a complex hydrographic network with 553 km^2 of surface; 199 km^2 belong to urban areas, while 354 km^2 to exurban areas with the closure section at Redefossi deviation confluence localized to the south of Milan city. These three water courses, situated to the north of Milan, flow in north–south direction, and they are interconnected by artificial channel networks made for irrigation and flood protection purposes. All catchments are regulated by structural measures along their waterways: the Ponte Gurone dam over the Olona basin, the north-west spillway channel (which is an Italian acronym of the Canale Scolmatore Nord-Ovest, CSNO) over the Seveso basin, which has a discharge capacity of 30 m^3/s, and the regulated Pusiano Lake over the Lambro River basin. Hence, to carry out a reliable analysis without any hydraulic disturbance, the section of the Seveso river closed to the municipality of Bovisio-Masciago (Figure 1) and upstream the CSNO was selected.

3 | TOOLS AND METHODS

In this section, the meteorological and hydrological models, as well as the available observed and forecast data and their statistical treatment and processing, are thoroughly described.

3.1 | The MOLOCH meteorological model

In the present study, the high-resolution meteorological model MOLOCH (Davolio, Henin, et al., 2017; Malguzzi et al., 2006), widely adopted by several regional meteorological services and national agencies to perform real-time forecasting in Italy, was chosen to carry out hydro-meteorological simulations over the selected SOL basins, especially to evaluate if the generated forecasts can replace observed ground measurements, which are necessary to initialize the FEST-WB hydrological model in case of data missing or ungauged basins.

The model was developed at the Institute of Atmospheric Sciences and Climate of the National Research Council of Italy (CNR-ISAC) where it is implemented over Italy within a daily operational chain (Davolio et al., 2020), that also comprises the hydrostatic model BOLAM (Buzzi et al., 2014), whose initial conditions are

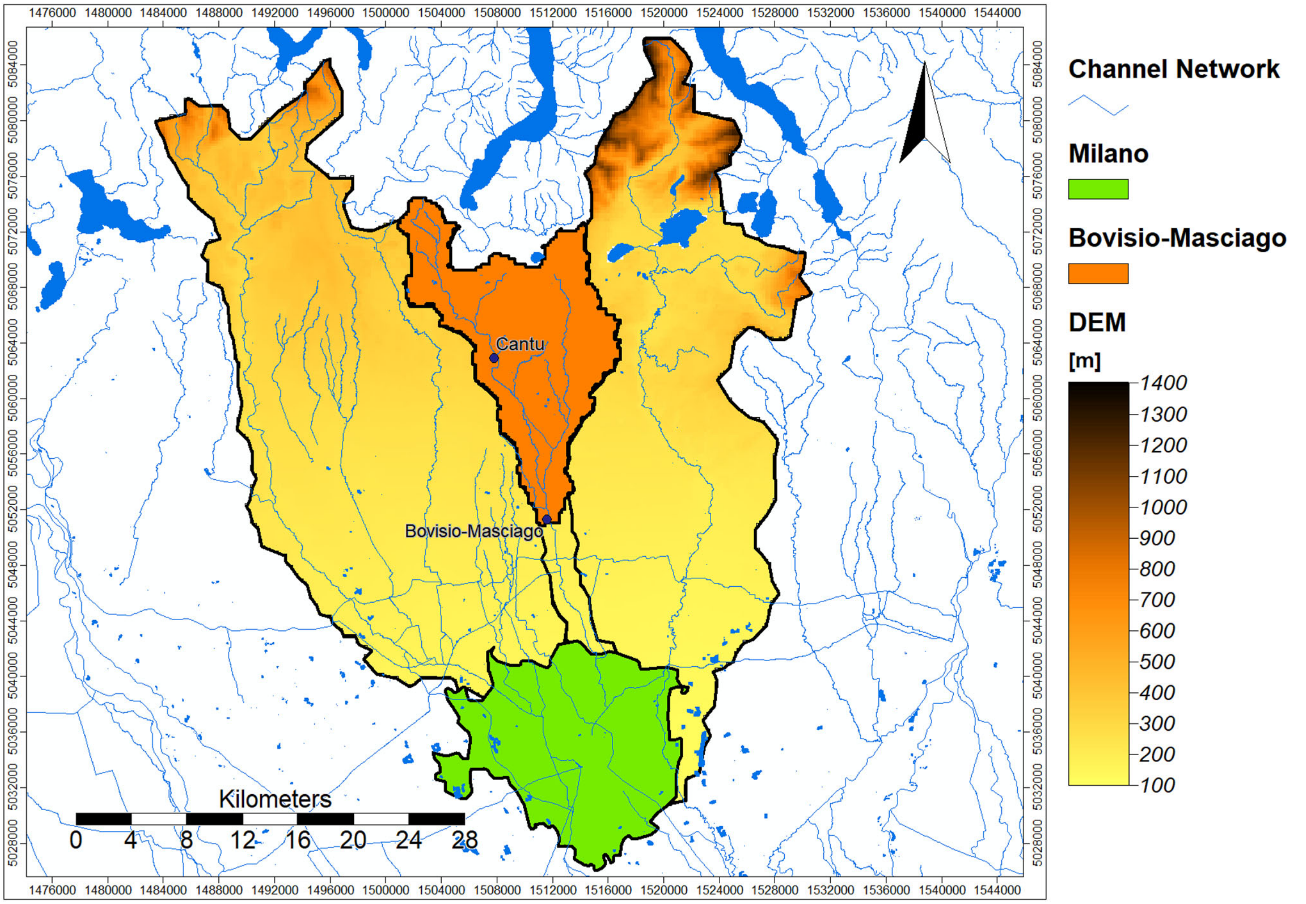

FIGURE 1 River basins draining to Milan urban area. The orange area shows the Seveso river basin closed at Bovisio-Masciago gauge section where all the analyses are performed.

provided by the analyses (00 UTC) of the Global Forecast System (GFS, NOAA/NCEP, USA). MOLOCH is nested (1-way) into the BOLAM run performed at coarser resolution, and it is initialized with a 3-h BOLAM forecast. This operational practice allows to initialize the high-resolution model with physical-consistent dynamical fields, since it avoids a pure interpolation from the global model, thus reducing the possible noise in the initial phase of the simulation and minimizing the spin-up period. However, for a limited period of few years, MOLOCH forecasts in the range +4 h to +24 were tested in place of 0–24 h interval, and no relevant differences were found in the performance.

Concerning general characteristics of the model and its operability, MOLOCH integrates non-hydrostatic, fully compressible equations for the atmosphere with a grid size of 1.25 km, 60 atmospheric levels. The spatial resolution of the model has had two main upgrades, changing from 2.2 to 1.55 km in March 2014, and from 1.55 to 1.25 km in October 2016. Additionally, it operates as short-range (up to 48 h) weather forecasting model, providing output fields at hourly frequency.

Model prognostic variables, pressure, virtual temperature, specific humidity, horizontal and vertical components of wind velocity, turbulent kinetic energy and five water species (cloud water, cloud ice, rain, snow, graupel/hail), are spatially represented on a latitude-longitude rotated Arawaka C-grid. In the vertical, MOLOCH employs a hybrid terrain-following coordinates, depending on air density, relaxing smoothly to horizontal surfaces at a higher elevation from the ground. Time integration is done with an implicit Euler-backward scheme for the vertical propagation of sound waves, and an explicit time-split scheme for the remaining terms of the equation of motion. Furthermore, three-dimensional advection is computed using a second-order Weighted Average Flux scheme (Hubbard & Nikiforakis, 2003), and divergence damping is included to prevent energy accumulation on the shorter space scales.

MOLOCH is a convection resolving model. Concerning the model physics, four components are parameterized. The atmospheric radiation is computed with a combined application of the Ritter and Geleyn (1992) and the ECMWF (Morcrette et al., 2008) schemes. The sub-

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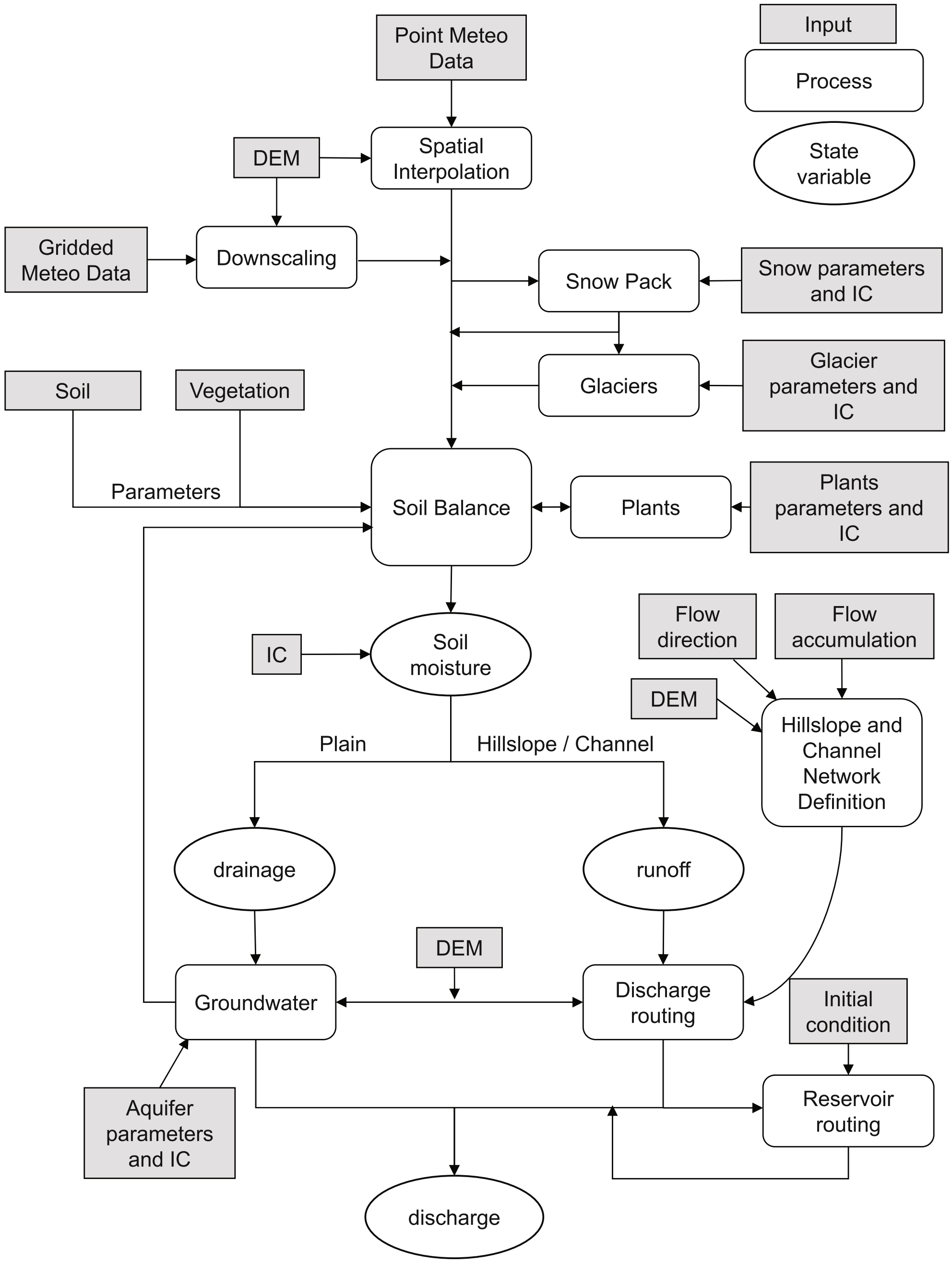

FIGURE 2 Scheme of hydrological processes implemented within the FEST-WB model with main state variables and input data.

grid turbulence parametrization uses a scheme based on an E-l, order 1.5 closure theory, where turbulent kinetic energy is evaluated (Trini Castelli et al., 2020). The microphysical scheme was initially based on the parameterisation proposed by Drofa and Malguzzi (2004), with successive upgrades. Finally, the soil model uses seven layers, whose depth increases moving downward, and describes orography, geographical distribution of soil types, soil physical parameters and vegetation coverage, as well as soil physical processes.

MOLOCH performance has been assessed in the framework of several international research programs (e.g., MAP D-PHASE, Rotach et al., 2009) or applications (e.g., Davolio et al., 2020; Davolio, Silvestro, & Gastaldo, 2017), including intercomparisons exercises (Ferretti et al., 2014; Senatore et al., 2020), as well as in the operational activities of the regional meteorological centres and institutions that implement MOLOCH for operational forecasting purposes (e.g., Mariani et al., 2015).

An exhaustive description of the models can be found in Davolio et al. (2020) and reference therein, while additional comments concerning forecast information obtained with MOLOCH model and the given use in the present study are done in further sections.

3.2 | The FEST-WB hydrological model

For rainfall run-off simulation, the FEST-WB model (Flash-flood Event-based Spatially-distributed rainfall-runoff Transformation – Water Balance mode) was employed in the present study. It is a physically based, distributed hydrological model developed in Italy at Politecnico di Milano (Rabuffetti et al., 2008; Ravazzani, 2013). The simulation domain is discretized into regular square cells (200 × 200 m, in this study, a grid-spacing one order of size finer than that of the MOLOCH soil model) where equations that describe hydrological processes are solved with hourly time step. The FEST-WB model is written in Fortran 90 with a modular approach, hence, only the dominant processes can be simulated for any specific studies (Figure 2).

For running a simulation, the FEST-WB model requires meteorological input data. These can be site measurements acquired by meteorological stations or multidimensional raster data coming from weather forecast models. Station-site data are interpolated over the simulation domain using inverse distance weighting. The snow module gets precipitation data and simulate snow accumulation, as snow water equivalent, and melting. Run-off computation is performed in each cell of the domain using the modified SCS-CN method extended for continuous simulations:

$$\mathrm{R} = \frac{(\mathrm{P}-\mathrm{I_a})^2}{\mathrm{P}-\mathrm{I_a}+\mathrm{S}} \tag{1}$$

with $I_a = 0.2\,S$ P is the precipitation [L], R is the run-off [L], S is the maximum retention capacity [L] and I_a is the initial abstraction.

S, is updated in each cell at the beginning of a precipitation event as

$$S = S_1 - \varepsilon(S_1 - S_3) \tag{2}$$

with

$$S_1 = S(CN_I) \tag{3}$$

$$\mathrm{S}_3 = \mathrm{S}(CN_{III}) \tag{4}$$

$$CN_I = CN_{II} - \left(20\frac{100-CN_{II}}{100-CN_{II}+EXP(2.533-0.0636(100-CN_{II}))}\right) \tag{5}$$

$$CN_{III} = CN_{II}\,EXP\,(0.00673\,(100-CN_{II})) \tag{6}$$

$$\varepsilon_t = \frac{\theta-\theta_r}{\theta_s-\theta_r} \tag{7}$$

TABLE 1 Number of ARPA Lombardy plus MNW stations per variable.

Data	P	T	RH	SR	W
ARPA	89	76	61	23	48
MNW	142	144	130	130	130
Total	231	220	191	153	178

where θ is the actual water content at time t [L^3/L^3], θ_s is the saturated water content [L^3/L^3] and θ_r is the residual water content [L^3/L^3].

The actual soil moisture is updated by solving the continuity equation:

$$\frac{\partial\theta}{\partial t} = \frac{1}{\mathrm{Z}}(P-R-D-ET) \tag{8}$$

where Z is the soil depth, D is drainage flux and ET is the evapotranspiration rate.

The effective evapotranspiration is estimated as a fraction of the potential rate of evapotranspiration, tuned by a function depending on soil moisture content. This potential rate is evaluated by means of the Priestley-Taylor radiation-based equation (Priestley & Taylor, 1972). Surface run-off is routed with the Muskingum-Cunge method in its non-linear form with the time variable celerity (Ponce & Yevjevich, 1978). Further details about model calibrations and applications are described in Ravazzani, Ghilardi, et al. (2014), Ravazzani, Gianoli, et al. (2014), Boscarello et al. (2014) and Ravazzani et al. (2016).

3.3 | Observed meteorological data

A climatological database was created for the period 2003–2020 containing information at hourly resolution of the following meteorological variables: precipitation (P, mm), 2-m air temperature (T, °C) and relative humidity (RH, %), incoming short-wave solar radiation (SR, W/m^2) and wind speed (W, m/s). Weather data inside and nearby the three SOL catchments were collected from ARPA Lombardy, and, since spring 2013, meteorological information was also acquired from the MNW association, which has an open-source database fed by citizen scientists. A comprehensive review about this amateur weather network can be found in Giazzi et al. (2022). In Table 1, the total number of stations per variable is shown.

Hence, combining the two datasets, a huge improvement of ground data coverage was obtained in the

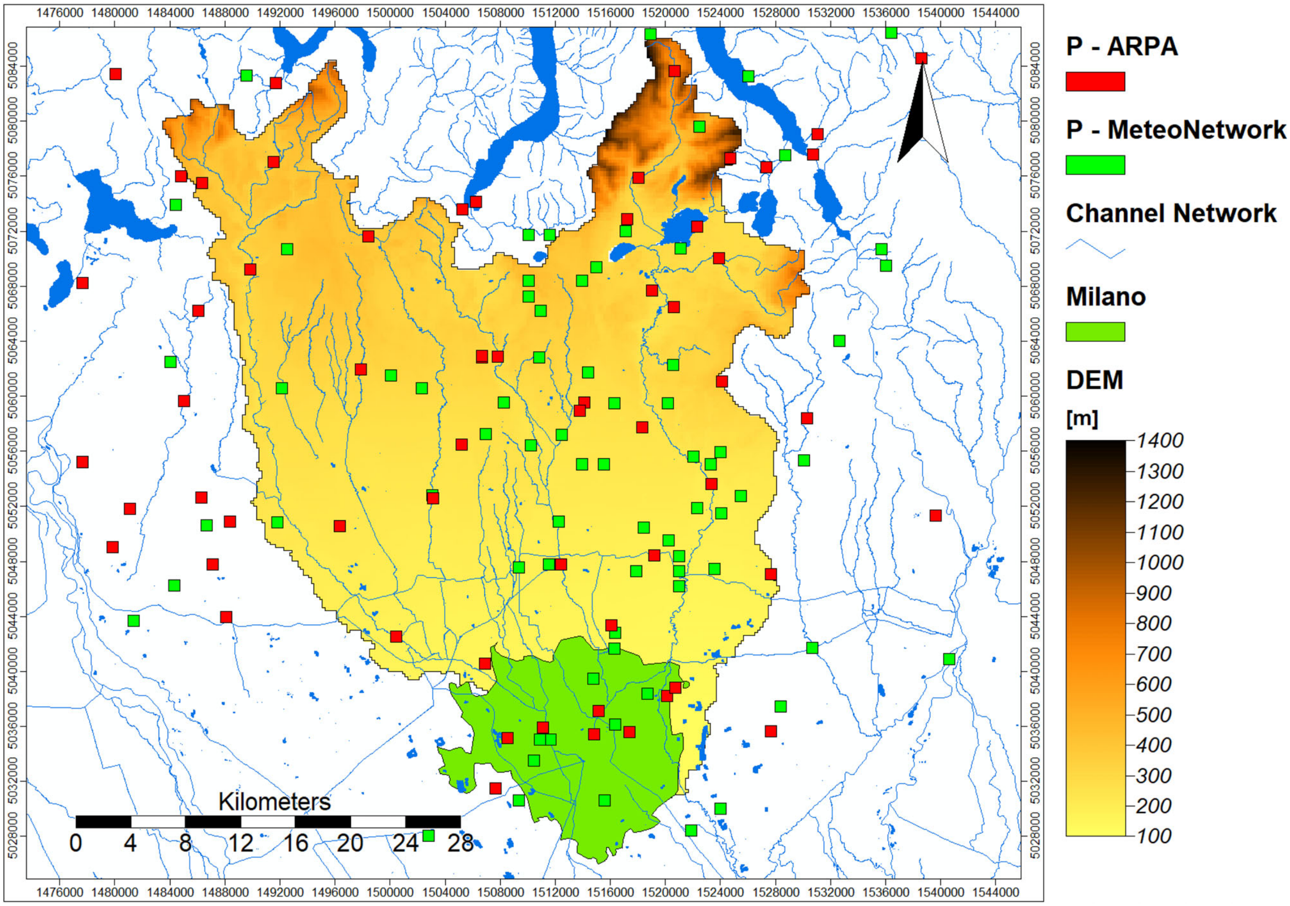

FIGURE 3 Map of rain gauges located in the SOL area coming from the ARPA Lombardy (in red) and MNW network (in green).

investigated area as reported in Figure 3, where a map of all rain gauges is shown.

Although the acquired data were previously validated by both ARPA Lombardy and MNW, an additional quality control procedure was conducted with the scope of identifying and substituting those values that may have no physical meaning, leading to better hydrological simulation results. In addition, missing days were carefully identified from the forecast dataset and removed from the series to be analysed.

3.4 | Coupling strategy for hydrological simulations

The applied coupling strategy, here proposed as main scope of the research, consists in initializing the FEST-WB hydrological model with forecast variables obtained from the MOLOCH meteorological model. Solar radiation, temperature, relative humidity and precipitation at hourly time steps were used, instead of observed ground measurements, as input to the FEST-WB model in order to, first, simulate hydrological quantities such as potential evapotranspiration, soil moisture and discharge, and, then, to create initial conditions for subsequent forecast run, hence, a comparison with two datasets of initial conditions, one obtained with MOLOCH forecast and the other with observed value, was carried out.

To achieve this aim, the following steps were undertaken: (i) initialization of the FEST-WB hydrological simulations with observed weather data in the period 2003 to 2020 to produce a climatological dataset; (ii) benchmark analysis of the MOLOCH forecasts in the overlapping period between observed and forecast information, that is, from January 2013 to December 2020; (iii) a sensitivity analysis with the one-factor-at-a-time (OAT) methodology (Borgonovo, 2010; Little, 1970; Stein & Alpert, 1993) to identify the meteorological forcing (beyond precipitation) that mostly influences the hydrological simulations; in particular, the FEST-WB model was forced with three observed input and one forecast data, taking turns among air temperature, relative humidity, precipitation and incoming solar radiation; (iv) initialization of the hydrological model with forecast weather data of the first 24 h by the MOLOCH model; this allows to perform a comparison in terms of hydro-meteorological variables with respect to simulations initialized with observed data. Common skill scores were used to evaluate the hydro-meteorological performance: Mean Error (ME), Mean Absolute Error (MAE), Root Mean Square Error (RMSE) and determination coefficient R^2 with a simple linear regression – least square method (Jolliffe & Stephenson, 2012; Wilks, 2006; WWRP-WGNE Joint Working Group on Verification Research, 2013, accessed on 1 July 2023).

4 | RESULTS AND DISCUSSION

A prime comparison of the hydrological simulations forced with observed and forecast weather data was performed for the period 2013–2020 in order to, first, evaluate the performance of the MOLOCH meteorological model and, afterwards, to evaluate its potentiality in providing a reliable dataset to create the initial conditions for the FEST-WB model in place of instrumental ground data.

4.1 | Evaluation of MOLOCH forecasts

In the following subsection, a comparison of the MOLOCH meteorological forcing is shown in terms of the statistical indexes at daily time scale.

Figure 4 depicts four scatter plots comparing daily observed and forecast data of temperature, solar radiation, relative humidity and wind. Concerning temperatures (Figure 4a), it is possible to observe a very close agreement between both datasets, reflected by means of the determination coefficient (R^2) equal to 0.98. Nevertheless, the sign of the mean error (ME) equal to −1.3°C, the linear regression under the diagonal and the larger amount of data points below 0°C in the bottom left portion of the scatter plot reveal that the MOLOCH model slightly underestimates temperature values, particularly below the freezing point. Notwithstanding this, the underestimation is, on average, equal to 1.4 and 1.71°C for the MAE and RMSE, respectively, in the analysed period.

Investigating daily solar radiation (Figure 4b), the coefficient of determination is equal to 0.92 between observed and forecast values, and the statistical indexes show low

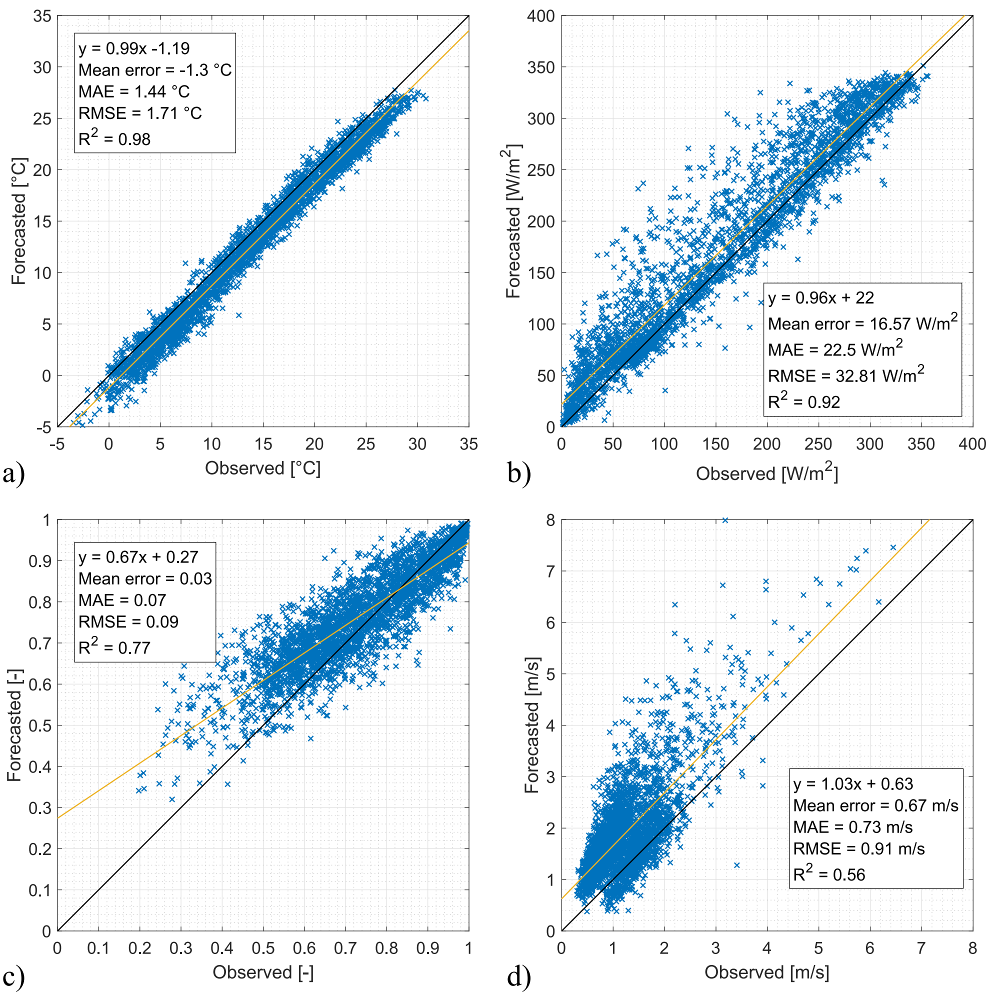

FIGURE 4 Scatter plots and statistical indexes between observed and forecast data by the MOLOCH model about daily mean temperature (a), solar radiation (b), relative humidity (c) and wind speed (d).

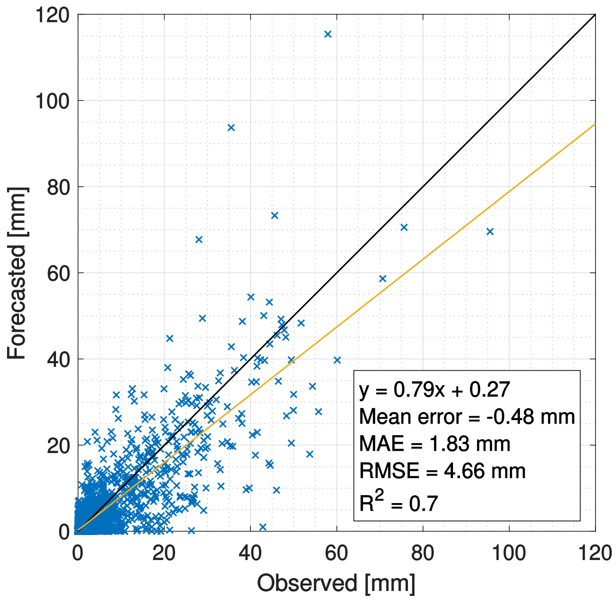

FIGURE 5 Scatter plots and statistical indexes between observed and forecast data by the MOLOCH model for daily accumulated precipitation.

errors compared with the order of magnitude of the variable; however, a general overestimation for the MOLOCH model is present; in fact, the ME, MAE and RMSE are equal to 16.5, 22.5 and 32.8 W/m^2, respectively.

For the relative humidity (Figure 4c), a decrease of the model performance is found; in fact, there is a large overestimation tendency for low values, while an underestimation for large RH values is present, leading the mean error equal to 3%. The agreement between observed and forecast information is not particularly high, since the coefficient of determination is 0.77 at daily scale, and the MAE and RMSE are equal to 7% and 9%, respectively.

Figure 4d shows the results concerning the wind speed. At daily time scale, a low correspondence between data is shown, since the R^2 coefficient is equal to 0.56; it is also observed an overestimation tendency especially for small values, which tends to grow increasing wind speed. Nevertheless, the ME, MAE and RMSE indexes remain below the threshold of 1 m/s. However, it must be taken into account that MOLOCH forecasts are referred at 10 m of elevation above the ground. Therefore, the current results may be affected by heterogeneity of measurement instruments' location since most of them are not mounted at the same height. A scale factor correction to the observed dataset could be applied, according to the wind profile equation, to perform a fairer comparison of wind speed. However, wind speed values do not influence the results of hydrological quantities since the potential evapotranspiration is assessed through Priestley and Taylor (1972) equation which does not consider the wind velocity component.

As far as precipitation is concerned, Figure 5 illustrates the model performance for the primary driving variable for rainfall–run-off transformation.

Generally, there is a reasonable agreement ($R^2 = 0.70$) between MOLOCH forecasts and observed data; however, a general underestimation is seen by the trend line, especially for intense precipitation. Additionally, to verify a possible seasonal dependence of the MOLOCH performance, the same analysis was repeated for winter months (December–February), spring (March–May), summer (June–August) and autumn (September–November) as shown in Figure 6.

Compared with the annual average, the forecast accuracy is higher in winter and gets worse in summer, with intermediate behaviour in spring and autumn. In particular, the average error and its magnitude are smaller in winter, and have a similar behaviour in the intermediate seasons, attaining the largest values in summer. Moreover, the underestimation tendency for high values of precipitation still remains, and it is particularly evident in summer. These results can be explained taking into account the different precipitation dynamics along the year, as described in the climatological characterization of the region (Section 2). The area of study presents a bimodal regime of precipitation with rainy (usually stratiform) periods in spring and autumn when a similar behaviour is revealed in the scatter plots; on the contrary, convective precipitations with significant rain intensities are common in summertime. Since accurate precipitation forecasting due to convective storms is still challenging, even for high-resolution meteorological models, especially at the small scales relevant for hydrological applications; this justifies the decrease in summer.

In summary, the MOLOCH performance was evaluated for the period 2013–2020 and a close agreement was found for daily mean temperature and solar radiation. Vice versa, the model relative humidity is affected by a relevant overestimation tendency for low values, and an opposite behaviour for high values. In addition, wind speed shows a marked overestimation for daily mean data, while for precipitation, a reasonable agreement between forecast and observed data is attained, despite an overestimation for heavy rainfall, mainly ascribable to intense summer convection.

4.2 | Sensitivity analysis of meteorological forecasts

A sensitivity analysis by means of the one-factor-at-a-time (OAT) methodology was performed in order to

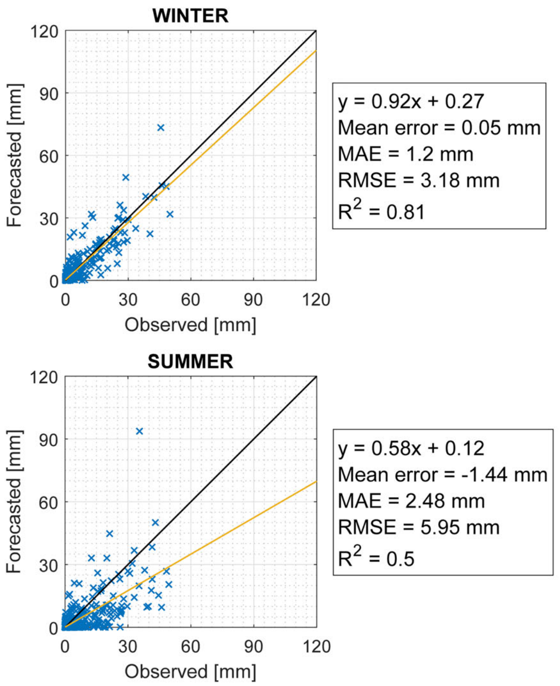

FIGURE 6 Scatter plots and statistical indexes between observed and forecast data by the MOLOCH model for daily accumulated precipitation in the four seasons.

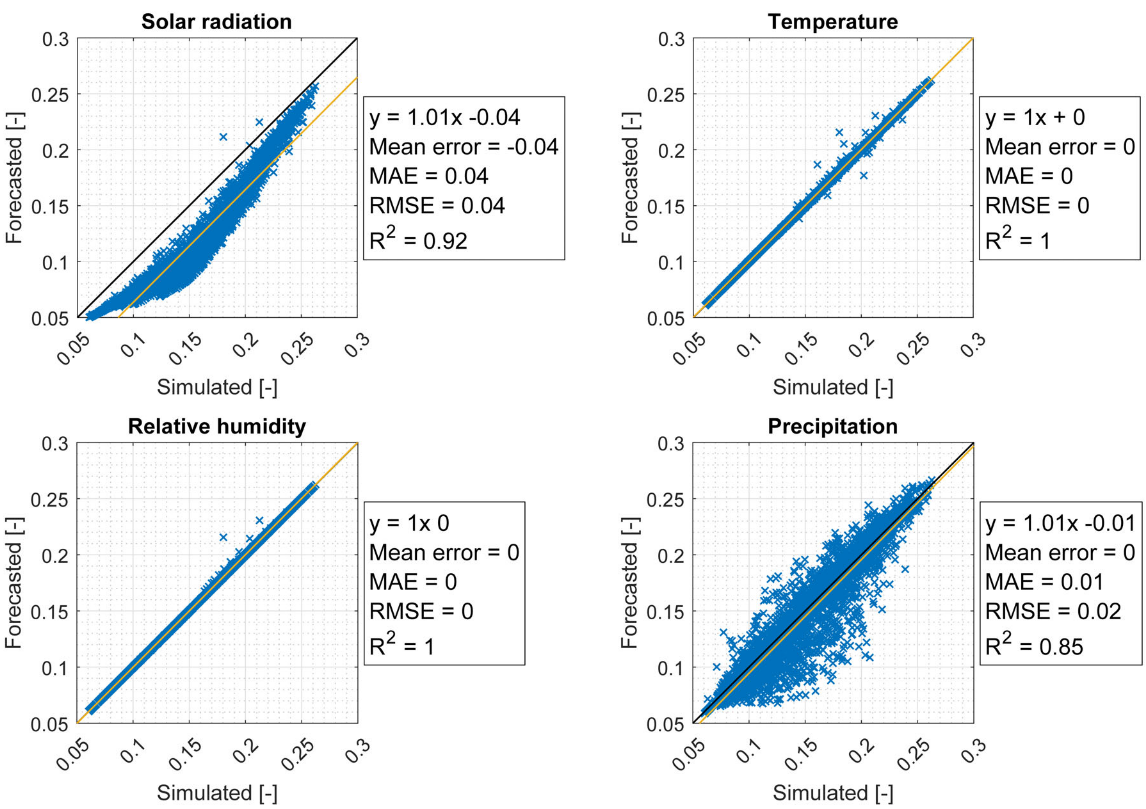

FIGURE 7 Sensitivity analysis of the mean daily soil moisture on four different meteorological variables forecasts.

identify the most relevant meteorological forcing, beside precipitation, for the simulation of the hydrological variables (i.e., soil moisture, potential evapotranspiration and discharge). In Figures 7–9, four scatter plots are presented for each hydrological variable at daily scale. Each represents the simulation results obtained by forcing the

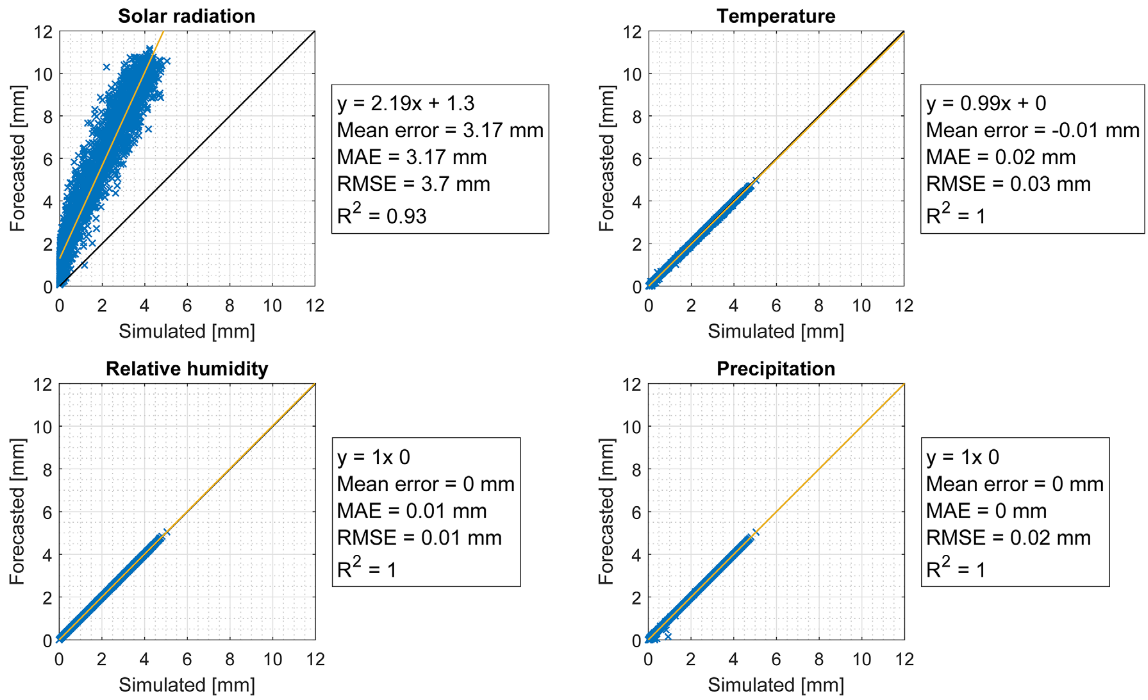

FIGURE 8 Sensitivity analysis of the daily accumulated evapotranspiration on four different meteorological variables forecasts.

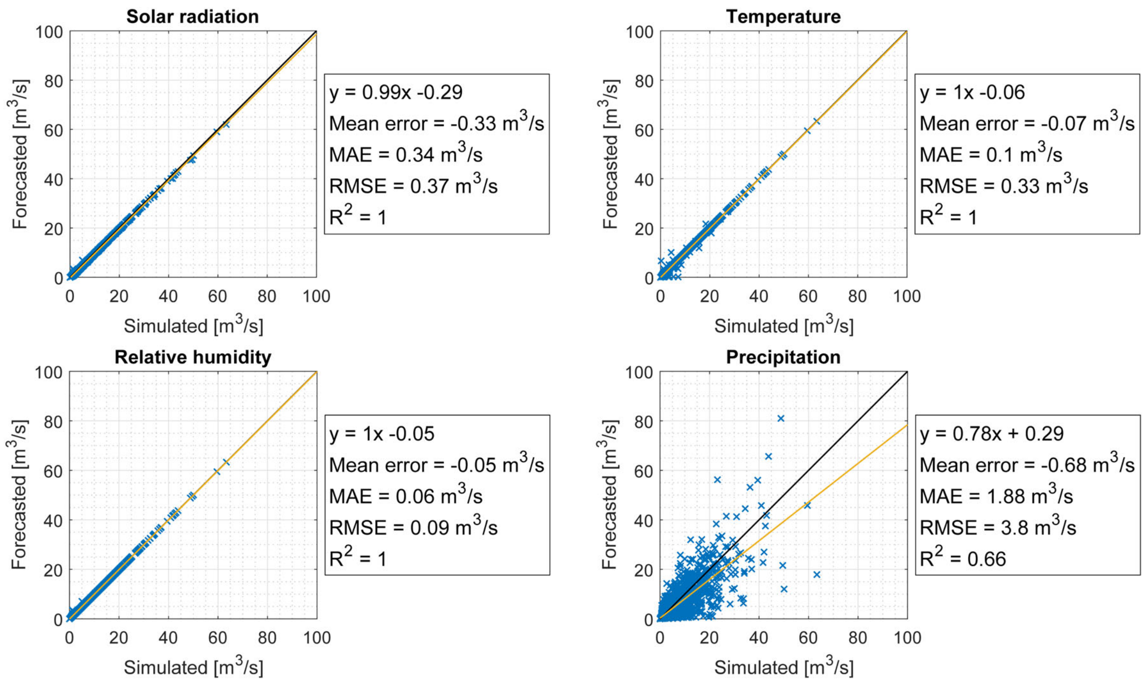

FIGURE 9 Sensitivity analysis of the daily peak flowrate on four different meteorological variables forecasts.

FEST-WB model using the observed data except for one variable (highlighted in bold in the title) which is provided by MOLOCH forecast. It is worth noticing that wind speed is not here considered, since it is not computed in the estimation of hydrological quantities in the present study.

Figure 7 shows the influence of different input meteorological variables on soil moisture simulations and reveals that, besides rainfall, solar radiation plays a crucial role as well. This means that an error in its forecast may generally decrease the accuracy in the soil moisture simulation. Hence, bearing in mind that the soil moisture is dynamically

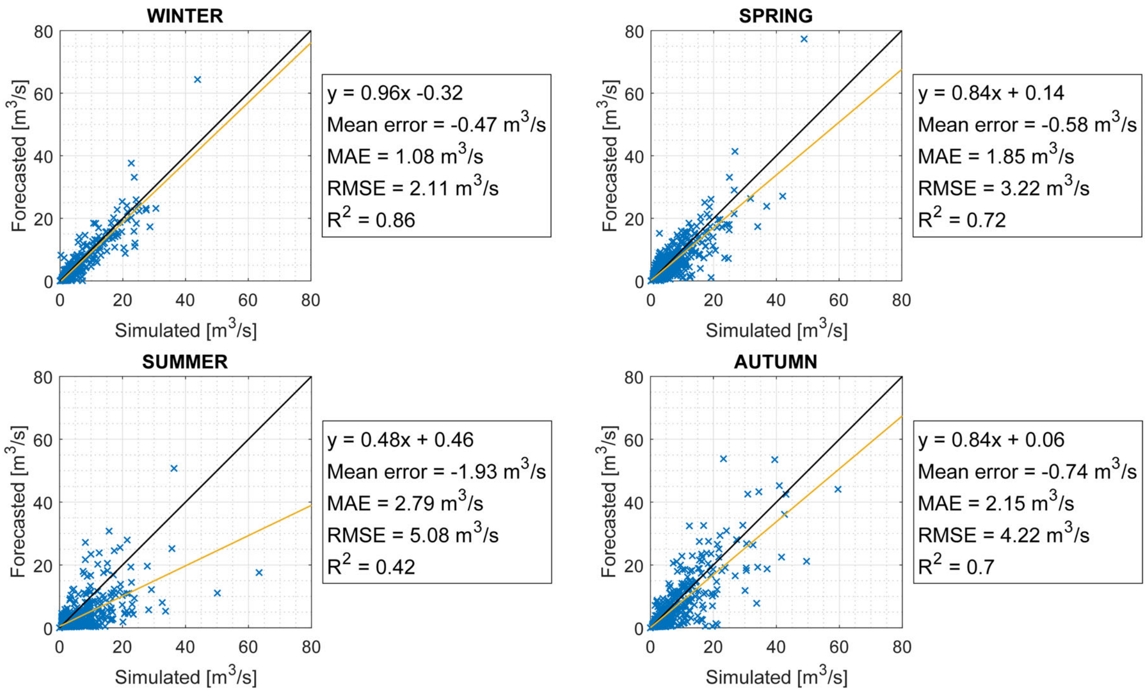

FIGURE 10 Sensitivity analysis for the daily peak discharge variable influenced by precipitation forecasts at seasonal scale.

described by the water balance equation in the FEST-WB model (Equation 8), which depends on precipitation, surface runoff, drainage fluxes and evapotranspiration, it is clear why forecasts of solar radiation (and indeed precipitation) affect the assessment of soil moisture variable. On the other hand, when forecast temperature and relative humidity are used as forcing variables, nearly perfect scores are obtained for soil moisture, demonstrating also a very weak impact of relative humidity model uncertainties, previously described.

Regarding potential evapotranspiration, results of the sensitivity analysis (Figure 8) show that solar radiation is the most relevant factor, and a marked overestimation is evident, while errors due to other meteorological variables do not influence its forecast. However, errors in solar radiation forecasting for evapotranspiration estimates generally have larger impacts on agricultural areas for water resource management and crop water requirements (Cai et al., 2007, 2009; Corbari et al., 2019; Pelosi et al., 2016) than in urban catchments which are prevalently covered by impervious surfaces.

Concerning the flow rate at Bovisio-Masciago closure section, results are shown in Figure 9. Among the four considered variables, only the forecast precipitation affects the daily peak discharge prediction, leading to a pronounced underestimation.

As done for precipitation, a possible seasonal behaviour for the daily peak discharge is analysed (Figure 10).

The scatter plots reveal that the different rainfall forecast accuracy of MOLOCH modulates the behaviour of the flowrate at seasonal scale. Thus, the predictability of flowrate is higher in winter ($R^2 = 0.86$) than in the other seasons, followed by spring and autumn with similar coefficients of determination (0.72 and 0.70, respectively), and finally summer where the agreement is very low (R^2 equal to 0.42).

4.3 | Influence of initial conditions on hydrological simulations

Having verified how far MOLOCH forecasts are reliable and that the hydrological variables are mostly affected by solar radiation and precipitation (particularly, in summertime), a new approach is here proposed to manage meteorological forecasts. In the common practice, before forcing any hydrological simulation with observed or forecast data, hydrological initial conditions (IC) have to be created running the FEST-WB model with ground measured data of the previous days (in this study, *day-1*); hence, once the initial conditions are obtained at a given current day (i.e., *day* + *0*), the model is ready to be fed by forecast data.

This analysis is set as it was in an ungauged basin where few (if any at all) ground measured data are present. Therefore, we exploit the first 24 h of weather forecasts as they were observations of the previous day. We try to investigate to what extent MOLOCH forecasts can be used to set up the ICs of the FEST-WB hydrological model in such a framework. Hence, we generated two

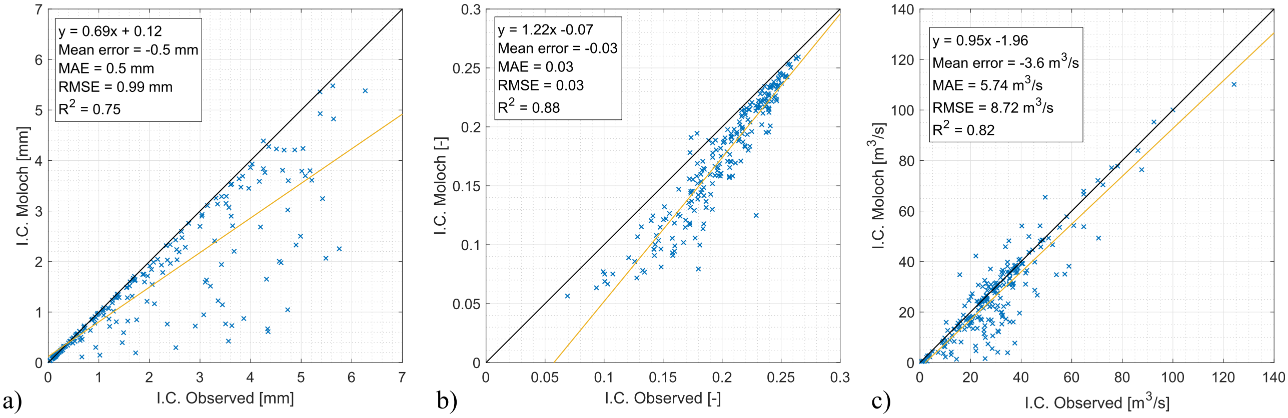

FIGURE 11 Scatter plots for daily (a) accumulated evapotranspiration, (b) mean soil moisture and (c) peak flow rate comparing hydrological forecasts forced with ICs by MOLOCH and with observed data at Bovisio-Masciago closure section.

sets of initial conditions, one obtained with instrumental data, and the other with MOLOCH forecasts; afterwards, we run the FEST-WB model to produce the two forecast scenarios with both datasets of initial conditions.

Figure 11 highlights the main results for three key components of the hydrological cycle, that is, potential evapotranspiration, soil moisture and discharge at Bovisio-Masciago closure section. A reasonable and good matching between the two sets of forecasts is attained, with a determination coefficient spanning between 0.75 and 0.88. Using the MOLOCH ICs instead of the observed ones produces lower forecast values for all the three hydrological variables.

The same exercise was carried out for the daily maximum flow rate for an upstream site of the River Seveso at Cantù closure section (Figure 12), which is 15 km north of Bovisio-Masciago city. Results show a general worsening of the skills scores in comparison with those obtained at the downstream section of Bovisio-Masicago. This indicates a stronger impact of the initial condition that can be due to the land cover and land use (LULC) characteristics of the catchment area closed at Cantù. In fact, this subbasin is less urbanized (Ceppi et al., 2022), and it presents more natural and undisturbed features, which generally require more accurate initial conditions in comparison with urban areas, the latter being less sensitive to the effect of atmospheric conditions. In fact, the Curve Number (CN) from the Corine dataset (https://land.copernicus.eu/, accessed on 1 July 2023) shows a mean value of 77 at Cantù closure section, while it increases up to 80 moving downstream to Bovisio-Masciago.

In general, taking the first 24 h of forecasts provided by MOLOCH to define the initial hydrological condition leads to a discharge estimation that is sufficiently accurate; however, specifically for heavy rainfall (and subsequently run-off) mainly caused by convective

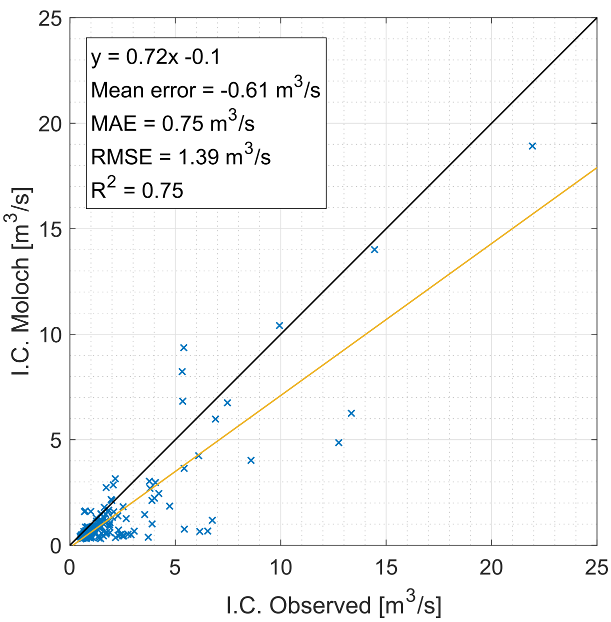

FIGURE 12 Scatter plot for the daily peak flow rate comparing hydrological forecasts forced with ICs by MOLOCH and with observed data at Cantù closure section.

phenomena, the error may become not negligible. In addition, it is worth noticing that the area of study has a very small size, lower than 200 km^2, and it is thus challenging to have accurate meteorological forecasts at such scales.

5 | CONCLUSIONS

Different factors may affect discharge forecasts, such as the lack of direct meteorological information, low predictability of some types of weather phenomena, uncertainty propagation through the forecasting chain and characteristics of the catchment determining the temporal scales of floods. Some actions should be carried out in order to overcome these difficulties, which are particularly relevant in ungauged basins where local and reliable measurements are hardly available.

In the present study, 8 years of hydrological simulations between 2013 and 2020 are investigated: in detail, we first compared observed weather data and high-resolution meteorological forecasts provided by the MOLOCH model; then, we carried out a sensitivity analysis about simulated hydrological variables obtained by forcing the hydrological FEST-WB model with measured and forecast meteorological information. Lastly, we run the hydrological forecasts using two datasets of initial conditions, one obtained with common ground instruments and the other using the MOLOCH forecasts as they were observations.

Concerning the benchmark assessment of meteorological variables, a good agreement with respect to a linear regression for temperature and solar radiation was found, while relative humidity and precipitation have a lower correspondence, and wind speed presents higher dispersion at daily scale.

The one-factor-at-a-time (OAT) methodology allowed to evaluate the performance of the MOLOCH model, providing its forecast as input into the FEST-WB model to simulate the discharge. This sensitivity analysis showed that solar radiation (beside precipitation) mostly affects the hydrological variables; in particular, a relevant overestimation of potential evapotranspiration and underestimation of soil moisture and, especially, of discharge are observed. This latter shows a seasonal behaviour with better values in winter, spring and autumn, while performances get worse in summer, which is significantly affected by local thunderstorms in the study catchments.

Dealing with discharge forecasting in ungauged basins, the results have shown that it is feasible to initialize the hydrological model with meteorological model forecasts. Considering the first 24 h of forecasts given by MOLOCH, an accurate discharge estimation is reached, but results may be sensitive to the local land cover and land use conditions over the basins: for instance, in urban areas, where soil conditions have less influence than in permeable territories, better scores are attained. However, the present study considered only a small-size catchment along the Seveso River, which is characterized by the presence of urban zones, a mountainous part and plain. Further studies in basins with different size and characteristics, for example, where snow dynamics play an important role, should be considered in order to clarify the robustness of the results here presented.

AUTHOR CONTRIBUTIONS

Alessandro Ceppi: Conceptualization (lead); data curation (lead); formal analysis (equal); investigation (equal); methodology (lead); writing – original draft (lead); writing – review and editing (lead). **Nicolás Andrés Chaves González:** Formal analysis (equal); investigation (equal); writing – review and editing (equal). **Silvio Davolio:** Data curation (equal); writing – review and editing (equal). **Giovanni Ravazzani:** Conceptualization (equal); methodology (equal); writing – original draft (equal); writing – review and editing (equal).

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CONFLICT OF INTEREST STATEMENT

The authors declare that they have no competing interests (both financial and non-financial ones).

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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