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Flood Prediction: Operational Hydrological Forecast with the Cetemps Hydrological Model (CHyM)

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Abstract

Hydrological forecasting is becoming increasingly important in the context of climate change impact assessment on people safety, economy, ecosystems and social sciences. Extreme weather events connected with water availability are becoming more frequent and predictions of hydrological phenomena deals with civil protection activities, as well as water management programs. Recently, regulation concerning the organization of the Civil Protection distributed Service strongly reiterates the role of the scientific community, as part of the system. Scientists are called to make innovative products available to end-users. From a technical point of view, the calibration of hydrological models over the Italian territory is challenging, due to its orographic and geomorphologic complexity and reduced historical hydrological time series availability, which are inhomogeneous among different Regions and catchments. Moreover, smallest basins, mainly located in Central and Southern Italy, requires higher horizontal resolution to be adequately resolved and high concentration of meteorological datasets, as well as high resolution meteorological forecasts. Meeting all those criteria deals with computational resources availability and a variety of end-users requirements in terms of hydrological simulation updating time and graphical representation. The WMO recommends that sample products should be readily available for potential customers. Starting from the positive outcome of many national and European projects the Centre of Excellence CETEMPS has developed its own experimental hydrological automatic forecasting system, the first, freely accessible online, to release daily hydrological stress deterministic simulations over the whole Italian territory.

Keywords: Hydrological modelling; Early warning system; Civil protection; Severe weather events; Hydrological tool; Flood prediction.

Introduction

The design of a flood prediction Early Warning System (EWS) is a challenging aspect in the field of hydrological modelling. Recently, the World Meteorological Organization stressed out as meteorological and water services are still separate entities in many countries, Italy included (WMO, Resolution 5.3(1)/1 (Cg-18)). Therefore, joint actions between organizations and end-users are urgently needed for water management improving, in all of its aspects. In this context, the World Bank has also recognized that products for end users should be usage-specific and available in the form of gridded numerical matrices, where observations from everywhere are assimilated into numerical weather and hydrological prediction systems. In the context of flood risk management, forecasts and warnings should be as accurate as possible, both in space and time, and particular emphasis is given to dissemination, using diverse means to match different sectors of society [1]. Consequently, development of dynamic models for real time forecasting with as narrow an error band as possible represents the major challenge for hydrological research.

The implementation of a hydrological model for operational purposes must deal with many critical aspects to be handled. First, the choice of the appropriate hydrological model and calculation schemes to be used; in particular, models for flood protection should be application-oriented [2]: as an example, operational models are needed to determine operation rules, for reservoirs management. Once the appropriate model has been chosen, its performance in predicting flood events must be assessed. This latter aspect implies the following operations to be accomplished [3]:

(i) Hydro-meteorological data transmission and collection;

(ii) Analysis of observations, as well as prediction of future rainfall, calculation of water elevations and/or discharge, both for nowcasting or few-days predictions; and

(iii) Dissemination of information to end-users.

Operations (i) and (ii) are connected with the model validation, to be carried out by selecting the appropriate validation method, as well as the most representative physical greatness to be used, which could not be the discharge value, merely [4,5]. This is particularly valid for hydrological models used in EWS, because the accuracy of flood forecast has a great impact on communities, since they are directly involved in mitigation and protection actions to be taken when a considerable flood risk is expecting to occur. In this context, Plate [2] highlighted as, in many cases, an erroneous forecast is worse than no forecast at all. The strategy to be used to calibrate and validate hydrological models depends on the hydrological data availability and reliability (i.e. dense, long and validated time series). The lack of good data strongly affects the application of distributed hydrological models [6]. Graphical representation of hydrological simulation outputs is as important as the hydrologic simulation itself: excessively simplified representation may lead to further errors, in addition to the intrinsic hydrological model uncertainties. Meeting end-user requirements for data representation, as well as understanding end-users desiderata is not always straightforward for scientists. Different end-users requires different products, for this reason, many tools have been developed to meet a variety of criteria; the diversity of these tools, as well as the need of non-experts to use them, suggests a non-trivial integration problem of building customized systems from components [7].

In this paper, the Cetemps operational hydrological forecasting system is presented. The Cetemps operational activity started in 2002, with the development of the Cetemps Hydrological Model (CHyM). Since then, the hydrological forecast, initially focused over the Abruzzo region in Central Italy, has been progressively improved through the participation to many national and international projects. In those occasions, we had the possibility to meet end users and develop dedicated hydrological products to be shared in different platforms. The Cetemps hydrological daily forecast is the first in Italy to be freely accessible, available over all catchments.

Materials and Methods

The operational hydrological forecast is organized by using a meteorological mesoscale model and a hydrological model in cascade, offline coupled. The meteorological model output fields (i.e. hourly accumulated rainfall and 2m temperature) are the required input for the hydrological model for the simulation of hydrological processes, therefore, the hydrological few-days forecast takes advantage from the meteorological forecast outputs.

The meteorological simulations are performed by using the Advanced Weather Research and Forecasting (WRF-ARW) model. The WRF-ARW, developed at National Center for Atmospheric Research (NCAR) is a non-hydrostatic model, Arakawa C grid staggering and multiple nesting capabilities [8]. Several operational forecast chains are available at CETEMPS, the latest at high resolution uses the following configuration: two-way nested domains with a spatial resolution of 3km for mother domain and 1km for child domain (centered in 41.916°N 12.47°E), respectively with 379x431 and 340x319 grid points. The first domain covers the Italian peninsula whereas, the inner domain covers Abruzzo region (Central Italy). Due to the geographic complexity of the Italian territory the orographic and topographic datasets are taken from MODIS products at 30 seconds resolution.

The initial and boundary conditions for the mother domain are provided by Global Forecast System (GFS) from the National Oceanic and Atmospheric Administration (NOAA) with a spatial resolution of 0.25°. The aforementioned operational chain is performed adopting the physics options proposed by Pichelli et al. [9] since 2006. The WSM6 scheme [10] with six class of hydrometeors is used for the microphysics, whereas vertical fluxes of momentum, moisture and heat in Planetary Boundary Layer (PBL) are parametrized using the MYJ scheme [11]. No cumulus scheme is adopted for both domains. Finally, the long wave and short-wave radiation are parametrized with Dudhia (Dudhia, 1989) and RRTM [12] schemes. A summary description of the physical parametrizations is reported in Table 1.

Table 1: WRF model set-up.

WRF Parametrizations	3km Domain	1km Domain
Microphysics	WSM6	WSM6
Cumulus parameterization	Explicitly resolved	Explicitly resolved
Long wave radiation	RRTM	RRTM
Short wave radiation	Dudhia	Dudhia
PBL	MYJ	MYJ

The WRF model outputs are used for the 2-days hydrological forecast, while the third and fourth days prediction is given by assimilating the MM5 meteorological forecast [13].

The CHyM model has been originally developed at CETEMPS (Centre of Excellence for Telesening of Environment and Model Prediction of Severe events, University of L'Aquila) since 2002, for flood prediction over the Abruzzo region. It is a distributed-grid-based model, where the main processes of hydrological cycle are explicitly parameterized. The continuity equation for the channel flow calculation is simplified according to the kinematic wave approximation of the shallow water equation [14], where the lateral inflow is balanced by the variation of the discharge in the channel length and the cross-sectional area in the time. The De Saint -Venant motion equation is simplified with the rating curve approximation, where the Manning's coefficient is depending

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on the land use. A complete mathematical description of CHyM parameterizations is given in Verdecchia et al. [15]. One of the main feature of the model is the application of cellular automata-based (CA) methods to both rebuilt the drainage network, starting from the Digital Elevation Model (DEM), and to spatialize meteorological data. This characteristic allows the model to run a hydrological simulation over any geographical domain, up to the resolution of the DEM (namely 90 meters in the current version), compatibly with the validity of the used numerical schemes. The CA-based algorithms are also used to spatialize meteorological data, merging different data sources in the same time step, according to a priority flag to be assigned to each data set [16].

Recently, due to the CHyM code high computational efficiency, the model was also applied to hydro-climatological studies [17,18] and flood forecast by using ensemble-prediction systems [19]. Tomassetti et al. [20] presented the first offline coupling with a mesoscale meteorological model, where the authors developed and validated a flood alarm index, based on the ratio between the total amount of drained rain in 48 hours and the drained area. The proposed approach was then improved during the national IDRA2 project (Italian acronym for "integration of sensor data and models for atmospheric and hydrological survey"), in partnership with the National Department of Civil Protection, and during the activities foreseen in a specific agreement between Cetemps and Abruzzo Region. In those occasions, a further enhancement of the flood alarm index was carried out over the Italian territory and specific tools were developed for the Abruzzo Region Civil Protection. As a result, the CETMPS was officially appointed as Civil Protection National Competence Center (Decree of the Head of the Civil Protection Department, issued on 14th April 2014) and Regional Competence Center in Abruzzo Region (Abruzzo Regional Council Decree no. 981/2006). Subsequent developments were carried out in the framework of the AdriaRadNet project, funded under the Adriatic-IPA CBC 2007-2014 (http://cetemps.aquila.infn.it/adriaradnet). The project brought together a heterogeneous partnership, formed by research institutes, civil protection authorities from Italy, Croatia and Albania. It aimed at creating an innovative decision support system to enhance the response capacity to extreme weather events affecting the security of people in the Adriatic areas, as well as the implementation of a flexible ICT platform for data sharing and consultation. In this context, the hydrological forecast was expanded over the Adriatic area and hydrological stress indices improved and tested over other geographical area outside the national boundaries (AdriaRadNet, 2014). A further development of the CHyM model prediction system was funded by the AdriaMORE project, in the framework of the Italy-Croatia INTERREG Programme (https://www.italy-croatia.eu/web/adriamore/) and in the national RoMA project (Resilience enhancement of a Metropolitan Area). In both projects, hydrological stress maps resulting from the CHyM hydrological simulations were made compatible with different platform for integrated environmental risk monitoring, as MyDewetra 2.0 and CipCAST, respectively [21].

Result and Discussion

The CHyM model operational forecast is issued over many geographical domains covering the whole Italian territory, the Drin and Neretva basins in Albania and Croatia, developed in the framework of the AdriaRadNet project. The covered geographical region is divided into 12 subdomains, with different spatial resolutions, ranging from 300 to 1000 meters, chosen by considering the catchment dimension, the different orographic and geomorphological structure, as well as administrative boundaries (figure 1a, 1c & 1d). The user-oriented hydrological model output is available at http://cetemps.aquila.infn.it/chymop.

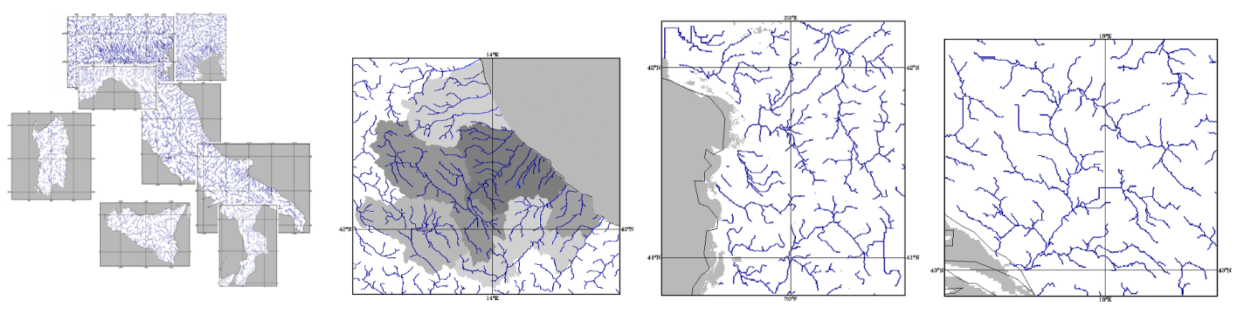
a) Sub-domains over Italy
b) Abruzzo Region basins (Central Italy)
c) Drin basin (Albania)
d) Neretva basin (Croatia)

Figure 1: Operational CHyM spatial domain over Italy, Albania and Croatia.

Continuous validation is carried out with particular regard to the Abruzzo Region domain, in particular (figure 1b), as this activity is foreseen in the official agreement between the CETEMPS and the Abruzzo Region Functional Centre (still ongoing). To this aim, a specific tool for visualizing hydrological output products is distributed to the local civil protection authorities. Moreover, a zoomed spatial domain with 300 m horizontal resolution, initialized by using WRF 1km forecast, is provided

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to the Functional Centre, as a dedicated operational simulation. However, the access to this forecast is restricted to the customer, then, is not shown in this paper.

The free access hydrological operational forecast is organized in a sequence of operations, dealing with data transfer protocols, pre-processing, simulations, post-processing and graphical representation. As mentioned in the previous section, the CHyM model is able to handle many meteorological data sources that can be used simultaneously in the same domain and in the same time-step. Different data sources are usually made available in different formats from various providers or service suppliers. For this reason, the hydrological simulation is preceded by a pre-processing phase, where all the input datasets are organized in the same format: the MuSEO format.

MuSEO files are binary files, where all meteorological data (observed or forecasted) are organized in geo-referred vectors, containing hourly variables values. Data vectors are divided by year, by source and by variable and then stored in an internal archive. During the model simulation, they are hieratically accessed by the CHyM modules, according to a priority flag to be set in the model name-list, at the beginning of a simulation. In the operational set-up, priority 1 is given to the rain gauges and thermometers data, conveniently gridded with a spatialization algorithm based on the cellular automata theory [16]. Subsequent priorities are given to weather radar estimations, satellite estimations and meteorological model simulations with decreasing spatial resolutions (when available). The binary nature of the MuSEO archive speeds the hydrological simulation. Both observed and predicted meteorological variables are converted and organized in MuSEO files.

The following observed meteorological variables are used as inputs for the CHyM model spin-up time, set to 72 hours for each subdomain:

a) Accumulated hourly precipitation by rain-gauges network [22];

b) Hourly air temperature at 2m from thermometer network [22];

c) Daily snow cover mask from MODIS Aqua and MODIS Terra detections (Hall and Riggs, 2016).

The meteorological variables used as inputs for the forecast time (96hrs, currently) are:

(i) Accumulated hourly precipitation simulated by the WRF meteorological mesoscale model;

(ii) Hourly air temperature at 2m simulated by the WRF meteorological mesoscale model.

The second phase of the operational cascade is represented by the hydrological simulation. It runs daily on a dedicated CETEMPS server with redundant characteristics, starting at 5a.m. (LT), once and the meteorological simulation is complete and the input meteorological variables are transferred to the operational server, to be pre-processed. As a consequence, observed meteorological variables are, assimilated into the CHyM model until 4a.m. (LT), which is, actually the time of the last meteorological observation available for the hydrological simulation. In figure 2, a graphical scheme of the hydrological simulation process is given.

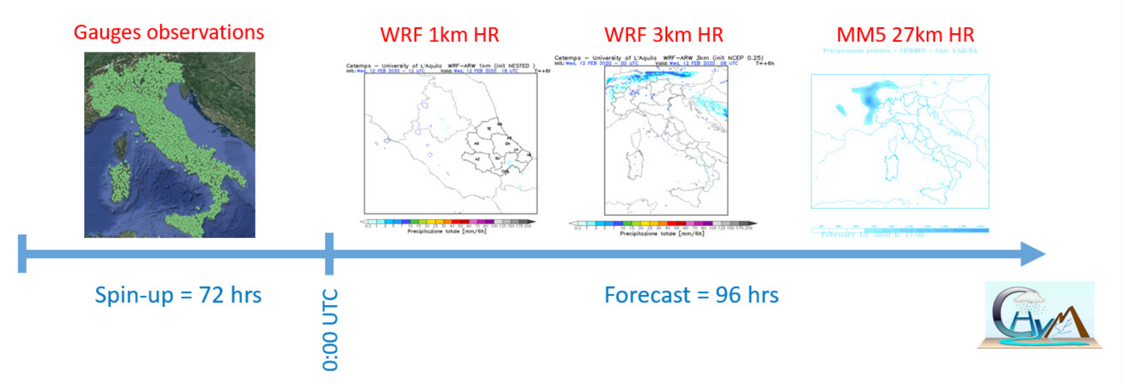

Figure 2: The CHyM model simulation set-up scheme.

Different meteorological inputs from different meteorological model settings are given to the CHyM model: the choice of using different meteorological model simulations depends on the geographical subdomain and the time-step of the hydrological simulation (see table 2 for details). In particular, the Italian Abruzzi domain (figure 1b) 24hrs hydrological prediction is carried out by assimilating 1 km spatial resolution WRF forecast, which is available for a spatial domain covering Central Italy, nested into a wider 3km horizontal resolution spatial domain, encompassing the Abruzzo region and the rest of Italy, Drin and Neretva basins from time-step 25 to 48. The last 24 simulated time-steps uses a coarser resolution MM5 run, set to 27km. The free accessible Italian, Albanian and Croatian hydrological forecasts are available each day at 2a.m. The restricted Abruzzo Region forecast runs twice a day, being available at 10a.m. and 4p.m.

Table 2: CHyM spatial subdomain set-up in terms of chosen horizontal resolution and meteorological forecast input source.

Subdomain (for numbering, please refer to http://cetemps.aquila.infn.it/chymop)	CHyM Horizontal Resolution	Meteorological Model Input
0. Abruzzo Region	300m	Timestep 1 to 48 WRF 3km
		Timestep 49 to 96: MM5 27km
1. Po Basin (Piedmont, Lombardy, Veneto, Trentino-Alto Adige, Friuli-Venezia-Giulia, Emilia-Romagna, and Liguria -North Italy)	1000m	Timestep 1 to 48 WRF 3km
		Timestep 49 to 96: MM5 27km
2. Liguria Region (North-West Italy)	400m	Timestep 1 to 48 WRF 3km
		Timestep 49 to 96: MM5 27km
3. Abruzzo, Lazio, Umbria and Marche Regions (Central Italy)	600m	Timestep 1 to 48 WRF 3km
		Timestep 49 to 96: MM5 27km
4. Veneto, Trentino-Alto Adige and Friuli-Venezia-Giulia Regions (North-East Italy)	800m	Timestep 1 to 48 WRF 3km
		Timestep 49 to 96: MM5 27km
5. Molise, Campania, Puglia and Basilicata Regions (South Italy)	500m	Timestep 1 to 48 WRF 3km
		Timestep 49 to 96: MM5 27km
6. Calabria Region (South-Italy)	300m	Timestep 1 to 48 WRF 3km
		Timestep 49 to 96: MM5 27km
7. Sicily (Island)	300m	Timestep 1 to 48 WRF 3km
		Timestep 49 to 96: MM5 27km
8. Sardinia (Island)	300m	Timestep 1 to 48 WRF 3km
		Timestep 49 to 96: MM5 27km
9 Tuscany and Emilia-Romagna regions (Central-North Italy)	800m	Timestep 1 to 48 WRF 3km
		Timestep 49 to 96: MM5 27km
10. Drin basin in Albania	800m	Timestep 1 to 48 WRF 3km
		Timestep 49 to 96: MM5 27km
11. Neretva basin in Croatia	800m	Timestep 1 to 48 WRF 3km
		Timestep 49 to 96: MM5 27km

The simulation output is written in a binary, sequentially-accessible format, containing 2D hydrological fields. However, the predicted discharge is not directly issued as a product to be displayed by the civil protection end-users. In order to better focus the hydrological information to the flood risk, two hydrological stress indices have been developed, with the aim of highlighting river segments where a flood is expected to occur (operational application can be found in Taraglio et al. [21]). The first one is the "Best Discharge Detection" (BBD) index, which is calculated as the ration between the simulated discharge values simulated over each grid-point of a river and the corresponding squared hydraulic radius, the latter being a function of the upstream drained area. BDD values are expressed as mm h^{-1}. When the BDD value exceeds a pre-defined threshold, the river segment is affected by a certain degree of hydrological stress. Three different stress degrees have been identified through the definition of likewise empirical thresholds. Then, four colour-codes (green, yellow, orange and red) are assigned to each river segment to identify the stress degree. The second hydrological stress index is the CAI (CHyM Alarm Index), which is linked to the precipitation, rather than the discharge. The CAI index is an improvement of the index developed by Tomassetti et al. [20] and is calculated for each grid-point of the spatial domain, as the ratio between the total precipitation drained by the cell, in a time interval corresponding to the mean concentration time, and the drained area upstream. Namely, it represents the average precipitation drained by a cell during a time interval corresponding to the runoff time.

An example of BDD hydrological stress map application is shown in fig.3, where the index values are reported for the whole Abruzzo Region spatial domain, for the forecast of a recent severe hydro-meteorological event, affecting this area on 14th May 2019. The complete discussion and validation of the case study goes beyond the main purpose of this paper, which is an illustration of the WRF-CHyM forecast scheme usage. In this event, maxima precipitation affected Apennine's ridge, while weaker precipitation occurred over coastal areas. Discharge peaks involved the main rivers of the North-eastern piedmont drainage network (Tronto, Vomano and Saline rivers). In the reported simulation, the hydrological forecast is issued by assimilating the WRF model forecast at 1km horizontal resolution (figure 3a).

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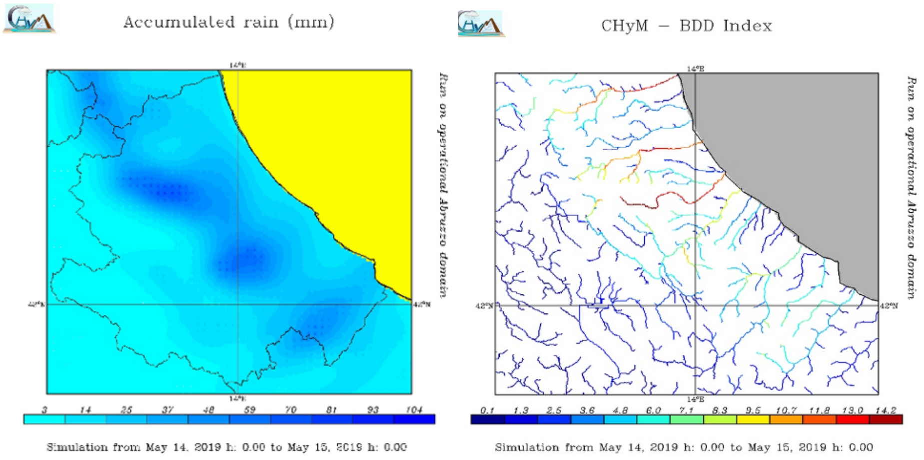
Major hydrological stress occurs over eastern side of Abruzzo, involving relevant catchments flowing into the Adriatic Sea. The most stressed rivers are highlighted in reddish colour-code in the BDD map (figure 3b). Since BDD index is computed by the model at hourly time step, a 24 hours BBD map is obtained by assigning to each grid-point of the drainage network the maximum BDD value occurred during the day.



a) 24h accumulated rainfall on May 14 2019 predicted by WRF model

b) BDD index map on May 14, 2019

Figure 3: An example of a stress index map obtained by assimilating WRF model meteorological input.

The same representation methodology is also used to release the CAI index map, not shown in this paper. The different nature of the two proposed indices allows using them in a complementary way, as BDD is more sensible to the typical fluvial flood dynamics, while the CAI index is particularly responsive to pluvial flood and flash flood events.

The graphical representation of the hydrological forecast may be considered of a secondary importance in the framework of hydrological prediction quality assessment. However, if we focus our attention to the actual purpose of a forecast, we may have to go beyond the formal validation through statistical scores [23-25].

For both the described deterministic and ensemble forecast chains, users may not be totally aware of the particular hydrological model used, its physical basis, as well as technical features related to the forecasting system set-up. Therefore, the graphical representation is the only way by means the civil protection authorities, or other end-users in general, may take decisions. For this reason, the aforementioned hydrological stress indices values are made available in a variety of images and formats:

a) In 2D maps, organized in hourly animated gif or static pictures with daily time frames;

b) In 2D animated graphs, where the temporal evolution of the two hydrological indices is shown, along the main rivers;

c) Georeferred Google Maps© files, where only indices colour-codes (hourly or daily) are represented;

d) kmz layers to be read on Google Earth© (hourly or daily);

e) ASCII-Grid raster files to be loaded into GIS environments;

f) NetCDF 2D maps (hourly or daily) available in Dewetra [22] and Mydewetra platforms.

Due to administration fees, not all the listed output is freely available for visualization.

Conclusion

The Cetemps hydrological operational short-range prediction system is based on the offline coupling of the WRF mesoscale meteorological model and the CHyM hydrological distributed model, the latter one, completely developed at Cetemps/University of L'Aquila. The hydrological forecast is freely accessible online at http://cetemps.aquila.infn.it/chymop, where is used to release hydrological stress conditions forecast over Italy and part of Albania and Croatia, by means of hydrological indices maps. The drainage network was extracted starting from the DEM data and using a cellular automata-based smoothing algorithm. In order to improve the drainage network reliability and the simulation itself, the geographical domain was divided into different subdomains with different horizontal resolution, chosen by considering orographic and geomorphological basin characteristics. Moreover, a plenty of graphical representations are available for end-users, as well as many formats, supported by the most diffused scientific packages and GIS-based software.

Declaration

Funding

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Availability of data and material

Data and materials availability are specified in the links inserted in the text and bibliography. Where not specified, they can be requested to the corresponding author.

Authors' contributions

Conceptualization: V.C. Methodology: V.C., A.L., B.T., V.M., A.R., R.F. and M.V. Discussion: V.C., A.L. and B.T. Data curation and software: V.C., A.L., B.T., M.V., V.M., A.R. and R.F. Writing-original draft preparation: V.C. Writing-review and editing: V.C., A.L., V.M., M.V, A.R., B.T. and R.F. Supervision: B.T.

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