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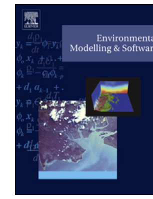

An automatic tool for reconstructing monthly time-series of hydro-climatic variables at ungauged basins

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A R T I C L E I N F O

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A B S T R A C T

Integrative information models for filling/reconstructing hydro-climatic time-series are required for a variety of practical applications. A GIS-based model for a rapid and reliable assessment of monthly time-series of several key hydro-climatic variables at the basin scale, is here developed as plug-in and applied to the entire region of Sicily (Italy). The plug-in, once the desired basin outlet section and time-window are selected, uses appropriate spatial techniques and algorithms to identify its drainage area and estimate the corresponding mean areal rainfall and temperatures time-series. A recent regional regressive rainfall-runoff model is successively applied for the assessment of the runoff time-series. Finally, a consolidated temperature-based method is applied to estimate monthly potential evapotranspiration time-series, while, actual evapotranspiration and soil moisture storage time-series are derived through a classical water balance model. The tool, supported by a preliminarily developed database, includes automatic procedures for data retrieving and processing and a user friendly interface.

Software availability

Name: Trinacria model for Monthly Time-Series (Tri.Mo.Ti.S.)
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Program language: Python
Software requirement: Quantum GIS 2.x (www.qgis.org), Grass GIS 7.x (www.osgeo.org/grass)
Source code: Available upon request

1. Introduction

The availability of long hydro-climatic data could serve research scientists, engineers and policy makers, since it is a fundamental prerequisite for the majority of the practical applications and theoretical modelling in hydrology and many other environmental disciplines. The knowledge of the key water cycle components at the basin scale and at relative coarse time-scales (monthly or annual) is of particular interest, for instance, for studies and analyses concerning water supply and watershed management, hydropower, agriculture and irrigation practices, climate change impacts and biodiversity conservation. New cross-sectoral disciplines, related to issues of sustainability and conservation of ecosystems (e.g., Yin et al., 2015) or aimed to the study of the mutual interactions between water and society (e.g., Sivapalan, 2015), urgently require new efficacious tools for reconstructing the natural hydrological response of river basins and quantify the human induced hydrological changes.

Most of the river basins across the world are practically ungauged, without *in-situ* monitoring instruments for the most important hydro-climatic variables (e.g., Gibbs at al., 2012; Visessri and McIntyre, 2016). Precipitation and temperature data are historically the most frequently measured climatic variables, even if the available time-series are often limited in sample size and/or discontinuous. The availability of measured flow time-series is currently still considerably scarce, and the measurements often suffer from systematic, random errors and gaps. *In-situ* monitoring of evapotranspiration or soil moisture storage is even rarer, despite the great economic, agronomic, ecological and biological interest associated to such measures.

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Today, remote sensing based data represents a valuable alternative for extracting spatially and temporally explicit information to monitor entire regions and additional value could be added through their integration with auxiliary data through a geo-informatics approach (e.g., Joshi et al., 2016). However, considerable limitations and challenges in the use of remote sensing data still persist: e.g. reliable, regular and extensive products could be rather expensive (especially for small areas); data are sometime ambiguously related to land use (e.g., Kim et al., 2012) and, thus, require the use of models or integration with ground-knowledge or user interpretation to infer land properties (e.g., Giri, 2012); measurement uncertainty can be large and resolution is often coarse (e.g., Lo Conti et al., 2014); the newness of such technology limits the temporal coverage of data; data management and interpretation can be difficult.

The aforementioned limitations of modern technologies and the recognized lack of field observations, both in space and in time, have catalyzed in recent years the development of several methods and techniques aimed to generate reliable estimates to infill missing data (e.g. Kim and Ryu, 2016) or reconstruct entire time-series (e.g., Pumo et al., 2014; 2016a; Viola et al., 2016, 2017).

Different modelling approaches have been also experienced and progressively improved over the past decades, with the objective of indirectly deriving a certain hydro-climatic variable starting from other monitored variables. For example, rainfall-runoff models allow for the runoff derivation from rainfall data and, often, some other interrelated variables, such as temperature or evapotranspiration. The existing models range from simple empirical and statistics techniques to complex conceptual or physically based models; some examples are the IHACRES (Jakeman et al., 1990), the SAC-SMA (Burnash, 1995), the HBV (Bergström, 1995), the tRIBS (Ivanov et al., 2004), the TOPDM (Noto, 2014), the EHSM (Viola et al., 2014).

Potential (*PET*) and actual evapotranspiration (*AET*) are very rarely measured due to the complex, expensive and hard methodology available (e.g., percolation gauge, weighing lysimeter). A number of methods and models are available for indirectly estimate also such variables using, for example, temperature based methods (e.g. Thornthwaite, 1948; Hargareaves-Samani, 1985), radiation-based methods (e.g. Priestley and Taylor, 1972) or combination methods such as the well-known Penman-Monteith method (Monteith, 1973).

Other indirect estimation methods are the so-called water balance models, which are particularly suitable for applications at the basin spatial-scale and monthly/annual time-scales (e.g., Vandewiele and Ni-Lar-Win, 2009). A comparison between different classical water balance models, including some variants of the *Thornthwaite-Mather model* (Thornthwaite and Mather, 1955), the *Palmer model* (Palmer, 1965) and the *Thomas abcd model* (Thomas, 1981), can be found, for example, in Alley. (1984). Although such models are quite old, they have been recurrently used over time for different water management issues, and their current effectiveness is demonstrated by the fact that many recent studies continue to adopt such approaches (e.g., Solander et al., 2010; Li et al., 2015; Saito et al., 2015).

Almost all the models' calibration procedures are essentially data-driven and, thus, require observed records for some data that usually are available only for a limited number of gauged basins. Appropriate regionalization techniques, defined in regions with consistent hydrological response (e.g., Oudin et al., 2008), can be used in order to apply such models also to other ungauged basins. Several regionalization procedures have been specifically developed for hydrological models, including simple spatial-proximity based methods (e.g., Vandewiele et al., 1991), which directly transfer entire parameter sets from the closest gauged basin, and more complex approaches based on physical similarity (e.g., McIntyre et al., 2005; Oudin et al., 2008, 2010; Andréassian et al., 2012), which try to integrate streamflow information from several sites in the neighborhood of the ungauged basin and additional "soft" information regarding land use, geomorphology and climate. The most commonly used regionalization method is based on parametric regression, which consists in developing "a posteriori" relationships between some morphological and climatic basins attributes and model parameters derived at gauged sites (e.g., Kim and Lee, 2014; Pumo et al., 2016b).

The basin-scale hydrological processes, as well as the different variables and basin's attributes involved in the various modelling approaches, are frequently characterized by a consistent spatial and/or temporal variability. The use of Geographical Information System (GIS) technology provides the ability to capture, store, process and visualize different and heterogeneous sets of georeferenced data. Although GISs in the past were mostly static in their geospatial representation of hydrological data, recent technological advancements are making such systems increasingly dynamic and capable of displaying data also temporally. Many GIS applications have been specially designed for hydrological purposes and some basic operations are routinely used and well consolidated such as, for example, the delineation of a watershed from a DEM or the extrapolation from point measurements of hydro-climatic data (e.g. precipitation, temperature, evapotranspiration, etc.) to areas using appropriate algorithms (e.g. Di Piazza et al., 2011, 2015).

Recent years have been witnessing an increasing interest on integrating of GIS and environmental modelling, with numerous examples of GIS application in hydrological modelling (e.g. Huang and Jiang, 2002; Castrogiovanni et al., 2005; Bhatt et al., 2014). The increasing hydro-climatic data availability (e.g. Arnone et al., 2013), also supported by satellite remote sensing data (e.g., Kim et al., 2012), the increased awareness of the hydrological processes and confidence in modelling approaches, and, finally, the development of new and efficacious information tools (e.g., Formetta et al., 2014) are all the fundamental ingredients for the modern hydrology, which should be capable of harmoniously integrating all these components.

The work proposed here moves exactly along this direction; a regional database also composed by several regional information layers, different spatial interpolation techniques and hydrological models are fully integrated, within a GIS environment, with the main aim of creating a reliable and comprehensive tool for filling/reconstructing historical hydro-climatic time-series, under natural conditions, at gauged and ungauged sites over a region.

The primary objective of this work is the creation of a new efficacious information infrastructure able to provide, for the specific case of Sicily, easily accessible and reliable estimates of six key hydrological variables (i.e. precipitation, temperature, runoff, potential and actual evapotranspiration, soil moisture storage) at any basins of the region and with regard to any historical time-window. At the same time, it is here described an easily transferable methodology that, with opportune adaptations, can be applied to different territorial contexts; for this reason, it is provided a comprehensive description of any single component of the system, from the information infrastructure to the implemented algorithms, detailing extensively the required database and information layers, the adopted spatial interpolation techniques, the entire modelistic chain, with the underlying hydrological models and their calibration procedures.

The proposed information model is a plug-in, named Tri.Mo.Ti.S. (*Trinacria model for Monthly Time-Series*, where *Trinacria* is the ancient name of Sicily), implemented within the open source GIS software Quantum GIS 2.14. The paper is structured as follows: the selected study area and the used data sources are described in Sect.