Hydrological analysis of the Upper Tiber River Basin, Central Italy: a watershed modelling approach

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Abstract:
The quantification of the various components of hydrological processes in a watershed remains a challenging topic as the hydrological system is altered by internal and external drivers. Watershed models have become essential tools to understand the behaviour of a catchment under dynamic processes. In this study, a physically based watershed model called Soil Water Assessment Tool was used to understand the hydrologic behaviour of the Upper Tiber River Basin, Central Italy. The model was successfully calibrated and validated using observed weather and flow data for the period of 1963–1970 and 1971–1978, respectively. Eighteen parameters were evaluated, and the model showed high relative sensitivity to groundwater flow parameters than the surface flow parameters. An analysis of annual hydrological water balance was performed for the entire upper Tiber watershed and selected subbasins. The overall behaviour of the watershed was represented by three categories of parameters governing surface flow, subsurface flow and whole basin response. The base flow contribution has shown that 60% of the streamflow is from shallow aquifer in the subbasins. The model evaluation statistics that evaluate the agreement between the simulated and the observed streamflow at the outlet of a watershed and other three different subbasins has shown a coefficient of determination ($R^2$) from 0.68 to 0.81 and a Nash–Sutcliffe efficiency ($E_{NS}$) between 0.51 and 0.8 for the validation period. The components of the hydrologic cycle showed variation for dry and wet periods within the watershed for the same parameter sets.

INTRODUCTION
Understanding and managing water resource problems involve complex processes and interactions at the surface, subsurface and their interface (Daniel et al., 2011). Different watersheds respond differently to the same change in those drivers, depending on physiogeographic and hydrogeologic characteristics within the system. Such effects are known to be heterogeneous and complex over time and space, which will result in scale dilemma (Bloschl and Sivapalan, 1995). Thus, the development of hydrologic and water management models has been the direct outcome of the need to understand hydrologic system behaviour with all physical and measured data.

Among the broad pallets of models, watershed-scale hydrologic models are mostly used to understand the dynamic interactions between meteorological forcing terms and land-surface hydrology (Singh and Woolhiser, 2002). They simulate hydrologic processes in a more holistic approach compared with many other models, which primarily focus on individual processes or multiple processes at relatively small- or field-scale without full incorporation of a watershed area. These models could be applicable to different purposes ranging from water quality modelling to flood and low flow simulation. Chow et al. (1988), Beven and Binley (1992) and Dingman (2002) provided a detailed classification of the hydrological models. In the last two decades, the use of such models for an assessment of the impact of climate change on water resources and agricultural productivity is becoming common practice (Xu et al., 2005; Fowler et al., 2007). Such approaches can be achieved by calibrating the watershed models on the basis of observed data and by identifying the essential parameter sets governing watershed responses. Watershed models become essential tools for water resources planning, development and management. The present study concerns characterization of the Upper Tiber River Basin using a modelling approach.

Tiber is the largest river basin in Central Italy (third largest river in Italy), draining towards the Mediterranean Sea covering land area of 17 500 km$^2$. Various authors have studied the hydrological behaviour of the basin (e.g. Corradini et al., 1995; Calenda et al., 2000; Melone et al., 2002; Di Lazzaro, 2009). The studies undertaken so far were conducted considering the individual processes taking place in the system, among others, flood forecasting (e.g. Calenda et al., 2000; Calvo and Savi, 2009; Napolitano et al., 2010), flood routing (Franchini et al., 2011) and soil moisture assessment (Brocca et al., 2009a; Brocca et al.,...
2009b) on selected parts of the Tiber River reach. Perhaps much attention has been given to the issues in flood risks as the Tiber River passes through many historical places in the regions’ urban areas including the old city of Rome (Calenda et al., 2005). However, most of the previous studies are associated to hydrologic event responses than focusing on continuous processes of the river system to the physiographic processes and climate variability taking place in the catchment. The work by Di Lazzaro (2009) perhaps provides important characteristics of the entire basin aiming to explore the capability of Width Function Instantaneous Unit Hydrograph in transferring information from gauged to ungauged basins. In the upper part of the basin, other small-scale studies have also been conducted. For example, at the confluence of Chiascio and Topino Rivers, closer to Ponte Nuovo at Torgiano flow outlet, there is known aquifer zone called Petrignano d’Assisi (covering 75 km²), which was studied in detail by Romano and Preziosi (2010). Brocca et al. (2009b) investigated the use of observed soil moisture data into rainfall–runoff model by conducting an experiment on a plot (ranging from 13 to 137 km² ) in the subbasin that can be upscaled to catchment level. They found that high variability in soil maximum retention plays a significant role on antecedent wetness condition for the hydrological response assessment. However, upscaling of such variability to a watershed level still remains a challenging research topic.

The precipitation and temperature characteristics of the Umbria region that consists of selected subbasins were studied by Todisco and Vergni (2008) and Vergni and Todisco (2011), with due emphasis on the extreme events and their impacts on crop production. Precipitation is reported to be decreasing with the increment of duration of dry period. The temperature is however reported to increase because the minimum temperature is increasing at a faster rate as compared with the maximum temperature in the region. Such changes are found to be determinant factors in the study of potential effect of climate change on water resources and evapotranspiration processes (Karl et al., 1993).

Thus, the aim of this study was to calibrate a watershed model that can help to understand catchment behaviour in the Upper Tiber River Basin. The catchment behaviour is explored considering the interaction between various hydrologic processes and external drivers like land use, soil properties, precipitation and temperature variability. It was also aimed to identify the most sensitive parameters and dominant hydrological processes in the area. The catchment responses to the climate input during the dry and wet years were also evaluated. To achieve this objective, we selected a widely used physically based Soil Water Assessment Tool (SWAT) among the available models. The ability of the model to simulate the various hydrological processes is also explored by considering different objective functions and statistical analysis.

DESCRIPTION OF THE STUDY AREA

Upper Tiber River Basin is located between 42.6°–43.85°N and 11.8°–12.92°E in the Umbria region of Central Italy. It covers an area of 4145 km² (20% of the Tiber Basin) with an elevation ranging from 145 to 1560 m a.s.l. (Figure 1). The area is predominantly mountainous, and land locked with the Italian Apennine in the eastern part represents an important physical boundary that causes variability in precipitation and temperature. Because of the topography and intense rainfall in the upstream of the
Ponte Nuovo outlet, the downstream reach experiences frequent floods. The basin is drained by the main Tiber River emanating near the Montecoronaro and the Chiascio and Topino Rivers from the left side. Figure 1 shows the location, topographic setting and subbasins boundaries used in the modelling process. Geologically, the catchment is predominated by low-permeability formations (flysch sandstone clay, clay and sandstone and limestone clay).

More specifically, Calenda et al. (2000) have also mentioned that the upper subbasin with an outlet at Ponte Nuovo (see Figure 1) is characterized by a basin lag time of 18–22 h and that the impermeable layer is assumed to be 84% of the total area (4147 Km²). The precipitation of the area is highly predominated by frontal processes coming from the Tyrrhenian Sea and orographic effect resulting from the high elevation ranges (nearly 165–1600 m a.s.l.).

**Data source and description**

Digital elevation model (DEM), weather data, soil data and land use/land cover data are the most important ones for the setup of the SWAT model and for the simulation of the hydrological components. Observed flow data at the main watershed and subbasin outlets are used for the calibration and validation of the model.

**Digital elevation model.** The DEM data were collected from Advanced Spaceborne Thermal Emission and Reflection Radiometer, which is a public data source provided by a joint program of Japan’s Ministry of Economy, Trade and Industry and the National Aeronautics Space Administration. Ten tiles that cover the Tiber Basin were downloaded from the abovementioned source and imported into ArcGIS. The DEM of the Advanced Spaceborne Thermal Emission and Reflection Radiometer with its 30-m resolution is used to delineate the watershed and to analyse the terrain characteristics. Catchment characteristics like slope gradient, slope length, stream network and stream characteristics (channel slope, length and width) were derived from the DEM using the automatic watershed delineation tool in ArcSWAT.

**Weather data.** The historical precipitation and temperature data for the study area have been provided by the hydrographic service of Umbria Region and further analysed by the Water Research Institute (IRSA-CNR) for quality control. The area is characterized by Mediterranean climate with precipitation occurring mostly from autumn to spring seasons. On the basis of the observed data in the period of 1961–1995, the mean annual rainfall is approximately 975 mm. The maximum monthly precipitation occurs in November (127 mm) and the minimum in July (44 mm). The average minimum and maximum temperatures are 15.9 °C and 27.4 °C, respectively, in the summer and 2.3 °C and 8.9 °C, respectively, in the winter. The distribution of the selected weather and gauging stations is shown in Figure 1. Relatively, there were a large number of stations over the entire basin; however, few meteorological stations have complete and continuous time series data. Moreover, some of those stations with complete data sets are located outside the selected subbasin boundary. Therefore, the missing values are calculated, including those stations lying near the subbasin in inverse distance weighted method.

**Soil and land use.** The soil data for the study area are obtained from two different sources that are publically available free of charge. The first source of data is the worldwide known Food and Agricultural Organization (FAO) soil (FAO, 2009), and the second source is from the Institute for Environment and Sustainability of the European commission Joint Research Center (JRC) (Panagos et al., 2011). The major difference between the two data sources is their spatial domain in which the later has a 1-km spatial resolution whereas the former has a 10-km spatial resolution. However, as the FAO soil is used as a base map for classification, the dominant soil types in the watershed are found to be the same from both sources. Therefore, to benefit from the finer resolution of the second sources, the essential soil input data (like available water content, hydrologic soil group, hydraulic conductivity, bulk density, etc.) were modified through the SWAT data editor module and implemented in the simulation.

There were four dominant soils (Figure 2a) found in the study area (namely, Be128-2/3bc-Eutric loam, Bd68-2bc-Dystric Cambisols loam, E23-2bc-Rendzinas clay Loam and Be129-1/2b-Eutric loam), the description of which are given in FAO soils (http://www.iiasa.ac.at/Research/LUC/External-World-soil-database/HTML/). The soil characteristic of the watershed in general is highly predominated by the soil hydrologic groups C and D, which are impermeable layers and expected to favour high surface runoff at the outlet.

The land use and land cover data with a spatial resolution of 300 × 300 m were collected from Medium Resolution Imaging Spectrometer. Further land use classification was made in the ArcSWAT model. The reclassified land cover in the watershed is predominated by agriculture and forested areas (see Table I).

**Observed flow data.** For calibration and validation purposes, we considered daily flow data for the period of 1961–1978 at Ponte Nuovo (Figure 1). The average daily discharge for the calibration period of (1961–1978) was 47.93 m³ s⁻¹, with a minimum value of 1.95 m³ s⁻¹ and maximum value of 917 m³ s⁻¹.

**DESCRIPTION OF HYDROLOGICAL MODEL**

The SWAT model was calibrated and applied for the prediction of streamflow and other hydrological components in the upper Tiber watershed. SWAT is a physically based spatially distributed watershed model (Arnold et al., 1998). This model was selected because of three main reasons: (i) the model is widely used in different part of the world even under scarce data condition (up-to-date publications can be explored from SWAT Literature Database; https://www.card.iastate.edu/swat_articles/ DOI: 10.1002/hyp

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index.aspx), (ii) it is freely available with detailed
documentation and progressive review works (e.g. Gassman
et al., 2007) and (iii) its GIS interface simplifies the spatial
data handling and catchment delineation in the modelling
processes. It is a continuous time model and allows
simulation of different hydrological processes in a water-
shed. The spatial unit for rainfall–runoff calculations is the
hydrologic response unit (HRU), which is a lumped land
area within a subwatershed comprised of unique land cover,
soil, slope and management combinations. The major
components of the model include weather, hydrology, soil,
plant growth, nutrients, pesticides and land management.
Within the HRU, water balance is represented by four
storage volumes: snow, soil profile (0–2 m), shallow aquifer
(typically 2–20 m) and deep aquifer (≥20 m).

In SWAT, the simulation of the hydrology of a watershed
can be performed in two separate divisions. The
first division is the land phase of the hydrological cycle, which
controls the amount of water, sediment, nutrient and
pesticide loadings to the main channel in each subbasin.
The second division is routing phase of the hydrologic cycle,
which can be defined as the movement of water, sediments,
nutrients and organic chemicals through the channel
network of the watershed to the outlet (Parker et al., 2007).

The hydrologic cycle in the land phase as simulated by
SWAT is based on the water balance equation:

\[ SW_t = SW_0 + \sum_{i=1}^{t} (R_{\text{day}} - Q_{\text{surf}} - E_a - W_{\text{seep}} - Q_{\text{gw}}) \]

where \( SW_t \) is the final soil water content (mm), \( SW_0 \) is the
initial soil water content on day \( i \) (mm), \( t \) is the time (days),
\( R_{\text{day}} \) is the amount of precipitation on day \( i \) (mm), \( Q_{\text{surf}} \) is the
amount of surface runoff on day \( i \) (mm), \( E_a \) is the amount of
evapotranspiration on day \( i \) (mm), \( W_{\text{seep}} \) is the amount of water
entering the vadose zone from the soil profile on day \( i \) (mm) and \( Q_{\text{gw}} \) is the amount of return flow on day \( i \) (mm).

Table I. Land use and land cover classes of the subbasin

<table>
<thead>
<tr>
<th>Land use/land cover types</th>
<th>SWAT code</th>
<th>% Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agricultural land (cropland and pasture)</td>
<td>AGRL</td>
<td>39.6</td>
</tr>
<tr>
<td>Rangeland (shrub and brush rangeland)</td>
<td>RNGB</td>
<td>29.6</td>
</tr>
<tr>
<td>Deciduous forest land</td>
<td>FRSD</td>
<td>26.0</td>
</tr>
<tr>
<td>Evergreen forested land</td>
<td>FRSE</td>
<td>0.9</td>
</tr>
<tr>
<td>Mixed range land</td>
<td>RNGE</td>
<td>0.5</td>
</tr>
<tr>
<td>Mixed urban or built-up land</td>
<td>URMD</td>
<td>3.2</td>
</tr>
<tr>
<td>Streams and canals</td>
<td>FRST</td>
<td>0.1</td>
</tr>
</tbody>
</table>

The simulated flow is further divided into the corresponding
surface flow and base flow for comparison with
observed flow data. An automated base flow separation
and recession analysis techniques (Arnold and Allen, 1999)
were used for this purpose. It is developed on the

details of equations and the methods used for the estimation
of the various hydrological processes were
given in the SWAT manual (Neitsch et al., 2005). On the
basis of data availability, the SCS curve number
procedure for surface runoff (USDA-SCS, 1972), the
Hargreave method for evapotranspiration (Hargreaves
et al., 1985) and the variable storage method (Williams,
1969) for flow routing were used in the present study.

MODEL SETUP

Modelling hydrologic responses over watershed requires
the use of soil maps or soil survey, soil hydrologic
characteristics and land use information in addition to
hydrometeorological data. The input data for the basins
were prepared (i.e. in the form of text or database files or
grid formats). After data preparation, the model setup then
performed the following four major steps: (i) watershed
delineation and derivation of subbasin characteristics, (ii)
hydrological response unit definition, (iii) model run and
parameter sensitivity analysis and (iv) calibration and
validation of the model including uncertainty analysis.

Figure 2. Dominant land use classes (a) and soil types (b) in the study area
basis of the recursive digital filter techniques (Nathan and McMahon, 1990) and filters surface runoff (high-frequency signals) from base flow (low-frequency signals). The filter can be passed over the streamflow data three times (forward, backward and forward). It can be downloaded from SWAT Web site (http://swatmodel.tamu.edu/software/baseflow-filter-program/), and the details of the methodology are explained by Arnold et al. (1995).

During the watershed delineation, the spatial data sets that include DEM, land use, soil maps and a predefined digital stream network of the main Tiber River were projected to the same coordinate system of zone 33 in Universal Transverse Mercator (UTM 33 N). The basin outlet at Ponte Nuovo was used, and the delineator in the ArcSWAT follows the steepest slope paths to define the stream networks. Unlike other automated catchment delineation processes, the procedures for filling the local depressions (fill sink), flow directions and derivation of flow accumulations, and so on, are performed using the SWAT interface. The two reservoirs in the upstream part of the Tiber River with a capacity of 142 Mm$^3$, and the second reservoir called Casanova was built on Chiascio River with a capacity of 185 Mm$^3$. However, it has to be noted that these reservoirs were not considered in the hydrological analysis because the calibration and the validation of the model are performed before 1995 (i.e. during these periods, the two reservoirs were only under construction). Finally, the basin was subdivided into 16 subbasins with their corresponding longest flow paths.

In the second step, the HRU definition was performed through the ‘HRU analysis’ module that requires the land use/land cover, the soil data and the slope of the basin. There are three options available in ArcSWAT for the definition of HRUs (Neitsch et al., 2005). This study adopted the method that can consider the spatial variability of the processes, and the data sets were prepared in spatial format and linked to the ArcSWAT. On the basis of the soil, land cover and slope data, the definition of HRU was performed that assigns a unique value for each unit in the subbasin. The FAO soil data set was linked to ArcSWAT, and the essential soil properties were updated using the data from the European commission JRC. Because the area has numerous rugged topographies, this study considered five classes of slope 0%–5%, 5%–10%, 10%–15%, 15%–20% and ≥20% to capture flow that occurs at the plain areas. The multiple HRU definition criteria were then performed using threshold values of 10% for land use, 20% for soil and 5% for slope of individual subbasin area. Overall, there were 334 HRUs defined in the entire subbasin area within 16 subbasins.

The third step is to run the model using the necessary weather data inputs and the essential information from the HRUs defined in the previous steps. Weather stations having relatively continuous daily precipitation and temperature (daily minimum and maximum) data were used in the model; in this study, we used 12 stations for precipitation and 4 studies for temperature. These weather stations were assigned to each subbasin based on their proximity to centroids of the subbasins. The simulation was run first for the calibration period of 1961 to 1970 using the first 2 years as a warm-up period. The warm-up period allowed insuring numerical stability so that the model can capture full operation of the hydrologic cycle.

The fourth step in the modelling process then relies on the outcome of the first simulation. These involve sensitivity analysis and calibration of the parameters based on selected parameter solution calibration algorithm. The fine tuning of the sensitive parameters then resulted in ranked outputs that show how the catchment behaves under the given conditions (see Table II).

**Table II.** Selected hydrologic parameters included in SWAT sensitivity analysis for the Upper Tiber River Basin (Central Italy)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Model process</th>
<th>Rank</th>
<th>Variation range</th>
<th>Fitted value</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALPHA_BF</td>
<td>Base flow recession constant (days)</td>
<td>Groundwater</td>
<td>1</td>
<td>0–1</td>
<td>0.055$^a$</td>
</tr>
<tr>
<td>CN2</td>
<td>SCS runoff curve number for moisture condition II</td>
<td>Runoff</td>
<td>2</td>
<td>±20%</td>
<td>–9$^a$</td>
</tr>
<tr>
<td>CH_N2</td>
<td>Manning’s roughness coefficient for main channel</td>
<td>Channel flow</td>
<td>3</td>
<td>0–1</td>
<td>–0.004$^c$</td>
</tr>
<tr>
<td>CH_K2</td>
<td>Effective hydraulic conductivity in main channel alluvium (mm h$^{-1}$)</td>
<td>Channel flow</td>
<td>4</td>
<td>0–150</td>
<td>15.0$^a$</td>
</tr>
<tr>
<td>GWQMN</td>
<td>Threshold water level in the shallow aquifer for return flow to occur (mm)</td>
<td>Groundwater</td>
<td>5</td>
<td>0–5000</td>
<td>350$^c$</td>
</tr>
<tr>
<td>RCHRG_DP</td>
<td>Aquifer percolation coefficient</td>
<td>Groundwater</td>
<td>6</td>
<td>0–1</td>
<td>0.10$^a$</td>
</tr>
<tr>
<td>SURLAG</td>
<td>Surface runoff lag coefficient</td>
<td>Runoff</td>
<td>7</td>
<td>0–2</td>
<td>1.00$^b$</td>
</tr>
<tr>
<td>ESCO</td>
<td>Soil evaporation compensation factor</td>
<td>Evaporation</td>
<td>8</td>
<td>0–1</td>
<td>0.85$^a$</td>
</tr>
<tr>
<td>SLOPE</td>
<td>Average slope steepness (mm$^{-1}$)</td>
<td>Geomorphology</td>
<td>9</td>
<td>±20%</td>
<td>–</td>
</tr>
<tr>
<td>SOL_Z</td>
<td>Soil depth</td>
<td>Soil water</td>
<td>10</td>
<td>20%</td>
<td>–</td>
</tr>
</tbody>
</table>

$^a$ Default values are replaced by this value (absolute change).
$^b$ Default values are multiplied by this percentage (relative change).
$^c$ Default values are increased by this value (absolute change).
Sensitivity analysis and calibration

After the first run (simulation) of the model, the responsiveness of different parameters was identified through sensitivity analysis. In this study, two approaches were used for sensitivity analysis and calibration: the fist approach is through automatic procedure and the second is through manual approach. In the automatic approach, the Latin Hypercube One-Factor-at-a-Time (van Griensven et al., 2006) method built in the ArcSWAT was used. For these analyses, there are 26 hydrological parameters in SWAT that are used to characterize the response of a catchment to the flow at the outlet. The sensitivities of such parameters are categorized into four classes according to Lenhart et al. (2002) on the basis of their mean relative sensitivity (MRS) values. MRS is a dimensionless index calculated as the ratio between the relative change of a model output and the relative change of a parameter. The variation in parameter is based on a fixed percentage of valid parameter range but not based on a fixed percentage of initial values. The mathematical explanation of this index is given by Lenhart et al. (2002), and the four classes include (i) small to negligible (0 ≤ MRS ≤ 0.05), (ii) medium (0.05 < MRS ≤ 0.20), (iii) high (0.20 < MRS ≤ 1) and (iv) very high (MRS ≥ 1) sensitivities. Ranking the parameters helps to realize the dominant process governing hydrologic system characteristics and to identify the influential parameters governing the processes.

Eighteen parameters were identified, and some parameter value ranges for the sensitivity analysis were considered on the basis of previous studies in the area rather than accepting the default values in the model. For example, the surface flow lag time (SURLAG) for the study area was reported to be more than 1 day (Calenda et al., 2000); however, this study allowed values between 0 and 2 days during sensitivity analysis so that the algorithm can optimize over this range. The sensitivity of all parameters was analysed using average observed flow at Ponte Nuovo outlet. The optimization procedure was then set to minimize the sum of squared error objective function. The final summary of parameters used in the sensitivity analysis and their description are given in Table II. On the basis of their relative indexes, the top 10 most sensitive parameters were considered for further use in the model calibration and validation processes. After identifying the most sensitive parameters, the model is set to run in autocalibration processes using parameter solution calibration algorithm (van Griensven et al., 2006), which is embedded in the ArcSWAT. The autocalibration was run for more than 1000 simulations, and the results of the best fit simulation were then compared with the observed flow at the outlet of the catchment.

The quantitative evaluation of each simulation result after parameter adjustment was performed on the basis of the values of some selected descriptive statistics and objective functions to determine the goodness of fit of the selected model (Legates and McCabe, 1999). The analysis used five commonly used goodness-of-fit tests, two of which have the dimension of the variables and three of which are dimensionless. These include the coefficient of determination ($R^2$), the Nash–Sutcliffe efficiency ($E_{NS}$) (Nash and Sutcliffe, 1970), the percent bias (PBIAS) (Yapo et al., 1996), the mean absolute error (MAE) and the root mean squared error (RMSE). Both $R^2$ and $E_{NS}$ ranges from 0 to 1, with the higher value indicating good agreement between the model and the observation. The PBIAS measures the tendency of the simulated flows to be larger or smaller than their observed counterparts; the optimal value is 0.0, positive values indicate a tendency to overestimation and negative values indicate a tendency to underestimation. For a perfect fit between the observed and the simulated flow data, the MAE and the RMSE values should be 0. However, because of various uncertainties even in the observation, perfect fit may not be expected. Singh et al. (2005) stated that values less than the standard deviation of the measured data may be considered as low and that either is appropriate for model evaluation. Following the recommendation of Moriasi et al. (2007), this study used the target objective functions: $E_{NS} > 0.5$, $-25\% \leq \text{PBIAS} \leq +25\%$ and $R^2$ to be closer to 1.

$$E_{NS} = 1 - \frac{\sum_{i=1}^{N}(O_i - S_i)^2}{\sum_{i=1}^{N}(O_i - \bar{O})^2}$$  

$$R^2 = \left[\frac{\sum_{i=1}^{N}(O_i - \overline{O})(S_i - \overline{S})}{\left[\sum_{i=1}^{N}(O_i - \overline{O})^2\right]^{0.5}\left[\sum_{i=1}^{N}(S_i - \overline{S})^2\right]^{0.5}}\right]^2$$  

$$\text{PBIAS} = \frac{\sum_{i=1}^{N}(S_i - O_i)}{\sum_{i=1}^{N}O_i} \times 100$$  

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{N}(O_i - S_i)^2}{N}}$$  

$$\text{MAE} = \frac{\sum_{i=1}^{N}|S_i - O_i|}{N}$$

where $O_i$ and $S_i$ represent the observed and the simulated flow data, respectively. $\overline{O}$ and $\overline{S}$ denote the average values of the observed and the simulated flow data, respectively.

Validation of the model

The validation of the model was performed using flow data at independent gauging stations and time window. The calibrated model at Ponte Nuovo is validated using mean monthly flow from 1970 to 1978. To test the performance of the model for the other part of the entire basin, we also compared some available flow data from other gauging stations with the output from the calibrated model. In this case, three gauging stations (namely, Santa Lucia, Ponte Felcino and Petriignano di Assisi) with observed data from 1991 to 1995 were used. The overall performance showed that the calibrated model has an acceptable agreement to simulate the flow at different subbasins in the watershed (see Table III).
RESULTS AND DISCUSSION

Parameter sensitivity analysis and model calibration

Flow parameters that govern the surface flow and groundwater flow have shown medium to very high relative sensitivity. The ranges of values used during the sensitivity analysis and the calibrated parameter value are shown in Table II. The analysis was performed using observed flow data at the basin outlet. Also, the model provides sensitivity results without flow data. Some parameters show negligible responses with the later approach, which is not actually the case when observed flow was used. For example, ALPHA_BF showed the first rank with an MRS of 1.09 when observed flow is used. However, without observed flow, it has got sixth rank with MRS value of 0.062. The study therefore relied on the sensitive parameters that responded well based on observed flow.

The parameters governing the hydrological processes in the entire watershed in the order of their sensitivity rank are shown in Table II (the first is the most sensitive). Groundwater flow parameters such as base flow recession coefficient (ALPHA_BF), threshold water level in the shallow aquifer (GWQMN) and aquifer percolation coefficient (RCHRG_DP) were identified as very sensitive parameters. Also, the soil moisture condition II curve number (CN2), the Manning roughness coefficient of channel flow (CH_N2), the effective hydraulic conductivity of the channel (CH_K2) and the surface runoff lag coefficient (SURLAG) are found to affect the surface runoff and other basin characteristics. The soil compensation factor was found to be the major determinant parameter for the evapotranspiration process in the subbasin. More specifically, it has to be noted that the ALPHA_BF, which governs the groundwater behaviour and the CN2 that govern surface runoff, were found to be the most sensitive parameters for the subbasin. This is due to the higher variable nature of the soil moisture in the study area, which was also reported by Brocca et al. (2011). As the area is dominated by low permeable layers, the sensitivity to the base recession factor was also expected. The slope of the subbasin was also one of the geomorphologic factors found to affect the catchment response behaviour as shown in Table II but has minor effect.

The sensitivity analysis was followed by the calibration of the parameters. Streamflow at the outlet was calibrated by manual and autocalibration procedures for the period of 1963–1970. Model performance was assessed using descriptive statistics and graphical representations. The autocalibration result showed an $R^2$ of 0.78 and an $E_{NS}$ of 0.51 at Ponte Nuovo station. On the basis of recommendations by Santhi et al. (2001) and Moriasi et al. (2007), the present result showed acceptable performance in terms of the $R^2$ and $E_{NS}$ for both manual and autocalibration. However, the autocalibration results in terms of PBIAS (47%), MAE (27 mm) and RMSE (34 mm) did not satisfy the recommended limits. This difference in the result of the two calibration approach is because $R^2$ and $E_{NS}$ are oversensitive to high extreme values (outliers) and insensitive to additive and proportional differences between model predictions and measured data (Legates and McCabe, 1999). Therefore, further manual calibration was performed, and the result satisfies the recommended limit as shown in Table III and Figure 4.

As depicted in Figures 3 and 4, the calibrated model slightly overestimate the flow in most cases, which can also be revealed from the PBIAS values. Therefore, to modify the discrepancies between the simulated and the observed

<table>
<thead>
<tr>
<th>Performance</th>
<th>Calibration at Ponte Nuovo (1960–1970)</th>
<th>Validation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{NS}$</td>
<td>0.85</td>
<td>0.8</td>
</tr>
<tr>
<td>PBIAS</td>
<td>–0.52</td>
<td>4.52</td>
</tr>
<tr>
<td>RMSE</td>
<td>18.95</td>
<td>21.9</td>
</tr>
<tr>
<td>MAE</td>
<td>13.44</td>
<td>13.9</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.85</td>
<td>0.81</td>
</tr>
</tbody>
</table>

Figure 3. Autocalibration results for monthly flow at Ponte Nuovo (1963–1970)

Table III. Performance of the model during the validation period
flow during the autocalibration procedure, we performed manual calibration using some relative (%) and absolute (±) adjustment on the selected parameters (Table II). The final fitted values were shown in Table II. The calibrated model showed an acceptable agreement between the observed and the simulated flow data for both daily and monthly time series. The negative value of the PBIAS indicates that there is a slight underprediction over the calibration period. Both MAE and RMSE values satisfied the requirement in which both are less than half of the standard deviation of the mean observed flow (i.e. 24.75 m$^3$ s$^{-1}$). The agreement between the observed and the simulated mean monthly flow data was also verified by analysing the mean observed and simulated flow data, which resulted in 52.97 and 55.37 m$^3$ s$^{-1}$, respectively. The average minimum flows also showed a good agreement with observed and simulated values of 4.64 and 5.51 m$^3$ s$^{-1}$, respectively. The hydrograph and rainfall time series showed the same pattern of maximum and minimum flow at the outlet (Figures 3 and 4). The calibrated model can be considered as a representative tool for further application through validation using independent data set at the main outlet of the watershed and subbasin locations.

For daily calibration, the model shows a satisfactory agreement in terms of frequency of flows as illustrated in Figure 5. Figure 5 shows that there is a slight overestimation of low flows by the model, which presumably could be due to the overextraction of groundwater at the outlet during the year 1970 as studied by Romano and Preziosi (2010). However, it can be stated that the best fit during the high flow revealed the capability of the model to capture extreme events that can further be used for flood studies in the area.

Base flow separation result using a digital filter (Arnold and Allen, 1999) also showed that most of the flow contributions during the calibration period are from the shallow aquifer flow. The filter was run over both the observed and the simulated flows, which resulted in average monthly base flow contributions of 61.8% and 62.4%, respectively, during the calibration period.

The monthly base flow variation at the outlet (Figure 6) showed that there is relatively better agreement between the observed and the simulated flows in terms of base flow than the surface flow. This is also correlated to the sensitivity analysis results where the groundwater flow parameters are highly governing the catchment characteristics as compared with surface flow parameters. Moreover, it can be inferred that the percentage bias that was seen earlier (that showed underestimation) was therefore due to the surface flow than the groundwater flow.

**Validation and performance evaluation of the SWAT model**

The validation of the calibrated model was performed using independent data. The five performance indicators during the calibration were again used in the validation period to evaluate the performance of the model. First, the model is validated at the same main basin outlet where the calibration was performed and then three other gauging locations were used for the period of 1991–1995. Two of the gauging stations were selected on the same reach of the Tiber River at the upstream of subbasin outlets (namely, Santa Lucia and Ponte Felcino) and the other station selected on the Chiascio tributary River. The summaries of model performance and validation results are shown in Figure 7 and Table III. At the selected validation stations and periods, all the performance indicators fall in the acceptable limits. Except the Ponte Nuovo station, the model underestimates the flow at all the gauging stations but still within the acceptable range. This difference was actually expected because the

![Figure 4. Manual calibration results for monthly flow at Ponte Nuovo (1963–1970)](image)

![Figure 5. Flow duration curves for Ponte Nuovo outlet](image)
The base flow separation was also performed for the validation period at the three selected gauging stations. It was shown that the base flow contributions at Santa Lucia, Ponte Felcino and Petignano di Assisi were seen to be 48%, 49% and 62%, respectively. Figure 8 shows the agreement between the observed and the simulated base flow during the validation period on the three subbasins. This indicates that the major groundwater
contributing area is located closer to the outlet and Petrignano di Assisi subbasin as it showed higher contribution with better agreement than the others.

**Hydrological water balance of upper Tiber watershed**

**Annual water balance components.** To evaluate the performance of the model for the hydrological water balance of the watershed, we estimated the major inflow and outflow components at the Ponte Nuovo outlet during calibration (1963–1970) and validation period (1971–1980). Also, the water balance for the validation period (1991–1995) was performed at the other selected three subbasins.

The summary of the annual water balance for the entire watershed and the subbasins are given in Tables IV and V. In this case, the total amount of precipitation falling on the subbasin (PRECIP) is considered as the major inflow component, whereas the actual evapotranspiration (ET) and the basin water yield (WYLD) are the major outflow components from the watershed. The WYLD in the SWAT model is defined as the summation of the surface water flow ($Q_{surf}$), the water that enters the stream from soil profile as lateral flow contribution ($Q_{lat}$) and the water that returns to the stream from the shallow aquifer also known as groundwater contribution ($Q_{gw}$) minus the total loss of water from the tributary channels as a transmission through the bed and finally reach the shallow aquifer as recharge. Another component is the percolation below the root zone commonly called *groundwater recharge* (PERC), which could be an inflow for flow at downstream of the subbasins. The water that remains in the soil profile of each subbasin is then considered as the soil water (SW) remaining at the end of the period.

From the result, it can be inferred that the maximum water yield was found in the year 1965 and 1978 for the calibration and validation period, respectively. The average simulated annual groundwater contributions were 60% and 49% for both periods, respectively. This slight decrease in groundwater contribution over the validation period is due to the consecutive ‘dry year’ occurrences as compared with the calibration period. However, the model was able to capture the effect of such frequencies, which were revealed here through smaller values of groundwater contribution. In fact, when the soil is dry enough, more infiltration was expected so that the water could join the stream either through lateral flow or deep aquifer recharge. However, in our case, the area is highly dominated by impermeable soil characteristics as explained in previous studies (e.g. Calenda et al., 2000; Di Lazzaro, 2009; Brocca et al., 2011). The dominance of such soil characteristics therefore favours surface flow than subsurface flows especially during dry period. This is also an evidence for frequent flood events along the Tiber River.

The water balance components for the validation period (1991–1995) at the three selected subbasin are also

<table>
<thead>
<tr>
<th>Year</th>
<th>PRECIP</th>
<th>ET</th>
<th>$Q_{lat}$</th>
<th>$Q_{surf}$</th>
<th>$Q_{gw}$</th>
<th>WYLD</th>
<th>PERC</th>
<th>SW</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) Calibration period</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1963</td>
<td>963</td>
<td>505</td>
<td>51</td>
<td>61</td>
<td>246</td>
<td>358</td>
<td>345</td>
<td>142</td>
</tr>
<tr>
<td>1964</td>
<td>1138</td>
<td>471</td>
<td>59</td>
<td>162</td>
<td>242</td>
<td>462</td>
<td>438</td>
<td>144</td>
</tr>
<tr>
<td>1965</td>
<td>988</td>
<td>419</td>
<td>50</td>
<td>159</td>
<td>252</td>
<td>460</td>
<td>354</td>
<td>144</td>
</tr>
<tr>
<td>1966</td>
<td>903</td>
<td>419</td>
<td>50</td>
<td>77</td>
<td>254</td>
<td>382</td>
<td>353</td>
<td>144</td>
</tr>
<tr>
<td>1967</td>
<td>671</td>
<td>366</td>
<td>29</td>
<td>98</td>
<td>98</td>
<td>225</td>
<td>173</td>
<td>144</td>
</tr>
<tr>
<td>1968</td>
<td>874</td>
<td>462</td>
<td>44</td>
<td>68</td>
<td>179</td>
<td>291</td>
<td>297</td>
<td>143</td>
</tr>
<tr>
<td>1969</td>
<td>915</td>
<td>420</td>
<td>47</td>
<td>102</td>
<td>249</td>
<td>398</td>
<td>339</td>
<td>144</td>
</tr>
<tr>
<td>1970</td>
<td>386</td>
<td>33</td>
<td>33</td>
<td>166</td>
<td>232</td>
<td>228</td>
<td>127</td>
<td></td>
</tr>
<tr>
<td>(b) Validation period</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1971</td>
<td>581</td>
<td>373</td>
<td>26</td>
<td>30</td>
<td>0</td>
<td>56</td>
<td>130</td>
<td>144</td>
</tr>
<tr>
<td>1972</td>
<td>807</td>
<td>464</td>
<td>39</td>
<td>53</td>
<td>74</td>
<td>167</td>
<td>258</td>
<td>132</td>
</tr>
<tr>
<td>1973</td>
<td>632</td>
<td>383</td>
<td>27</td>
<td>52</td>
<td>53</td>
<td>132</td>
<td>160</td>
<td>137</td>
</tr>
<tr>
<td>1974</td>
<td>677</td>
<td>399</td>
<td>33</td>
<td>48</td>
<td>76</td>
<td>157</td>
<td>197</td>
<td>135</td>
</tr>
<tr>
<td>1975</td>
<td>842</td>
<td>455</td>
<td>38</td>
<td>104</td>
<td>83</td>
<td>225</td>
<td>234</td>
<td>141</td>
</tr>
<tr>
<td>1976</td>
<td>1016</td>
<td>466</td>
<td>52</td>
<td>110</td>
<td>201</td>
<td>363</td>
<td>379</td>
<td>144</td>
</tr>
<tr>
<td>1977</td>
<td>854</td>
<td>377</td>
<td>44</td>
<td>99</td>
<td>229</td>
<td>373</td>
<td>328</td>
<td>144</td>
</tr>
<tr>
<td>1978</td>
<td>940</td>
<td>432</td>
<td>53</td>
<td>71</td>
<td>286</td>
<td>409</td>
<td>381</td>
<td>142</td>
</tr>
</tbody>
</table>

Table V. Average annual water balance components at selected subbasins (1991–1995)

<table>
<thead>
<tr>
<th>Subbasin</th>
<th>Area (km²)</th>
<th>PRECIP (mm)</th>
<th>ET (mm)</th>
<th>$Q_{lat}$ (mm)</th>
<th>$Q_{surf}$ (mm)</th>
<th>$Q_{gw}$ (mm)</th>
<th>WYLD (mm)</th>
<th>PERC (mm)</th>
<th>SW (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Santa Lucia</td>
<td>688</td>
<td>882</td>
<td>464</td>
<td>74</td>
<td>117</td>
<td>62</td>
<td>254</td>
<td>220</td>
<td>133</td>
</tr>
<tr>
<td>Ponte Felcino</td>
<td>287</td>
<td>883</td>
<td>428</td>
<td>73</td>
<td>114</td>
<td>96</td>
<td>283</td>
<td>263</td>
<td>127</td>
</tr>
<tr>
<td>Petrignano di Assisi</td>
<td>86</td>
<td>886</td>
<td>469</td>
<td>41</td>
<td>131</td>
<td>65</td>
<td>237</td>
<td>238</td>
<td>110</td>
</tr>
</tbody>
</table>

summarized in Table V as annual average. In this case, it can be seen that the rainfall is nearly the same, however, surface water exceeds the groundwater contribution at all the subbasins for the following reasons: (i) the land cover characteristic was dominated by agriculture and mixed urban areas that can potentially minimize the infiltration potential of the soil and increase runoff coefficient (Figure 2b), and (ii) the shape of the catchment is also more narrowed at the upstream, which favours fast occurrence of the quick flow and surface runoff to the main stream.

For the entire watershed, the summary of average annual water balance components is given in Table VI. From this result, it is clear that the decrease in all values of hydrological component is associated with the decrease in precipitation amount. Contrary to this, the potential evapotranspiration, estimated based on minimum and maximum temperature, showed an increase. Such effects in weather variables could call for further study about impact of climate change using different climate scenarios.

Water balance components for wet and dry years. To understand the watershed behaviour for the wet year (high rainfall) and dry year (low rainfall), this study analysed the model results by defining dry and wet years in relative terms. The dry years were defined in this study as the year when the total annual rainfall is less than the mean annual rainfall (i.e. negative deviation from the mean). The other years that have total annual rainfall greater than the mean annual rainfall (i.e. positive deviation from the mean) were then considered as wet years. The analysis is performed for the entire basin at Ponte Nuovo outlet and the three upstream subbasins separately.

Table VII shows the mean annual values of minimum and maximum flows at the basin outlets. The minimum flows were well simulated than the maximum flows at all outlets except for the calibration period of Ponte Nuovo (Figure 5). The model predicts the low flow that is supplemented more by base flow contribution to the total streamflow reasonably well.

The big difference in extreme condition like minimum flow values at Ponte Nuovo could be the effect of rainfall data quality. This analysis was interested in evaluating the overall catchment response behaviour than extreme conditions. The water balance components for the driest and wettest years of each basin were summarized in Table VIII. The results shown in Table VIII mainly focused on the components of groundwater recharge, surface flow, evapotranspiration and amount of water

### Table VI. Average annual water balance components for the entire watershed (all values are in millimetres of water)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Precipitation</td>
<td>1056</td>
<td>901</td>
</tr>
<tr>
<td>Surface runoff</td>
<td>167</td>
<td>111</td>
</tr>
<tr>
<td>Lateral flow</td>
<td>80</td>
<td>68</td>
</tr>
<tr>
<td>Shallow groundwater flow</td>
<td>179</td>
<td>91</td>
</tr>
<tr>
<td>Groundwater re-evaporation</td>
<td>95</td>
<td>95</td>
</tr>
<tr>
<td>Deep aquifer recharge</td>
<td>31</td>
<td>23</td>
</tr>
<tr>
<td>Total aquifer recharge</td>
<td>309</td>
<td>230</td>
</tr>
<tr>
<td>Total water yield</td>
<td>421</td>
<td>267</td>
</tr>
<tr>
<td>Percolation out of soil</td>
<td>300</td>
<td>228</td>
</tr>
<tr>
<td>Evapotranspiration</td>
<td>510</td>
<td>494</td>
</tr>
<tr>
<td>Potential evapotranspiration(^a)</td>
<td>953</td>
<td>969</td>
</tr>
<tr>
<td>Transmission losses</td>
<td>5</td>
<td>4</td>
</tr>
</tbody>
</table>

\(^a\) Potential evapotranspiration is not part of the water balance.

### Table VII. Dry and wet years during the model calibration and validation at different stations

<table>
<thead>
<tr>
<th>Subbasin</th>
<th>Period</th>
<th>Mean annual rainfall (mm)</th>
<th>Dry years</th>
<th>Wet years</th>
<th>Minimum flow (m(^3) s(^{-1}))</th>
<th>Maximum flow (m(^3) s(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Obs</td>
<td>Sim</td>
</tr>
</tbody>
</table>
stored in the subsurface system. In most cases of the dry year, the contribution of the groundwater flow to the total streamflow is higher than the surface flow contribution. More specifically, as we move down from the upstream subbasins to the outlet, the groundwater flow contribution shows an increasing trend. Referring back to Table II, it is also worth to note that the subbasin is highly sensitive to parameters that govern groundwater characteristics including base flow recession constant (ALPHA_BF), threshold water in the aquifer for return flow to occur (GWAMN) and aquifer percolation coefficient (RCHRG_DP). On the other hand, the parameter that governs water in the shallow aquifer returning to the root zone in response to a moisture deficit during the time step was negligible, and the groundwater delay time fitted during the calibration was higher (~31 days), which favours more aquifer storage. Because of the abovementioned reasons, the simulation result showed higher values of groundwater storage.

### CONCLUSION

Through a reasonable definition of multiple hydrological response units and through the use of relatively continuous time series weather as well as flow data, SWAT was successfully calibrated and validated for the study area. The model was calibrated using observed daily flow data at Ponte Nuovo outlet in the Upper Tiber River Basin. Like many other river basins in different part of the world (Gassman et al., 2007; Bekele and Knapp, 2010; Setegn et al., 2010), the model was able to capture all the watershed responses. The calibration and the validation results indicate that the model can be used for further application in the study area, especially for monthly and annual time steps. It was also found that the parameter set used during calibration period at the outlet performed very well for the other subbasins at the upstream part of the watershed. Such performance could assist the use of parameter transferability to other ungauged subbasins in the area. In case of scarce subsurface flow observation data, the prediction capability of the model to simulate the groundwater contribution to the total streamflow at the outlet can be considered as a better alternative for the study area.

The result of the present study showed that the major contribution of flow was from the aquifer zone closer to the outlet that reaches up to 60% of the streamflow contribution. The dry and wet period catchment water balance also showed the ability of the model to simulate the pattern of flow consistent with the weather data inputs. The flow frequency analysis has also shown that there is a strong agreement between the observed and the simulated flow for high and average flow than the low flow conditions. On the other hand, the calibration and the validation results showed that there was a consistent pattern of flow and rainfall. Therefore, it can be concluded that the model is more sensitive to weather variables than surface dynamics.

The behaviour of the watershed in terms of response to streamflow at the outlet was successfully evaluated by identifying sensitive parameters. In general, the identified parameters can be grouped into three on the basis of their significance to the system. The first category is the parameters that govern surface flow behaviour in the system, namely, antecedent moisture conditions II (CN2) and soil evaporation compensation factor (ESCO), which are the dominant ones. The second category is the parameters that govern subsurface water response, including base flow recession constant (ALPHA_BF), threshold depth of water in the shallow aquifer required for return flow to occur (GWQMN) and deep aquifer percolation fraction (RCHRG_DP). The third category is the parameters that govern the entire watershed, including the Manning’s roughness coefficient of the channel (CH_N2), the effective hydraulic conductivity of channel (CH_K2), the slope of the subbasin (SLOPE) and the surface runoff lag time (SURLAG). Through the proper adjustment of these parameters, the model can be used as a decision tool in water resources planning and management for the study area.
HYDROLOGICAL ANALYSIS

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REFERENCES


