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Evaluating the Influence of DEM Resolution and Potential Evapotranspiration Assessment on Groundwater Resources Estimation with a Reverse Hydrogeological Balance Method †

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Abstract: Quantifying groundwater resources is important for effective water resource planning and management at the river basin scale, and it has to take into account all the natural and anthropogenic components of the water balance, i.e., rainfall and runoff processes, as well as mutual interactions between surface water and groundwater, but also artificial groundwater recharges (i.e., from irrigation) and groundwater extractions. In the present study, a reverse hydrogeological balance model was applied to estimate the active mean annual recharge of the northern Etna groundwater system within the Alcantara river basin in the Sicily region (Italy), based on precipitation, temperature, and potential evapotranspiration in the area. The main objective of this study was to quantify how the digital elevation model (DEM) resolution influences the groundwater resource estimation through the abovementioned methodology and how this is also influenced by the method for potential evapotranspiration assessment. Groundwater and surface flow for our case study have been evaluated for five different DEM resolutions (20, 60, 100, 300, 500 m) and with three different theoretical approaches for evapotranspiration calculation (Turc Method, Modified Turc Method, and Budyko Method). Results were validated against isochronous recorded data of river discharge at the Moio Alcantara cross-section and show how the reverse hydrogeological balance method shows better performance if implemented with the Budyko Method for estimating evapotranspiration and by using a DEM with a 60 × 60 m grid resolution.

Keywords: hydrological water balance; groundwater-fed catchment; DEM resolution; Budyko

1. Introduction

Quantifying aquifers' active recharge is a relevant factor in the field of water resources planning and management. Direct quantification of active recharge of an aquifer cannot ignore the complexity and consistency of the data necessary for the estimation of a global hydrogeological balance (Schoeller 1962 [1]; Lerner et al. 1990 [2]), which must take into account not only natural inflows and outflows, but also water exchanges between surface and groundwater, artificial recharges (irrigation, urbanization, re-infiltration), and related withdrawals. Reverse evaluation techniques (Lerner et al. 1990 [2]) allow to estimate the average annual water resources of a given hydrogeological structure in a sufficient way to determine their importance and further developments.

The aim of this study is to quantify the influence of the spatial resolution of the digital elevation model (DEM) at the base of the method used for the evaluation of the groundwater resource of a volcanic aquifer in Sicily, in particular the hydrogeological basin of the northern side of Mount Etna (Figure 1). The applied methodology is based on the reverse hydrogeological balance technique and consists of a numerical model that can be implemented in GIS (Civita 1975; Civita and De Maio 1997a and 1997b) [3–5]. Water resources are therefore estimated in terms of active mean annual recharge, for different resolutions of the DEM meshes, in order to identify an optimal resolution (Sharma et al. 2011) [6]. Different methods for estimating real evapotranspiration in the hydrological model are also used: firstly the method proposed by Turc (1954) [7], then the same Turc method but modified for Sicilian basins (Santoro 1970) [8], and the method based on Budyko curves (Blöschl et al. 2013; Blöschl et al. 2012; Sivapalan et al. 2011; Viglione 2013) [9–12].

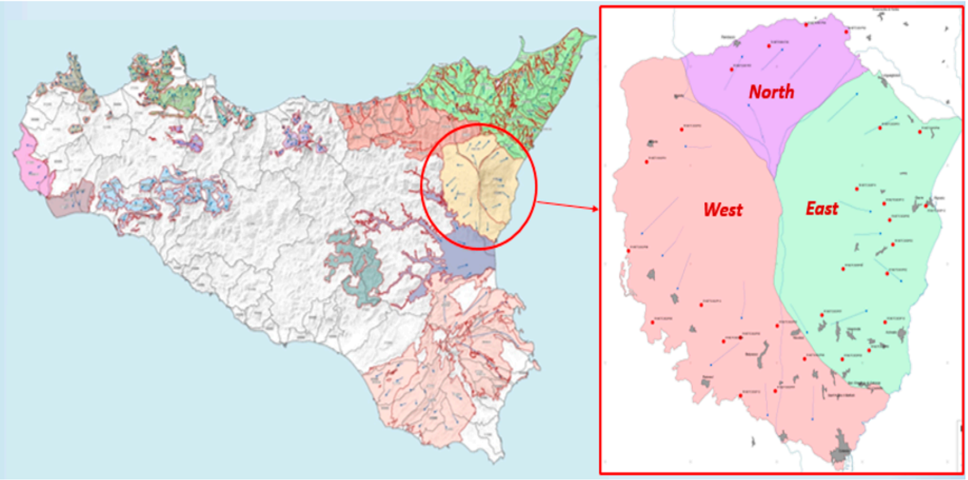

Figure 1. Main hydrogeological complexes in Sicily and the hydrogeological basin of Mount Etna (Sogesid, 2007 [13]).

2. Materials and Methods

In this study, the northern side of the hydrogeological basin of Mount Etna was considered as the case study. The groundwater resources of this hydrogeological basin serve the civil, irrigation, and industrial use, as well as the environmental use, by feeding the middle-valley stretch of the Alcantara River through springs.

The Alcantara River Basin (see Figure 2) is located in northeastern Sicily (Italy), encompassing the north side of Etna Mountain, the tallest active volcano in Europe. The river basin has an extension of about 603 km^2. The headwater of the river is at 1400 m asl in the Nebrodi Mountains, while the outlet in the Ionian Sea is reached after 50 km. Table 1 lists the main morphometric and hydrologic characteristics of the entire river basin, as well as of its main sub-basin, at Moio Alcantara.

With the *reverse hydrogeological balance* technique, the mean annual active recharge of a given area is calculated from the effective rainfall and the hydrogeological conditions that are incorporated in the infiltration index (X), determined on the basis of the superficial lithological characteristics (if the rocks are surfacing or under poor soil cover) and/or of the hydraulic characteristics of the soil. The method involves a series of steps in which the values of effective rainfall, corrected temperatures, real evapotranspiration, surface runoff, and effective infiltration are calculated cell by cell in the grid. Then, a computation is carried out at the river basin scale by adding the contributions relative to the various cells. In general, the method is validated by comparing modeled versus observed data, where these are available. In this case, the streamflow series observed at the hydrometric station of Moio Alcantara, which subtends the sub-basin highlighted in red in Figure 2, are used as observed data.

Table 1. Main characteristics of the Alcantara Basin and Moio Alcantara sub-basin (excerpted from Borzì et al. 2019 [14]).

Characteristic	Alcantara Basin	Moio Alcantara Sub-Basin
Area (km^2)	603	342
Mean elevation (m asl)	531	1142
Max elevation (m asl)	3274	3274
Min elevation (m asl)	0	510
Main river length (km)	54.67	34.66
Medium river slope	0.059	0.080
Mean annual rainfall (mm)	880	874
Mean annual runoff (mm)	342	222
Mean annual runoff coefficient	0.39	0.25
Permeable area (%)	43	46

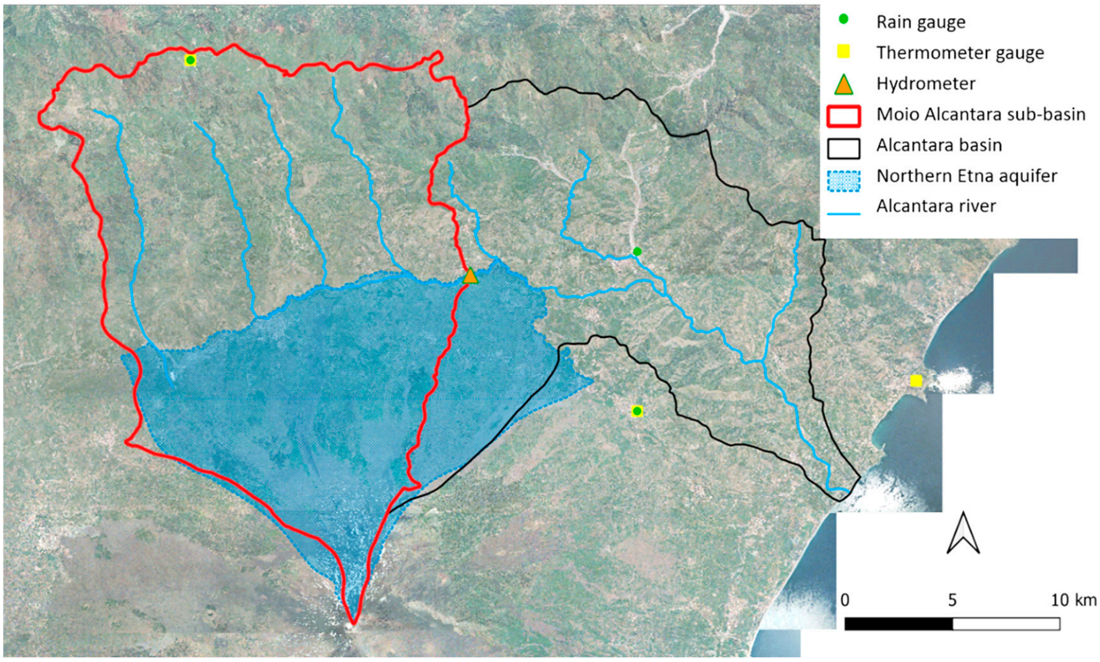

Figure 2. Moio Alcantara sub-basin (in red) and the Northern Etna groundwater aquifer (in light blue). (Excerpted from Borzì et al. 2019 [14]).

Since the proposed method relies on numerical computations carried out in a GIS environment, its results are strongly linked to the characteristics of the available information layers and, in particular, on the topography of the area under study. For this reason, the need arises to define the optimal spatial resolution for the correct evaluation of the available water resources. This issue is usually addressed by a sensitivity analysis of the DEM resolution (Sharma et al. 2011; Bormann 2006; Chaubey et al. 2005) [6,15,16]. In particular, in the present study DEM resolutions of 20, 60, 100, 300, 500 m were considered in the application of the reverse hydrogeological balance for the estimation of the groundwater resource.

Among its various steps, the model requires the calculation of specific evapotranspiration. In the inverse hydrogeological balance method, the latter is traditionally calculated by using the Turc model (1954), a function of precipitation and of the evapotranspiration power of the atmosphere. Santoro (1970) proposed a specific formulation of the Turc model for Sicilian basins. The most recent literature, on the other hand, refers to the Budyko curves (Blöschl et al. 2013; Blöschl et al. 2012; Sivapalan et al. 2011; Viglione 2013) [9–12], which provides an estimation of evapotranspiration as a function of precipitation and the Aridity Index.

In what follows, the calculation of groundwater recharge was therefore carried out for different DEM spatial resolution and evapotranspiration models mentioned above. The application of the method involves the use of isochronous rainfall and temperature, and possibly flow rate, measurements for a period of about 10–20 years. In this study, the period between 1981 and 2000 was chosen as the reference period, for which all these data are available.

3. Validation of the Methodology

For this study area, at the moment, there are no complete and reliable data on outflows from groundwater (spring discharges, water withdrawals for different uses, or other losses form the hydrogeological system) in order to be able to make comparisons on the estimated values obtained with the inverse hydrogeological balance method.

To verify the reliability of the model outputs, an alternative method was therefore adopted, based on the comparison of the surface runoff rates estimated by the different applications of the model and those observed in a specific river section equipped with a hydrometer.

Flow measurements are available along the Alcantara River at several points; in particular, here the Alcantara a Moio station was taken as the reference point (Figure 2), as it is particularly representative of the area object of study. It is located upstream of the natural springs (resurgences); consequently, it is fed only by waters of superficial flow of the two slopes. Furthermore, as reported in the Water Protection Plan of Sicily Region (Sogesid, 2007) [13], the basin subtended by the Moio-Alcantara cross-section does not show superficial derivations from the watercourse. This section subtends an area of 342 km^2 with an average altitude of 1142 m asl and a hydrometric zero at an altitude of 510 m asl.

For a reliable validation, it is essential that the hydrometric series refers to the same time period used for rainfall and temperatures in the model, i.e., the period from 1981 to 2000. The records at the Moio station in this time period are not continuous, as the recorded data are available for only 13 years out of 20. Estimated data for the missing years are retrieved by the Water Protection Plan.

The average annual flow rate from historical series (13 years out of 20) at this station is equal to 2.013 m^3/s; the average annual flow rate including the estimated data is instead equal to 2.305 m^3/s. It was decided to compare the latter value with the surface runoff R derived from the various applications of the inverse hydrogeological balance method to the left-side portion of the river at the Moio-Alcantara cross-section, summed to the surface runoff rate relative to the right-hand side (corresponding to the northern part of the Etna aquifer), complementary of the effective infiltration through which the average annual active recharge of the same hydrogeological basin was estimated.

4. Results and Discussion

The following tables show the results outcoming from the application of the reverse hydrogeological balance to the case study. In particular, Table 2 reports the results of the application with the classical Turc formula, Table 3 those obtained by the Santoro correction for Sicilian basins applied to the Turc formula, and Table 4 lists the results corresponding to the method implementing the Budyko formula for evapotranspiration assessment. In all the tables, moreover, the relative error (in percent) is reported with respect to the flow rates recorded in the Moio cross-section.

From the results, it is clear that, as regards the influence of the calculation method of evapotranspiration, the Santoro formula provided the worst outcomes in terms of accuracy. This suggests that the Santoro formula, specific for Sicilian basins, was not more suitable for this case study than the original Turc formula. This is explained by the fact that the Turc formula was applied to humid climates, while the one corrected by Santoro referred to arid and semiarid climates. Finally, the model that used the Budyko formulation turned out to be the best performing. As regards the influence of the resolution of the DEM on the estimation of the groundwater resource, it can be seen how the use of the DEM at 60 m corresponds in the latter case to the lowest value of the relative error, although there is a slight difference in the estimated value of the water resources compared to the results obtained with the other DEM resolutions, which are more or less similar to each other.

Table 2. Results of the application of the reverse hydrogeological balance to the case study: Evapotranspiration calculated with the classical Turc formula.

DEM Resolution	20 m	60 m	100 m	300 m	500 m
Estimated groundwater resource [Mm^3]	99.39	97.06	101.36	101.72	102.66
Surface runoff values from model simulations [m^3/s]	2.418	2.405	2.428	2.427	2.421
Relative Error [%]	4.93	4.35	5.33	5.29	5.06

Table 3. Results of the application of the reverse hydrogeological balance to the case study: Evapotranspiration calculated with the modified Turc formula for Sicilian's catchments.

DEM Resolution	20 m	60 m	100 m	300 m	500 m
Estimated groundwater resource [Mm^3]	100.86	104.44	102.65	103.02	103.86
Surface runoff values from model simulations [m^3/s]	2.550	2.576	2.565	2.563	2.558
Relative Error [%]	10.92	11.78	11.30	11.23	11.00

Table 4. Results of the application of the reverse hydrogeological balance to the case study: Evapotranspiration calculated with Budyko formulation.

DEM Resolution	20 m	60 m	100 m	300 m	500 m
Estimated groundwater resource [Mm^3]	67.11	77.33	67.95	68.19	68.51
Surface runoff values from model simulations [m^3/s]	2.261	2.318	2.265	2.263	2.260
Relative Error [%]	1.88	0.59	1.68	1.78	1.93

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