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The Nationwide Water Budget Estimation in the light of the New Permeability Map of Italy

La stima del bilancio idrologico nazionale con il contributo della nuova Carta della Permeabilità d'Italia

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Riassunto

Il bilancio idrologico è uno degli strumenti fondamentali per la gestione sostenibile delle risorse idriche. Negli ultimi decenni, la conoscenza della distribuzione delle risorse nello spazio e nel tempo sta assumendo sempre più interesse a causa della crescente pressione legata all'aumento della popolazione, all'inquinamento delle acque e ai cambiamenti climatici. Nell'ambito del bilancio idrologico, particolare interesse assume in Italia la stima della ricarica di falda, poiché oltre l'80% del prelievo di acqua per uso domestico e potabile è derivato dalle acque sotterranee. In questo contesto, l'Istituto Superiore per la Protezione e la Ricerca Ambientale (ISPRA) ha sviluppato un modello matematico per la stima delle componenti del bilancio idrologico a scala nazionale e macro-regionale denominato BIGBANG.

La componente di ricarica della falda è stimata come percentuale del surplus idrico mensile del suolo attraverso il coefficiente di infiltrazione potenziale, funzione della permeabilità dei complessi idrogeologici.

In questo lavoro viene effettuato un confronto, a livello nazionale e sub-nazionale, tra le stime di due delle principali componenti di bilancio idrologico, quali la ricarica degli acquiferi e il ruscellamento, effettuate sulla base della nuova e più dettagliata Carta della Permeabilità d'Italia prodotta dall'ISPRA e della vecchia mappa dei complessi idrogeologici, tuttora in uso, e finora adoperata nel modello di bilancio BIGBANG.

Abstract

The hydrological budget is one of the fundamental tools for the sustainable management of water resources. In the last decades, the knowledge of the distribution of freshwater resources in space and time is becoming of great concern due to the growing pressure related to increasing population, water pollution, and climate change. Furthermore, in the scope of hydrological balance, the estimation of aquifer assumes particular concern in Italy. In fact, more than 80% of water withdrawal for domestic and drinkable use is derived from groundwater.

In this context, the Italian Institute for Environmental Protection and Research (ISPRA) has developed a mathematical model for estimating the hydrological budget components at a national and macro-regional scale called BIGBANG.

The aquifer recharge is estimated as a percentage of the monthly soil water surplus by the potential infiltration coefficient defined as a function of the permeability of the hydrogeological complexes beneath the soil layer.

In this paper, a comparison highlighting the differences between the estimations of the long-term annual average of two of the main hydrological budget components, aquifer recharge and surface runoff, at national and sub-national levels, is carried out. The estimations are based on the new and more detailed Permeability Map of Italy produced by ISPRA and on the old map of the hydrogeological complexes currently used at national level used so far in the BIGBANG budget model.

Introduction

The hydrological budget is one of the fundamental tools for the sustainable management of water resources (Healy et al. 2007). In recent years, the problem of water scarcity, due to the increase in water demand, water pollution, and climate change, has made the water balance an even more important process for an equitable and sustainable allocation of freshwater resources (Braca and Ducci 2018).

The European Commission has also underlined the importance of this approach, specifically elaborating a guideline on water balance for the correct implementation of the Water Framework Directive (WFD) 2000/60/EC (European Commission 2015). The WFD has introduced a legal framework for sustainable management of water resources across Europe aiming at equitable access to water and ensuring the total needs of all natural ecosystems.

In the perspective of proper management of water resources, assessing the availability of the groundwater resource is a fundamental task (Ducci and Sellerino 2015; Westenbroek et al. 2018), also considering climate change (Ducci and Tranfaglia 2008). Although there is uncertainty about the future climate in Italy, there is some confidence that increased average temperatures and reduced annual rainfall will be faced in the future (Braca et al. 2019, Peres et al. 2019, Spano et al. 2020). Special attention is then paid in Italy to groundwater resource, where more than 80% of the withdrawals for civil and drinkable use comes from groundwater bodies (GWBs) (Istat, 2021).

In this context, the Italian Institute for Environmental Protection and Research (Istituto Superiore per la Protezione e la Ricerca Ambientale - ISPRA), as part of its institutional tasks, has developed a mathematical model for estimating the hydrological budget components at national scale called BIGBANG, Italian acronym of "Bilancio Idrologico GIS BAsed a scala Nazionale su Griglia regolare" meaning regular gridded nationwide GIS-based hydrological balance (Braca and Ducci 2018, Braca et al. 2019).

Based on the results of the BIGBANG model (version 4.0), in 2021 ISPRA published a systematic and detailed assessment for the period 1951–2019 of the water budget components and the natural availability of both surface water and groundwater resources (Braca et al. 2021).

This paper, after a description of the structure of the spatially distributed water balance model, presents and discusses a comparison, at national and at sub-national level, between the estimations of the long-term annual average (LTAA), referred to the period 1951-2019 of the aquifer recharge and the surface runoff hydrological budget components. This last one is strictly related to the first one due to the adopted conceptual model which will be clarified in the following sections.

These estimations are based on two different maps: the new and more detailed map of permeability produced recently by ISPRA (Gafà et al. 2019) (hereafter indicated briefly as "new map"), and the map of the hydrogeological complexes of Mouton (Mouton et al. 1982) used previously and until now in the BIGBANG water budget model (hereafter indicated briefly as "old map"). This comparison allowed to point out the importance of adequately detailed hydrogeological maps for the water budget estimation at different scales and sustainable management of water resources.

As a whole, this study focuses on the influence over the water budget components estimations based on the data from the new Permeability Map of Italy produced by ISPRA (Gafà et al. 2019) and used as input of the BIGBANG model.

Data and Methods

The study areas

Italian territory, with an extension of more than 300,000 km^2 spanning more than 10 latitude degrees (about from 35° to 47° degrees of latitude), presents a large variety of hydrogeological and morphological features associated with a great variation of climate types from North to South, which causes a very different distribution of water resources availability. Thus in this paper, it is not practicable to describe in detail Italian hydrogeological features, but many references are reporting them (Boni et al. 1986; Allocca et al. 2007; Civita 2008). From a climatic point of view, Italy is characterized by a semiarid type climate in the South, a sub-humid type in the northern plains, and a humid type in the Alps and Apennines (Mennella 1972). The analysis performed in the following sections is applied to the whole Italian territory and its subdivision in River Basin Districts (hereafter briefly indicated with RBDs) as prescribed by European Water Framework Directive (WFD) 2000/60/EC and as identified by Italian Law N. 221/2015 to highlight the variability of hydrogeological characteristics and water balance components along with the national territory. RBD means the area of land and sea, made up of one or more neighboring river basins together with their associated groundwater and coastal waters, which is identified under Article 3(1) of WFD as the main unit for management of river basins. Italy is divided into seven RBDs (Fig.1), whose extensions are shown in Table1.

Tab. 1 - Italian River Basin Districts after Italian Law N. 221/2015.
Tab. 1 - Distretti Idrografici italiani ai sensi della L. 221/2015.

River Basin District *Distretti idrografici*	Area km^2	RBD/Italy %
Eastern Alps	34,805	11.5%
Po River	82,977	27.5%
Northern Apennines	24,340	8.1%
Central Apennines	42,373	14.0%
Southern Apennines	67,646	22.4%
Sardinia	24,100	8.0%
Sicily	25,832	8.6%
ITALY	302,073	100.0%

Fig. 1 - Italian River Basin Districts after Italian Law N. 221/2015.
Fig. 1 - Distretti Idrografici italiani ai sensi della L. 221/2015.

The BIGBANG model

The BIGBANG water budget model uses a spatially distributed approach to take into account the variability of climatic quantities and physical and hydrogeological characteristics (Braca et al 2021).

The components of the hydrological balance such as total precipitation, potential and actual evapotranspiration, surface runoff and groundwater recharge are estimated at monthly time interval. By simple aggregation, the same quantities are deduced for each multi-monthly and annual time interval. The hydrological factors of total precipitation, actual evapotranspiration, surface runoff, and groundwater recharge are evaluated on a 1 km resolution grid, in the ETRS89 Datum, using the Lambert Azimuthal Equal Area (LAEA, EPSG:3035) projection. The model is implemented in a GIS environment (ESRI 2014) to exploit its powerful graphics and calculation features.

The water budget model used in BIGBANG follows the approach suggested by Thornthwaite and Mather (1955) and it simulates on each grid cell: soil moisture variations, actual evapotranspiration, groundwater recharge, and surface runoff, using a set of climatic data, as precipitation and temperature, soil and land-use data, hydraulic and geological properties.

The governing equation is based on mass balance written for the i-th month:

$$P_i - E_i = R_i + G_i + \Delta V_i \quad (1)$$

where P is the total precipitation, E is the actual evapotranspiration, R is the surface runoff, G is the groundwater recharge and ΔV is the sum of the change in soil moisture and the snow cover storage volume (Fig. 2). All the factors have been evaluated in millimeters per month. The BIGBANG model takes also into account in each cell the effect of the artificial land cover. Equation (1) is applied on each 1 km grid cell without considering the horizontal flow of water among adjacent cells neither on the land surface neither in the soil.

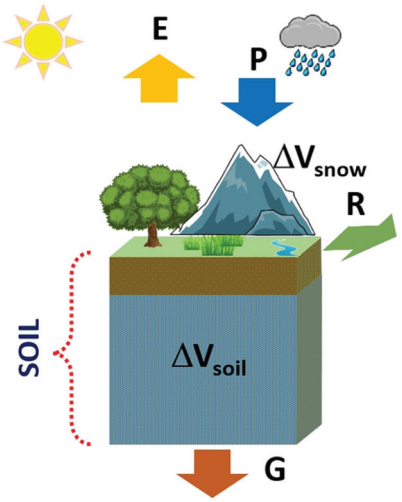

Fig. 2 - Soil water budget scheme in BIGBANG model (after Braca et al. 2021)
Fig. 2 - Schema del bilancio idrologico nel suolo nel modello BIGBANG (tratta da Braca et al. 2021).

The BIGBANG model schematizes as a reservoir a volume of the soil of 1 square kilometer for 1 meter deep, whose maximum capacity is given by the available water storage (AWS), depending on soil texture. The variable representing the soil moisture at the end of the month is water storage (WS). In the soil model, rainfall is assumed to infiltrate into the soil from which moisture is depleted by the actual evapotranspiration (AET). When the soil storage is full, the exceeding rainfall (SURPLUS) becomes surface runoff and aquifer recharge, according to the recharge scheme. Evapotranspiration is assumed to continue at its potential rate (PET) until the soil water storage reaches an intermediate characteristic value WS*, generally assumed equal to half AWS (Kandel et al. 2005) (Fig. 3).

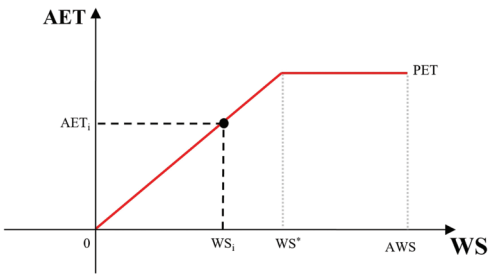

Fig. 3 - Actual evapotranspiration calculation scheme in BIGBANG model (after Braca et al. 2021)
Fig. 3 - Schema di calcolo dell'evapotraspirazione reale nel modello BIGBANG (tratta da Braca et al. 2021)

Afterward, evapotranspiration decreases linearly to zero until the storage is empty, reaching the water quantity known as wilting point. At moment, the BIGBANG model uses the 1 km grid of AWS derived from the LUCAS_TOPSOIL dataset (Toth et al. 2013).

The aquifer recharge component is then estimated, in a very simplified manner, as a percentage of the monthly soil water SURPLUS through the potential infiltration coefficient (PIC), as a function of the permeability of the hydrogeological complexes below the soil layer (Celico 1988):

$$G_i = \frac{PIC}{100} \times SURPLUS_i \quad (2)$$

and the surface runoff is calculated as the complement to SURPLUS:

$$R_i = \left(1 - \frac{PIC}{100}\right) \times SURPLUS_i \quad (3)$$

Where:

$$SURPLUS_i = \max\left\{\left[\left(P_i - PET_i\right) - \left(AWS - WS_{i-1}\right)\right], 0\right\} \quad (4)$$

with symbols having the meanings as before explained.

Further and more detailed information about BIGBANG model can be found in the dedicated ISPRA report (Braca et al. 2021).

The new ISPRA permeability map

The BIGBANG model estimates aquifer recharge and surface runoff from the potential infiltration coefficient (PIC). In the first estimate, the PIC was derived from the Mouton old map. However, by using more detailed cartography the model could achieve better results. For this reason, the new Permeability Map of Italy, developed by ISPRA (Gafà et al. 2019), was used as input for the BIGBANG model.

The Permeability Map at a scale of 1:100,000 was based on the Geological Map of Italy at the same scale and the derived Lithological Map. Before proceeding with the assignment of permeability values to the various geological units outcropping on the surface, many studies, regarding the development of permeability maps from the international to national and regional scale were collected from the scientific literature. Considering the most interesting of those experiences (Lewis et al. 2006; Gleeson et al. 2011; Kannangara and Sarrukkalige 2011; Huscroft et al. 2018; British Geological Survey 2021) and following the guidelines of the Geological Survey of Italy for the elaboration of hydrogeological mapping (Servizio Geologico Nazionale 1995; Servizio Geologico d'Italia 2018), the permeability classes were defined. The permeability type was also taken into consideration: primary (by porosity, P), secondary (by fracturing and/or karstification, F), and a combination of them (mixed, M). Each type of permeability was associated with a degree of permeability (K), from 1 to 4, which describes the maximum and minimum rate of water infiltration into the porous or fractured rock. The combination of the type (porosity, P, fracturing and karst F, and mixed M) and the degree of permeability (from 1 to 4, decreasing filtration rate ranges) led to the definition of the permeability classes.

The permeability classes and the approximate reference values of K are shown in Table 2.

Tab. 2 - Permeability classes as a combination of type and degree of permeability.

Tab. 2 - Classi di pemeabilità definiti in base alla combinazione fra il tipo e il grado di permeabilità.

Degree of permeability	Type of permeability		
	Porosity	Fracturing/ karst	Mixed
1 - highly permeability AP ($K>10^{-2}$ m/s)	P1	F1	M1
2 - moderately permeability MP ($10^{-2}>k>10^{-6}$)	P2	F2	M2
3 - low permeability SP ($10^{-6}>K>10^{-9}$)	P3	F3	M3
4 - very low permeability BP ($K<10^{-9}$)	P4	F4	M4

The permeability map was then created by associating a permeability class to lithology (Todd and Mays 1980; De Marsily 1986; Singhal and Gupta 2010; Fetter 2018) also considering the porosity and fracturing characteristics. For the application of the BIGBANG model, a range of PIC values was associated with each permeability class (Tab. 3). PICs are infiltration rates derived from observations of sample catchments and experiences in various parts of the Italian peninsula (e.g. Boni et al. 1982; Celico 1988). With the same rock formation, variations in PIC are linked to various factors such as slope gradient, vegetation cover, surface alteration of the rocks, etc.

Tab. 3 - Potential infiltration coefficient (PIC) and permeability classes.

Tab. 3 - Valori del coefficiente di infiltrazione potenziale (CIP) e classi di permeabilità.

Permeability Class *Classi di permeabilità*	PIC *CIP* %	
	max	min
P1	100	85
P2	85	50
P3	50	10
P4	10	0
F1	100	85
F2	85	60
F3	60	15
F4	15	0
M1	100	85
M2	85	55
M3	55	10
M4	10	0

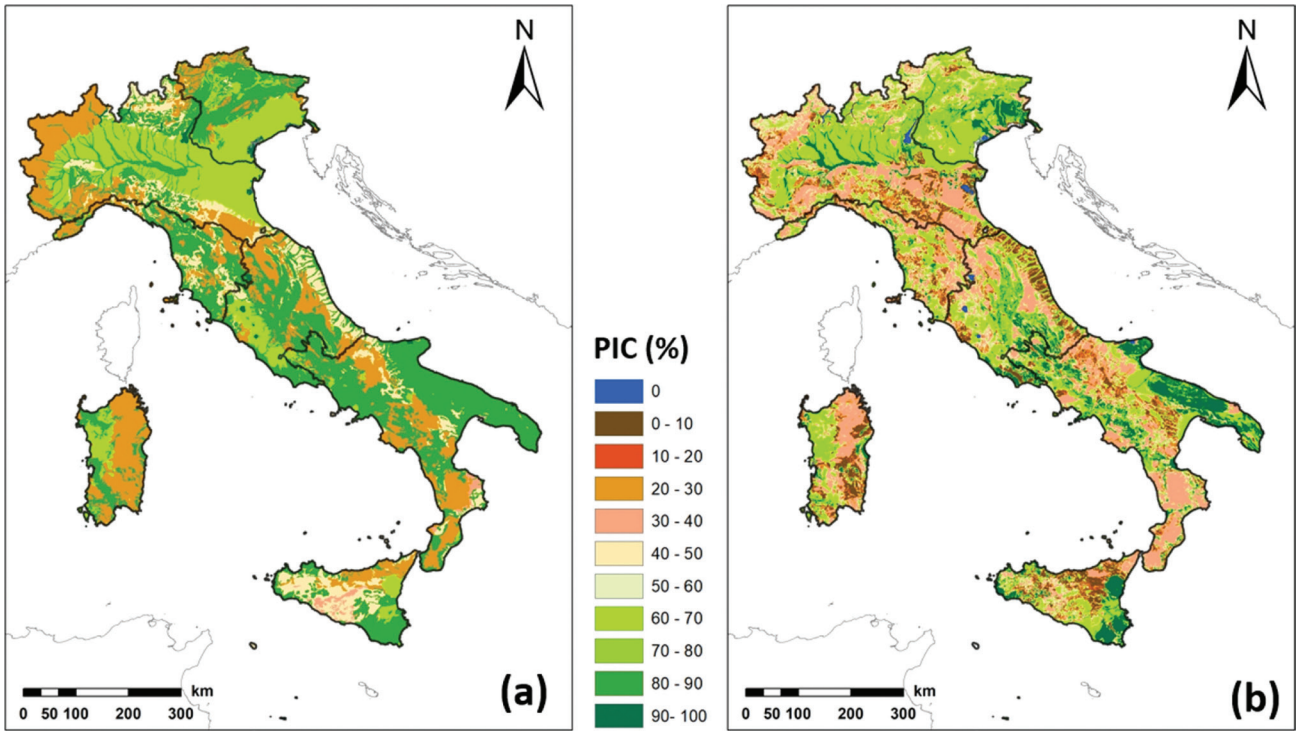

Fig. 4 - (a) Potential Infiltration Coefficient – PIC map based on Mouton map of hydrogeological complexes; (b) Potential Infiltration Coefficient - PIC map based on new ISPRA permeability map.

Fig. 4 - (a) mappa del CIP basato sulla carta dei complessi idrogeologici di Mouton; (b) mappa del CIP basato sulla nuova carta della permeabilità dell'ISPRA.

Each permeability class has been assigned to a guideline value range for PIC, characterizing lithology. As shown, the old map in Fig. 4a is coarser and less detailed than the new map in Fig. 4b. This map has been built on the same regular grid of 1 km resolution to be compliant with the BIGBANG model.

The average value on the national territory of the PIC is found to be 58.1% considering the Mouton old map. Instead, based on the new ISPRA permeability map, the national average value of the PIC is reduced by 6.3%, getting a value of 51.8%. The same situation is found in the territories of RBDs. The new map leads to a lower average value of PIC in each RBDs, with the maximum reduction in Northern Apennines District equal to 11.2% (Tab.4).

Tab. 4 - Average Potential Infiltration Coefficient (PIC) based on old and new permeability map.

Tab. 4 - Media del coefficiente di infiltrazione potenziale (CIP) basata sulla vecchia e sulla nuova carta della permeabilità.

	Average Potential Infiltration Coefficient - PIC *Media del Coefficiente di infiltrazione potenziale - CIP*		
River Basin Districts *Distretti idrografici*	PIC old map *Vecchia mappa CIP* %	PIC new map *Nuova mappa CIP* %	Difference *Differenza* %
Eastern Alps	68.2	64.7	-3.4
Po River	55.4	47.9	-7.5
Northern Apennines	56.6	45.4	-11.2
Central Apennines	60.1	51.7	-8.4
Southern Apennines	62.0	55.6	-6.4
Sardinia	44.7	43.3	-1.5
Sicily	53.9	51.1	-2.8
ITALY	58.1	51.8	-6.3

Results

At the national level, the long term annual average (LTAA) estimate of the recharge of aquifers obtained by the BIGBANG model fell by 6.0% (Tab. 5). Also for all the territories of the RBDs, except for Sardinia, the estimation of the aquifer recharge has undergone a reduction but to a very different extent. From a high reduction of 18.0% for the Northern Apennine District to a 2.7% reduction for the Po River District. Only for the District of Sardinia, the LTAA of groundwater recharge estimate has experienced an increase, although limited, of 1.9%.

In a substantially symmetrical manner, the estimate of the average value of surface runoff had an increase for the national territory and for all River Basin Districts, with the exception of Sardinia. Nationwide, the percentage increase was 6.1%, while the maximum value of 17.7% occurred in the Northern Apennines District (Tab. 6).

Discussion

The aquifer recharge is a very complex process to evaluate, which is affected by many, factors: meteorological, hydrological, geological, morphological, topographical, soil type, vegetation, human, etc.

Nevertheless, differently from the major part of groundwater recharge studies that have usually been done at a small-scale (i.e. focusing on a small area) or relating to particular groundwater body or particular lithology (Allocca et al. 2013; Jean Olivier et al. 2022), BIGBANG model is implemented to provide estimations of water balance components at macro-region or national scale, and therefore it has been possible to discard all the details of the processes and utilize a very simplified schematization (Yeh 2007; Johnson 2012). Consequently, the results of the study should be interpreted whereas these are estimates at a macro-regional scale and through a simplified model. Comparison between the estimates of the recharge of

Tab. 5 - LTAA of total precipitation and LTAA of aquifer recharge estimation based on new and old PIC map .

Tab. 5 - Precipitazione annua media e stima della ricarica degli acquiferi annua media di lungo periodo basata sulla vecchia e sulla nuova mappa del CIP .

	Total precipitation Precipitazione totale	Aquifer Recharge Ricarica degli acquiferi		
River Basin Districts *Distretti idrografici*		PIC old map *Vecchia mappa CIP*	PIC new map *Nuova mappa CIP*	Percentage difference *Differenza percentuale*
	mm	mm	mm	%
Eastern Alps	1192.9	406.8	388.9	-4.4
Po River	1022.3	220.0	214.1	-2.7
Northern Apennines	1040.5	258.7	212.2	-18.0
Central Apennines	949.3	236.8	214.5	-9.4
Southern Apennines	912.8	228.1	216.1	-5.3
Sardinia	701.5	109.5	111.6	1.9
Sicily	670.8	115.9	112.2	-3.2
ITALY	953.0	230.9	217.1	-6.0

Tab. 6 - LTAA of total precipitation and LTAA of surface runoff estimation based on new and old PIC map (CIP in Italian).

Tab. 6 - Precipitazione annua media e stima del ruscellamento annuo medio di lungo periodo basato sulla vecchia e sulla nuova mappa del CIP (PIC in inglese).

	Total precipitation Precipitazione totale	Surface Runoff Ruscellamento		
River Basin Districts *Distretti idrografici*		PIC old map *Vecchia mappa CIP*	PIC new map *Nuova mappa CIP*	Percentage difference *Differenza percentuale*
	mm	mm	mm	%
Eastern Alps	1192.9	245.6	267.4	8.9
Po River	1022.3	291.6	297.5	2.0
Northern Apennines	1040.5	262.4	308.9	17.7
Central Apennines	949.3	188.7	211.0	11.8
Southern Apennines	912.8	208.6	220.6	5.8
Sardinia	701.5	171.1	169.0	-1.2
Sicily	670.8	140.6	144.8	3.0
ITALY	953.0	228.3	242.2	6.1

the aquifers between national and local scale approaches, lead to acceptable differences attributable to several factors and to a different characterization of climatic variables (Braca and Ducci 2018).

By analyzing values shown in Table 4 and Table 5, there is no perfect correspondence between the variations of PIC and the variations of aquifer recharge (Fig. 5).

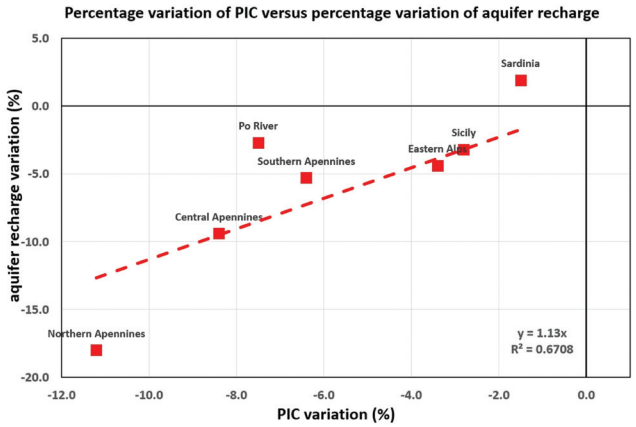

Fig. 5 - Percentage variation of average aquifer recharge versus percentage variation of average PIC in RBDs.

Fig. 5 - Variazione percentuale della ricarica degli acquiferi media rispetto alla variazione percentuale del CIP medio nei Distretti idrografici.

In the same manner, by analyzing values shown in Table 4 and Table 6 there is no perfect correspondence between the variations of PIC and the variations of surface runoff (Fig.6).

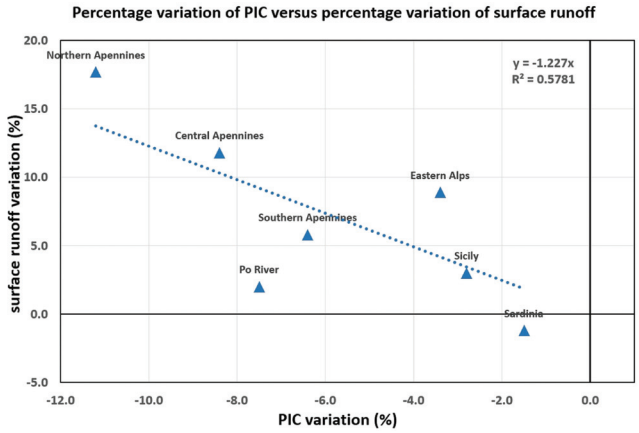

Fig. 6 - Percentage variation of average surface runoff versus percentage variation of average PIC in RBDs.

Fig. 6 - Variazione percentuale del ruscellamento medio rispetto alla variazione percentuale del CIP medio nei Distretti idrografici.

It is worth highlighting that even if the national average value of the PIC is greater than 50%, the estimate of the average recharge of the aquifer is less than 50%. This circumstance is explained by the non-homogeneous spatial distribution of precipitation that provides the input to the water cycle. It is well known that the distribution of water resources is strictly related to the distribution of precipitation.

The use of the PIC map based on the new ISPRA permeability map does not affect the estimate of the total water resources, defined, according with the main international organizations, as precipitation minus actual evapotranspiration (Eurostat/OECD 2021), but merely divides the resource differently between surface water and groundwater amounts (Fig. 7).

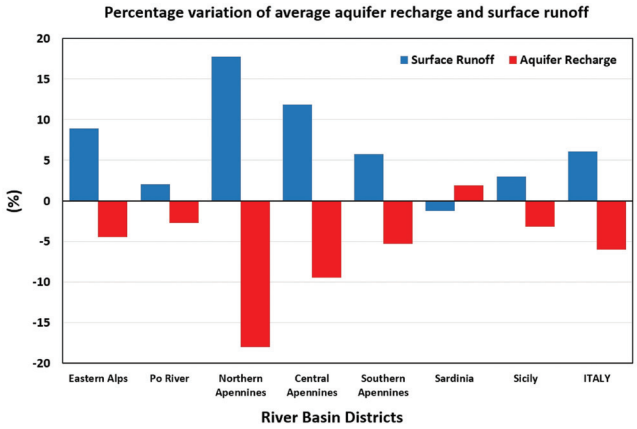

Fig. 7 - Percentage variation of average aquifer recharge and surface runoff between the old and new ISPRA permeability map.

Fig. 7 - Variazione percentuale della ricarica degli acquiferi e del ruscellamento valutate con la vecchia e nuova carta del coefficiente di infiltrazione potenziale.

At this stage of the study, there are still no elements to establish the actual improvement of the estimates through the adoption of the new permeability map but it is assumed that the enhancement of the basic information, as in fact is the new map, may improve the result, applying the same schematization of the processes.

Conclusions

The BIGBANG model is a useful tool for providing assessments at a different time and spatial scales of the natural availability of water resources. The knowledge of this availability is of fundamental importance for implementing a sustainable use of the resource itself, which, moreover, avoids exceeding the limit of its renewability within the natural hydrological cycle. However, the deterioration in the quality of water resources, the occurrence of water scarcity events and the reduction in resource availability caused by climate change increase the problem of over-exploitation and the depletion of non-renewable resources.

In this way, the BIGBANG can increasingly become an operational tool to support sustainable and adaptive management of water resources, particularly in situations of drought and water crisis, providing reliable information in a systematic and timely manner.

In this study, the difference in the estimates of the components of the hydrological balance resulting from the adoption of PIC derived from the new permeability map produced by ISPRA is presented.

Considering the same extremely simplified model for estimating the aquifer recharge and surface runoff, suitable for large-scale approaches, it is likely that the adoption of a more recent and more detailed map can provide better estimates, remaining these estimates in any case affected by high uncertainty.

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Competing interest
The authors declare no competing interest.

Author contributions
All authors conceived of the presented paper. Braca and Bussettini developed the water balance model and performed the computations. Gafà, Monti, Martarelli, Silvi and La Vigna elaborated the new permeability map of Italy. All authors discussed the results and contributed to the final manuscript.

Additional information
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