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Runoff coefficient and average yearly natural aquifer recharge assessment by physiography-based indirect methods for the island of Sardinia (Italy) and its NW area (Nurra)

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SUMMARY

Runoff estimation and water budget in ungauged basins is a challenge for hydrological researchers and planners.

The principal aim of this study was the application and validation of the Kennessey method, which is a physiography-based indirect process for determining the average annual runoff coefficient and the basin-scale water balance. The coefficient can be calculated using specific physiographic characteristics (slope, permeability and vegetation cover) and a parameter that defines climatic conditions and does not require instrumental data. One of the main purposes of this study was to compare the average annual runoff coefficient obtained using the Kennessey method with the coefficients calculated using data from 30 instrumented drainage basins in Sardinia (Italy) over 71 years (from 1922 to 1992). These measurements represent an important and complete historical dataset from the study area. Using the runoff coefficient map, the method was also applied to assess the effective annual recharge rate of the aquifers of the Calich hydrogeological basin in the Nurra Plain (Alghero, NW Sardinia-Italy). The groundwater recharge rate was compared with rates calculated using the standard water balance method. The implementation of the method at the regional and basin scales was supported by GIS analyses. The results of the method are promising but show some discrepancies with other methodologies due to the higher weights given to the physiographic parameters than to the meteorological parameters. However, even though the weights assigned to the parameters require improvements, the Kennessey method is a useful tool for evaluating hydrologic processes, particularly for water management in areas where instrumental data are not available.

1. Introduction

The water budget of a region is usually calculated before other hydrogeological methods are applied because it provides an accurate estimate of the water resources of the area. Generally, it is more practical to estimate the water balance at a scale smaller than the global scale, such as that of a watershed.

Methods for determining groundwater recharge have been intensively discussed in literature (Simmers, 1998; Lerner et al., 1990; De Vries and Simmers, 2002; Scanlon et al., 2002).

Groundwater recharge can be estimated using several approaches depending on the availability of data and the required level of accuracy, including the following: (1) inflow estimation, such as soil moisture budgets and tracers (Allison et al., 1994); (2) aquifer response (water level fluctuation method) (Sophocleous, 1991); (3) catchment water balance (Essery and Wilcock, 1990) and chloride and bromide mass balance methods (Bazuhair and Wood, 1996). Recharge can also be estimated using numerical groundwater models.

Background information on climate, geomorphology, including topography, vegetation, irrigation, soil type, permeability, physiographic setting, subsurface geology and hydrology (water-table depth, gaining vs. losing streams) must be used to develop a conceptual model (Batelaan and De Smedt, 2007). Regional groundwater models are often steady state (Sophocleus and Perkins, 2000; Carrera and Medina, 1999) and therefore need long term average recharge input.

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Recharge rates are among the most poorly constrained hydraulic parameters in almost all groundwater flow and transport models (Lerner et al., 1990; Anderson and Woessner, 1992). Therefore, recharge is often used as an adjustable parameter during model calibration (Anderson and Woessner, 1992; Sanford, 2002). Consequently, inadequate control of recharge rates can lead to a situation of non-uniqueness of flow model solutions, which may render many water resource management models unusable (Brooks et al., 1994). Furthermore, spatial variation in recharge, due to distributed land cover, soil texture, slope, etc., can be significant and should be accounted for in water budget models. Additionally, numerical models are extremely data intensive and their operation is in general beyond the capability of ground water using communities. More complete reviews of all these recharge methods are presented in Scanlon et al. (2002) and Cherkauer and Ansari (2005).

However, as models do not produce unique solutions, they should not be relied upon as a sole technique for estimating recharge (Scanlon et al., 2002).

To simulate the long-term average groundwater recharge, surface runoff and evapotranspiration in Dire Dawa (Ethiopia), Tilahun and Merkel (2009) used WetSpass, which is a spatially-distributed water balance model. WetSpass is a physically-based methodology that utilises land cover, soil type, topography and long-term average standard hydrometerological parameters as input. It integrates GIS and the water balance method (Batelaan and De Smedt, 2001, 2007).

Additional concerns influencing the choice of a method include time and cost constraints. If recharge estimates have to be developed in a short time (months), techniques based on long-term monitoring (several years) cannot be used.

Because the cost of field surveys restricts the ability to collect large amounts of experimental data, it has become increasingly necessary to develop methodologies that describe on-going processes and project scenarios using a limited amount of data.

Certain boundary conditions (system stresses), such as precipitation, evapotranspiration, aquifer recharge, and stream flow discharge, are not easily quantifiable, or data regarding these parameters are often not available. In these cases, their values must be estimated using an objective procedure (called model calibration or parameter estimation) that is consistent with observed field measurements (Ghiglieri et al., 2010; Spadoni et al., 2010).

What is needed then is a relatively simple, reasonably accurate estimate of groundwater recharge that relies on readily available information.

This paper presents a methodology to calculate recharge and runoff coefficient from readily available ground surface information without long-term monitoring. The method is viewed as providing a reasonable, but conservative, first approximation of water budget, which can then be fine-tuned with other methods as time permits.

In this study, we applied and validated the Kennessey method, which is a physiography-based indirect method for determining the average annual runoff coefficient and the water budget of a watershed.

This approach is not a substitute for traditional methodologies that rely on expensive field datasets, but it has important advantages in providing a first approximation of the basin-scale water balance, particularly in ungauged watersheds. Moreover, among the simple empirical models, the Kennessey method provides values by accounting for the main factors wherefrom the components of the water budget are influenced: climate characteristic, surface permeability, mean slope and vegetation cover.

Kennessey (1930) first applied the method in studying several basins in Hungary, and it has been subsequently applied and modified by several authors, who have validated the reliability of the method under different climatic and physical–geographical conditions in several basins in North-Central Italy (Tardi and Vittorini, 1977; Barazzuoli et al., 1986; Bauducco et al., 1994; Gazzetti et al., 2005; Spadoni et al., 2010; Grillone et al., 2014). In addition, runoff has been calculated using an adaptation of the method proposed by Kennessey (1930) to identify the factors that control the recharge/discharge processes of several springs in the Apennine Mountains of Central Italy (Spadoni et al., 2010).

The primary objective of our research is to apply and validate the Kennessey method on 30 basins that are homogeneously distributed across Sardinia (Italy) using 71 years of observations and measurements (NSISS) (RAS and EAF, 1998) at a scale of 1:25,000. The second objective is to apply the Kennessey method at a local scale in the Calich hydrogeological basin (Nurra, NW Sardinia) to calculate the runoff data that are necessary to define the effective infiltration from the water balance equation. The overlay of the effective infiltration results over the spatial distribution of the aquifers (Ghiglieri et al., 2006, 2009a,b) allowed for the regulatory reserves/stocks volumes, which are expressed in $m^3\ year^{-1}$, to be estimated for each aquifer. These volumes were compared with those estimated by Ghiglieri et al. (2010) by applying the classical method of the hydrogeological balance (Civita et al., 1995; Civita and De Maio, 2001). The scale of the information in the Calich basin is 1:25,000.

As the proposed model adopts a geographically based integrated evaluation system, a Geographical Information Systems (GIS) was used for data acquisition and processing. The advantage of embedding the methodology in GIS is that it can allow easy evaluation of the effects of land cover changes on recharge. Additionally, the GIS approach proves to be very useful in the spatial analysis of the simulated recharge, and could be used to optimise the recharge conditions and improve groundwater protection and sustainability. Additional advantages derive from the fact that in recent years many countries have provided spatial variable physiographic (i.e. land cover, geological, morphologic, etc.) data in digital form. Moreover, hydrogeological modelling using GIS has become a standard for environmental studies and allows for the integration of diverse datasets (Shaban et al., 2006; Storck et al., 1998; Vijay et al., 2007).

2. Description of the study areas

2.1. General setting of Sardinia

Sardinia, which is located in the Mediterranean Sea (Fig. 1a), is composed of Palaeozoic and pre-Palaeozoic granitic basement rocks that are overlain by discontinuous sedimentary and volcanic units deposited in marine or continental environments between the Permo-Carboniferous and the Quaternary (Carmignani et al., 2001). Sardinia is approximately rectangular in shape and has a total surface area of 24,089.53 km^2, including several small islands. Although hills make up more of the island (67.9%) than mountains (18.5%) and plateaus and internal and coast plains (13.6%), and although the area has an average elevation of 334 m, the slopes are so steep that most of the island is considered mountainous. The average high and low temperatures are 8 °C and 21 °C, respectively, and the annual average temperature is 14.5 °C. The average precipitation is 764 mm (approximately 18 billion $m^3\ year^{-1}$), but the intensity and length of the rainy season varies from year to year (Delitala et al., 2000). Furthermore, the combined effect of temperature and high winds on the island causes an inflow loss due to significant evapotranspiration. The unique physiographic conditions of Sardinia cause torrential flows in almost all of the rivers; the maximum runoff occurs in the autumn and spring, and runoff is lower during the summer.

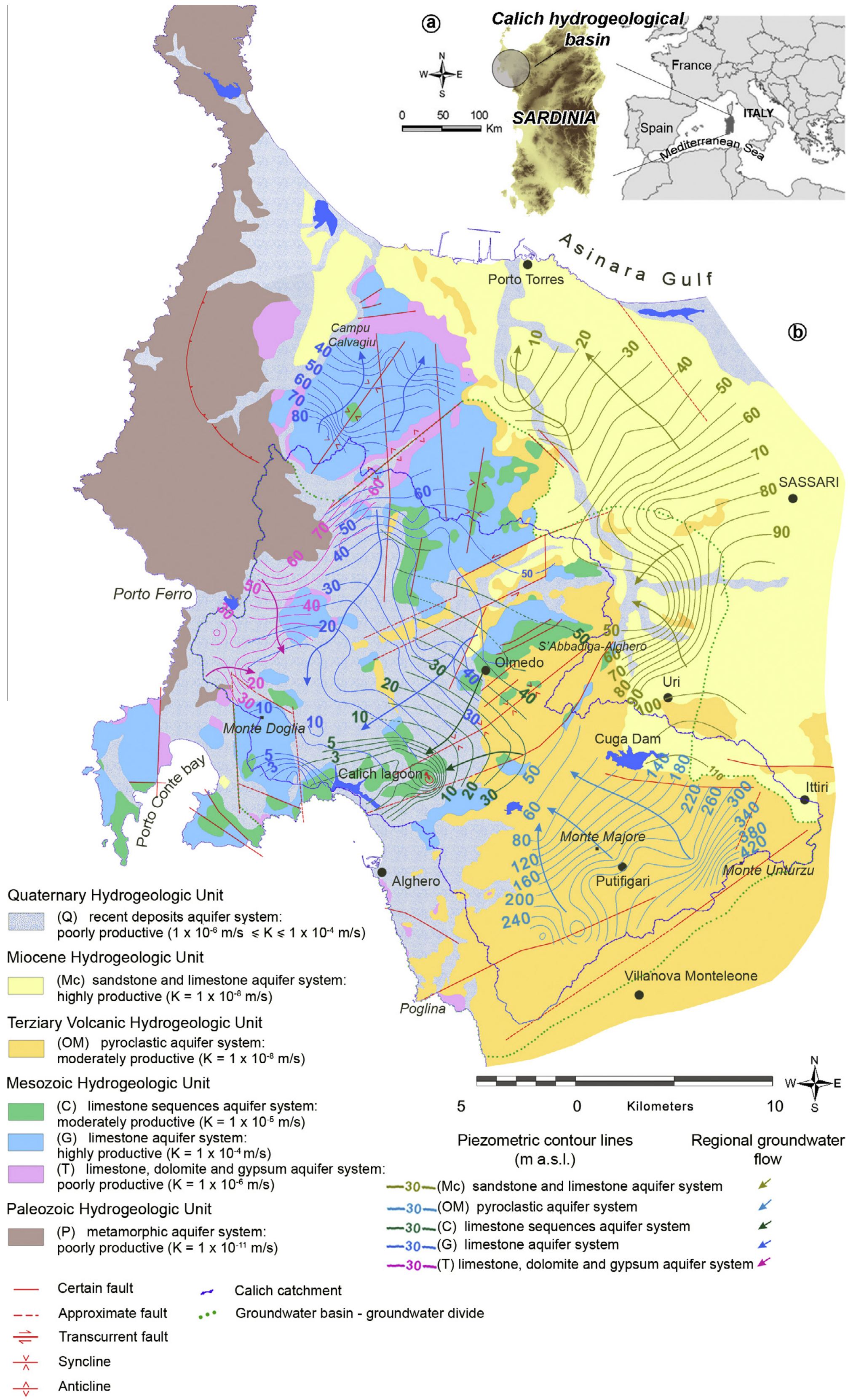

Fig. 1. (a) Map of Sardinia. (b) Hydrogeological map of the Calich hydrogeological basin (modified from Ghiglieri et al., 2009a).

2.2. General setting of the Calich hydrogeological basin

The Nurra Region (Fig. 1b) is located in northwest Sardinia and covers an area of 578 km^2. The region is part of the hydrogeological basin that underlies the Calich coastal lagoon. The surface runoff is funnelled into small valleys and flows directly into the sea. The catchment area generally drains towards the southwest. The area has a dry/sub-humid Mediterranean climate, and the mean annual rainfall ranges from 475 mm in low-lying areas to 900 mm at higher elevations. The mean annual temperature is 15.7 °C (Motroni et al., 2003). The study area contains a complete stratigraphic sequence ranging in age from the Palaeozoic to Quaternary. A hydrogeological assessment was performed using data collected during geological and structural surveys, geophysical prospecting and a detailed hydrochemical study conducted during the *Integrated Research Project for applying new technologies and processes for combating desertification* (RIADE Project) (Ghiglieri et al., 2006, 2009a).

Five main hydrogeologic units were identified and are divided into seven hydrogeologic complexes that are characterised by medium to high yields. The groundwater in the different aquifers is exploited using deep boreholes that can attain discharges as high

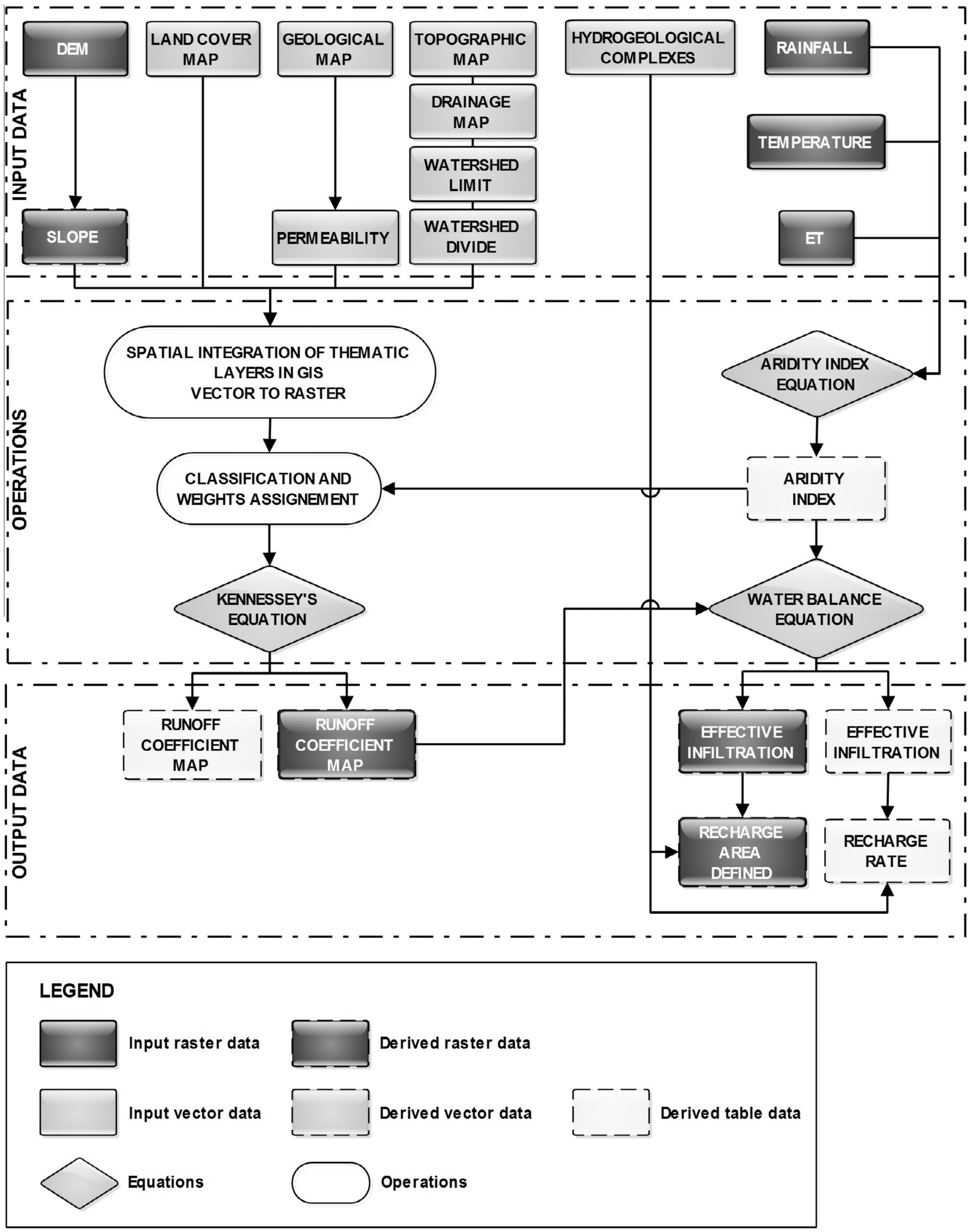

Fig. 2. Conceptual workflow for the calculation of the runoff coefficient (C_k) using the Kennessey method and for the assessment of the average yearly natural aquifer recharge.

as 145 L s^{-1}. Fig. 1b shows the hydrogeological setting as well as the main groundwater flow directions for each aquifer (Ghiglieri et al., 2006, 2009a,b).

3. Materials and methods

The mean annual runoff coefficient (C_k) is determined using the Kennessey method with the following procedure, as reported in the conceptual workflow in Fig. 2.

The value of C_k of a river basin is the sum of three components (C_a, C_v, and C_p), which represent the effects of the slope, vegetation land cover, and permeability of the outcropping rocks, respectively, on the surface runoff. According to the physical meaning of each component, partial runoff coefficient increases with increasing slope, with decreasing soil permeability, and by passing from forest land use to bare rock. Furthermore, partial runoff coefficient increases when passing from dry to wet climate basin conditions.

Each component is classified into four classes, and a coefficient related to three possible values is assigned to each class based on climatic conditions (Table 1). Because Kennessey (1930) does not mention the criteria that should be used to choose each series of coefficients based on climatic conditions, the annual average aridity index I_a (Tardi and Vittorini, 1977) was used in this study and is determined according to De Martonne (1926):

$$I_a = \frac{\left[\left(\frac{P}{T+10}\right) + \left(12\frac{p}{t}\right)\right]}{2} \quad (1)$$

where P is the annual average inflow (mm), T is the annual average temperature (°C), and p and t are the inflow and the temperature of the hottest month, respectively (expressed in mm and °C, respectively). Barazzuoli et al. (1986) pointed out that this index, because it is a function of rainfall and temperature, which have the greatest influence on the climate, is better than other average climatic conditions in specific areas.

As shown in Table 1, each of the three series of coefficients corresponds to an interval of values of the aridity index I_a.

Once the partial runoff coefficients (C_a, C_v, and C_p) are calculated, the basin C_k is evaluated by its simple addition, after weighting the basin homogeneous area fractions, where homogeneity has to be intended for each of the classes.

The hydrogeological balance method (Civita et al., 1995; Civita and De Maio, 2001) consists of a numerical model that was designed to evaluate the mean annual groundwater recharge (effective infiltration). Based on values reported in the literature and knowledge gained directly in the area, potential infiltration coefficients (C_i) were assigned to the hydrogeologic units (Table 2). With the effective precipitation (EP) and the areas of the outcropping geological features (Ai) of each hydrogeologic unit (assuming that there is no hydraulic communication between the overlaying aquifers), the effective infiltration I_e, or direct recharge, can be obtained for each aquifer:

$$I_e = \frac{\sum_{i=1}^{n} \mathrm{Ai} * \mathrm{Ci} * \mathrm{EP}}{\sum_{i=1}^{n} \mathrm{Ai}} \quad (2)$$

The runoff coefficient and the groundwater recharge were calculated using a procedure within a GIS (ESRI ArcGIS 10) in which each vector information layer was converted to raster format using a regular square grid and then processed by overlay mapping (Fig. 3). This procedure allowed for the water balance to be calculated for each grid cell of the river basins. The model was developed using an existing dataset that was updated with recently acquired data. All of the data were made homogeneous (i.e. in terms of units of measurement), verified, and entered into a database. Each thematic layer was reclassified using the classes and coefficients provided by the methodology (Table 1). The determination of the average annual runoff coefficient (C_k) depends on the development of three thematic maps (one for each parameter) for the zone in which the basin lies to calculate the relative areas of the different classes and then derive the contribution of each to C_k.

3.1. Calculation of the runoff coefficients of 30 watersheds in Sardinia

The slope layer was developed using the Forestry Inventory of the Autonomous Region of Sardinia database (IFRAS, 1994), which contained approximately 150,000 geo-referenced topographic elevation points. These data are coincident with the nodes of a two-dimensional square grid of 400-m cells that covers all of Sardinia. The slope map was developed in a GIS environment using the Digital Terrain Model (DTM), which was obtained using the Triangulated Irregular Network method (TIN).

The land cover layer was obtained by reprocessing the original mapping data that are available in the literature, particularly from the CORINE (Coordination of information on the environment) Land Cover project, prototype project founded by the European Environment Agency (EEA, 1997). After accuracy assessment (i.e. ground-truth) the 40 classes of the CORINE Project were merged, based on remote sensing analysis and interrogation of the database, into the four classes of land cover determined by the Kennessey method (Table 3).

According to the official 1:200,000 scale regional map (Carmignani et al., 2001), the geological features of the study area include 63 different outcrop lithologies. Using this thematic layer and based on the Kennessey method, the four classes (high, good,

Table 1
Table of Kennessey coefficients classified by aridity index (I_a) (Spadoni et al., 2010).

	Aridity index (I_a)		
	$I_a < 25$	$25 < I_a < 40$	$I_a > 40$
	Coefficients		
Slope (C_a)			
>35%	0.22	0.26	0.30
10% < S < 35%	0.12	0.16	0.20
3.5% < S < 10%	0.01	0.03	0.05
<3.5%	0.00	0.01	0.03
Land cover (C_v)			
No vegetation	0.26	0.28	0.30
Grazing land	0.17	0.21	0.25
Cultivation/shrubby	0.07	0.11	0.15
Woods/forests	0.03	0.04	0.05
Permeability (C_p)			
Very low	0.21	0.26	0.30
Low	0.16	0.21	0.25
Medium	0.12	0.16	0.20
Good	0.06	0.08	0.10
High	0.03	0.04	0.05

Table 2
Potential infiltration coefficients (C_i) assigned to the hydrogeologic units (Ghiglieri et al., 2006).

Hydrogeologic complexes	Potential infiltration coefficient (C_i)
(P) – Metamorphic aquifer system	0.2
(T) – Limestone, dolomite and gypsum aquifer system	0.5
(G) – Limestone aquifer system	0.8
(C) – Limestone sequences aquifer system	0.6
(OM) – Pyroclastic aquifer system	0.4
(Mc) – Sandstone and limestone aquifer system	0.4
(Q) – Recent deposits aquifer system	0.5

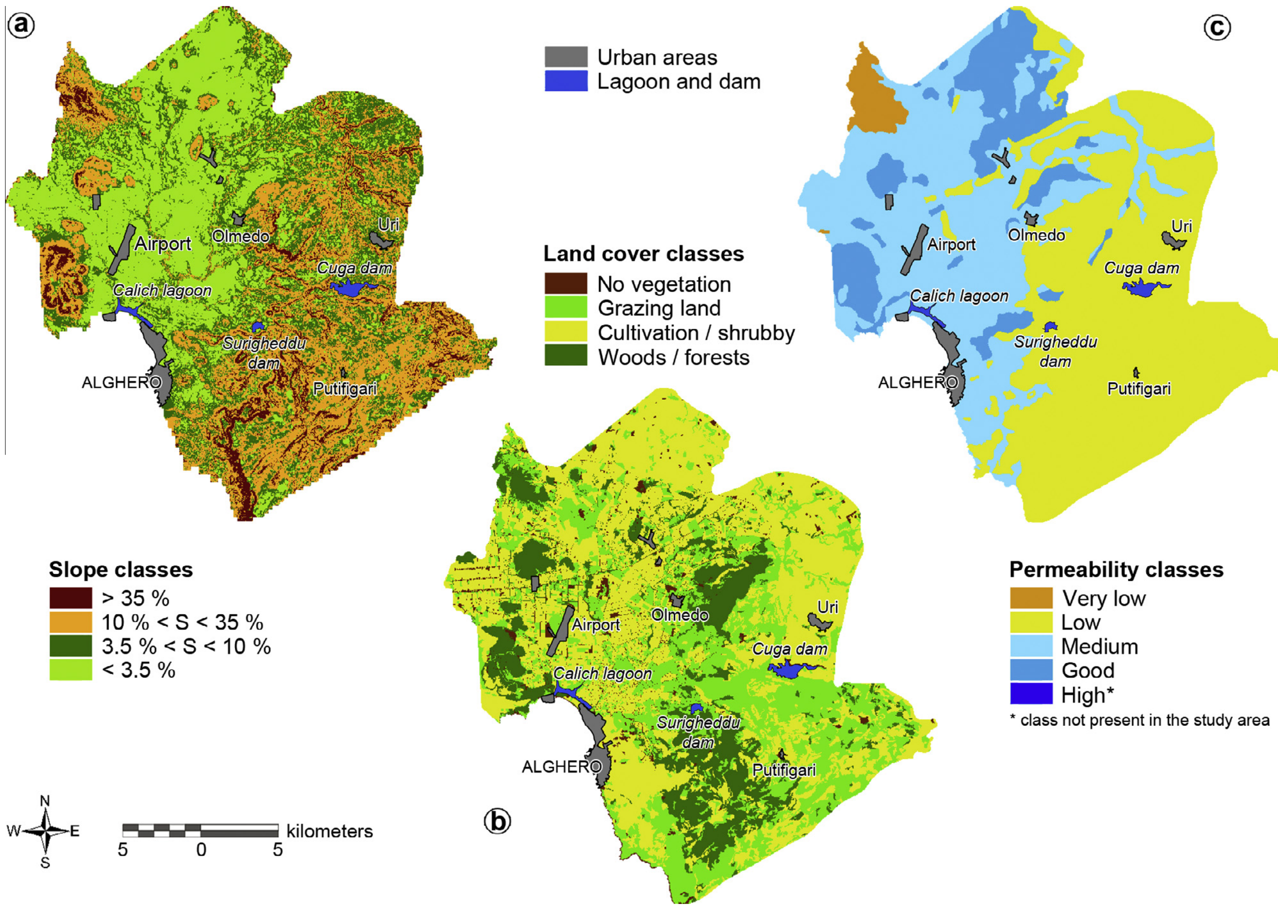

Fig. 3. Classification of the data layers according to the Kennessey method: (a) slope, (b) land cover, and (c) permeability.

Table 3
Classes of land cover.

Class	Description
Land cover (C_v)	
No vegetation	Areas lacking vegetation or with sparse vegetation cover, thus having minimum participation to the transpiration process
Grazing land	Areas covered mainly by herbaceous and/or shrub vegetation
Cultivation/shrubby	Units characterised by forest features (even sparse) and by tree and herbaceous cultivations
Woods/forests	Units consisting of real and proper forests, with 75% trees and the rest possibly shrubs and small trees

medium, and very low) were associated with K permeability values ($\mathrm{m\ s^{-1}}$) using data from the literature (Civita and De Maio, 2000) and personal unpublished data (Table 4).

Climate data were derived from the New Superficial Hydrology Assessment of Sardinia (NSISS) made by Autonomous Region of Sardinia and Autonomous Agency of Flumendosa (RAS and EAF, 1998). The records, which were collected from 30 watersheds, are homogeneously distributed across Sardinia. Data are available for 71 years (from 1922 to 1992).

3.2. Calculation of the runoff coefficient and the effective infiltration of the Calich hydrogeological basin

3.2.1. Runoff coefficient C_k

Elevation and slope data were obtained from the digital terrain model that was extracted from the Regional Technical Map at a scale of 1:10,000 (RAS, 1998). The slopes, expressed as percentages, were classified into four classes based on the model here proposed (Kennessey, 1930; Spadoni et al., 2010), and the

Table 4
Classes of permeability.

Class	K ($\mathrm{m\ s^{-1}}$)	Lithologies
Permeability (C_p)		
Very low	$<10^{-9}$	Ancient clay alluvial deposits, volcanic rocks, impermeable metamorphic formations highly
Medium	$>10^{-9}$, $<10^{-4}$	Sandstones and conglomerates, slightly fissured volcanic rocks, dolostones, slightly karstified limestones and metalimestones, granitoids, dikes
Good	$>10^{-4}$, $<10^{-2}$	Karst limestones and dolostones, fissured dikes
High	$>10^{-2}$	Recent alluvial deposits, ancient metalimestones and metadolostones which have undergone a karstification process more intense

contribution of each class to the runoff coefficient was calculated (Table 5, Fig. 3a).

The land cover layer was obtained by integrating the 1:5,000 scale map compiled during the RIADE Project for the plains areas (Ghiglieri et al., 2006) with the 1:25,000 land cover map developed by the Autonomous Region of Sardinia (RAS, 2003) for the hilly region in the southern part of the study area. Based on this background information, several accuracy assessment (i.e. ground-truth) were conducted using photo interpretation and field investigations to confirm the correspondence between the mapping units and the units present in the region. Table 5 and Fig. 3b show the contributions of each class to the runoff coefficient and their spatial distribution.

The permeability layer was derived from the RIADE Project (Ghiglieri et al., 2006, 2009a,b). Each hydrogeologic complex was defined by the aggregation of geological formations with similar permeabilities collected from the scientific literature (Civita and De Maio, 2001) and validated through transitory pumping tests (Ghiglieri et al., 2006, 2009a) (Table 5 and Fig. 3c).

Temperature and precipitation data were provided by the Hydro Meteorological and Climatic Department of the Regional Environmental Protection Agency of Sardinia (ARPAS). In particular, we used the average annual rainfall and temperature data related to the reference climate decades (1961–1990) (WMO, 1996) and to single years (2003, 2004, and 2005) (Table 6). In addition, the monthly rainfall and the average temperatures of the driest months of the four reference periods were also used to calculate the aridity index (Tardi and Vittorini, 1977) (Table 6).

The annual average aridity index I_a was calculated for the four periods (Eq. (1)) with the GIS raster calculator process and a grid of 250×250 m cells (Ghiglieri et al., 2006). The aridity indexes of all four periods were less than 25 (Table 7). For this reason, the analysis considered the series of coefficients related to the class $I_a < 25$ for each thematic layer defined by the Kennessey method.

The area of the Calich hydrogeological basin was modelled as a regular square mesh with 50-m cells. Once the coefficient series was defined for each layer based on the aridity index values, the medium values of the runoff coefficient C_k (Table 5), and the spatial distributions within the basin were determined using overlay mapping as a sum of the C_a, C_v, and C_p values of each cell. The

Table 7
Aridity index calculated for the reference periods: 1961–1990, 2003, 2004, and 2005.

	1961–1990	2003	2004	2005
Min	11.63	10.04	11.92	10.51
Max	19.97	13.70	15.07	15.06
Mean	13.70	11.16	13.01	12.20

Table 5
Contributions of slope, land cover, and permeability to the runoff coefficient C_k.

Class	Coeff.	Area (km^2)	Area (%)	Class contribution to C_a
Slope (C_a)				
>35%	0.22	42.3	7.32	0.016
10% < S < 35%	0.12	174.35	30.19	0.036
3.5% < S < 10%	0.01	147.46	25.53	0.003
<3.5%	0.00	213.48	36.96	0.000
				$C_a = 0.055$
Class	Coeff.	Area (km^2)	Area (%)	Class contribution to C_v
Land cover (C_v)				
No vegetation	0.26	25.76	4.39	0.011
Grazing land	0.17	177.18	30.23	0.051
Cultivation/shrubby	0.07	286.65	48.91	0.034
Woods/forests	0.03	96.55	16.47	0.005
				$C_v = 0.102$
Class	Coeff.	Area (km^2)	Area (%)	Class contribution to C_p
Permeability (C_p)				
Very low	0.21	15.85	2.71	0.006
Low	0.16	291.60	49.75	0.080
Medium	0.12	210.11	35.85	0.043
Good	0.06	68.57	11.70	0.007
High	0.03	Not present		
				$C_p = 0.135$
				$C_k = C_a + C_v + C_p = 0.292$

Table 6
Annual rainfall and rainfall in the driest month (top) and average annual temperature and temperature in the driest month (bottom) recorded during the four reference periods: 1961–1990, 2003, 2004, and 2005 (ARPAS).

	1961–1990		2003		2004		2005	
	P	p (July)	P	p (July)	P	p (July)	P	p (May)
Min	529.56	3.30	529.93	0.11	612.69	0.01	527.41	0.00
Max	873.40	6.98	660.22	0.38	703.25	1.18	681.13	0.63
Mean	639.76	4.99	590.52	0.22	662.34	0.51	608.07	0.27
	T	t (July)	T	t (July)	T	t (July)	T	t (May)
Min	13.63	22.45	14.15	23.27	13.23	21.16	12.66	15.71
Max	16.65	24.15	17.43	26.39	16.56	24.03	15.96	18.21
Mean	15.74	23.73	16.60	25.70	15.73	23.34	15.13	17.61

P = annual rainfall in mm; p = rainfall in the driest month in mm; T = annual average temperature in °C; t = average temperature in the driest month in °C.

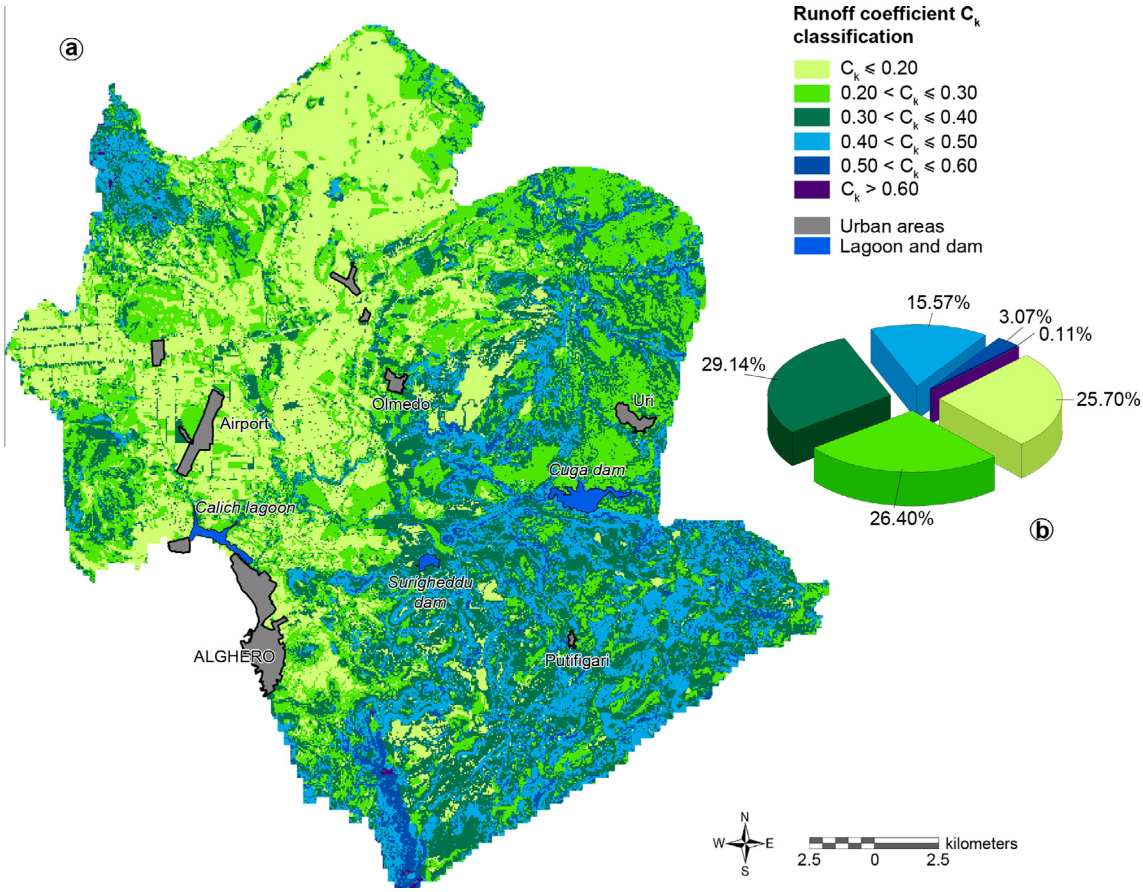

Fig. 4. (a) Runoff coefficient map; (b) distribution of runoff coefficient classes.

Table 8
Comparison of calculated and measured runoff coefficients for 30 watersheds in Sardinia.

Code	Watershed	S	D	A	I_a	$C_s = D/A$	C_k	P.D. $[(C_k - C_s)/C_s] * 100$
B2	MANNU DI S. SPERATE A MONASTIR	475.20	104.4	600.8	13.67	0.174	0.292	67.82
B3	CIXERRI A UTA	533.17	196.8	722.1	14.72	0.273	0.289	5.86
B4	RIO DI PALMAS A MONTI PRANU	439.07	165.8	745.1	14.61	0.223	0.326	46.19
B5	FLUMENTEPIDO A FLUMENTEPIDO	68.32	136.4	712.8	14.02	0.191	0.266	39.27
B6	FLUMINIMAGGIORE A FLUMINIMAGGIORE	80.97	360.3	790.5	15.86	0.456	0.424	−7.02
B7	TIRSO A RIFORNITORE TIRSO	581.35	210.4	742.2	17.81	0.283	0.268	−5.30
B8	TALORO ALLA PASSERELLA GAVOI	224.37	512.0	972.3	25.08	0.527	0.447	−15.18
B9	TIRSO A S. CHIARA D'ULA	1278.59	196.1	760.7	17.77	0.258	0.288	11.63
B10	ARAXISI A ORTO SCIAVICO	122.44	393.6	981.8	24.63	0.401	0.395	−1.50
B11	FLUMINEDDU O MASSARI AD ALLAI	692.90	206.1	783.3	17.65	0.263	0.296	12.55
B12	TEMO A REINAMARE	174.40	327.1	828.0	18.49	0.395	0.303	−23.29
B13	MANNU DI PORTO TORRES A PEDRAS ALVAS	226.23	169.2	792.1	17.57	0.214	0.296	38.32
B14	MANNU DI OZIERI A PONTE DELLA LEGNA	335.73	219.6	711.6	16.19	0.309	0.252	−18.45
B15	RIO DI BUTTULE A BUTTULE	173.85	207.0	733.0	17.30	0.282	0.365	29.43
B16	MANNU DI OZIERI A FRAIGAS	240.75	227.8	643.9	14.85	0.354	0.236	−33.33
B17	MANNU DI BERCHIDDA A BERCHIDDA	354.47	374.2	888.8	21.95	0.421	0.305	−27.55
B18	RIO DI OSCHIRI A CONCARABELLA	352.30	283.6	767.3	18.73	0.370	0.288	−22.16
B19	COGHINAS A MUZZONE	428.76	212.3	695.1	16.74	0.305	0.279	−8.52
B20	LISCIA A LISCIA	559.91	272.0	864.5	19.46	0.315	0.278	−11.75
B21	CEDRINO A CEDRINO	617.18	342.3	848.2	20.01	0.404	0.325	−19.55
B22	FODDEDDU A CORONGIU	52.67	342.3	893.0	18.79	0.383	0.325	−15.14
B26	FLUMENDOSA A GADONI	246.68	563.9	922.2	23.21	0.611	0.431	−29.46
B27	FLUMENDOSA A VILLANOVATULO	127.64	507.1	823.3	20.67	0.616	0.371	−39.77
B28	FLUMENDOSA A MONTE SCROCCA	468.10	234.3	715.7	17.22	0.327	0.392	19.88
B29	FLUMINEDDU A STANALI	392.26	331.5	804.5	18.11	0.412	0.383	−7.04
B30	SA PICOCCA A MONTE ACUTO	119.01	313.4	785.3	16.45	0.399	0.458	14.79
B31	MOGORO A S. VITTORIA	249.05	161.1	723.9	15.20	0.223	0.274	22.87
B35	RIO LENI A VILLACIDRO	57.27	431.3	963.7	19.24	0.448	0.392	−12.50
B43	ALTO FLUMENDOSA *AGGREGATA*	176.27	545.2	1019.2	24.46	0.535	0.407	−23.93
B47	FLUMINIMANNU A SARCIDANO *AGGREGATA*	86.51	262.8	765.1	18.22	0.343	0.215	−37.32

Area (S) is in km^2; average annual runoff (D) and average annual rainfall (A) are in mm $year^{-1}$; aridity index (I_a), measured runoff coefficient (C_s), and Kennessey runoff coefficient (C_k) are adimensional; P.D. = percentage deviation in %.

overlapping of the three maps determined a set of combinations of the coefficients, which led to the map of C_k. The 64 possible combinations of classes (four for each layer) and the C_k values were divided into six classes (Barazzuoli et al., 1986). The spatial distribution of the runoff coefficient is shown in Fig. 4a.

3.2.2. Effective infiltration I_e (natural recharge of the aquifers)

The standard water balance equation was used to calculate the effective infiltration I_e:

$$I_e = P - Et - R \quad (3)$$

where P is the annual average precipitation, Et is the real evapotranspiration, and R is the runoff. The balance was calculated for the reference periods 1961–1990, 2003, 2004, and 2005. Calculations were performed for each 50×50 m cell in the study area. Annual real evapotranspiration was calculated (Ghiglieri et al., 2006) using the equation proposed by Turc (1954):

$$Et = \frac{P}{\sqrt{0.9 + \frac{P^2}{(300+25T+0.05T^3)^2}}} \quad (4)$$

where T is the average annual temperature in degrees Celsius.

The values of C_k obtained using the Kennessey method were used to calculate the total annual runoff R by applying the following equation (Spadoni et al., 2010):

$$R = (P - Et) * C_k \quad (5)$$

Finally, I_e was calculated for each cell in the study area as the difference between the average annual precipitation, evapotranspiration, and runoff according to Eq. (3).

4. Results

In the regional-scale study, the annual average runoff coefficient values assessed through the Kennessey method (C_k) and those calculated based on the measured data (C_s) were compared using percent deviations (Table 8). The results are shown in Fig. 5, which shows the catchment in four colours depending on the percent deviation $[(C_k - C_s)/C_s] * 10$.

The results obtained using the Kennessey method corresponded well with the measured data in some cases (basins B10, B7, and B3) and poorly in others (B2, B4, B27, and B5). In 20% of the cases, the deviations were less than 10%; in 33% of the basins, the deviations were between 10% and 20%. For 21%, the deviations were between 20% and 30%, and the deviations were greater than 30% in 21% of the basins. The best agreement was obtained in the case of the Araxisi basin (B10) (−1.50%), whereas the worst (67.82%) was in the case of the Mannu of San Sperate basin (B2). This basin has a runoff coefficient calculated by observed data equal to 0.174, which is the lowest of all of the basins. The results are not related to the size of the basins. It should be noted that this evaluation did not consider the difference between superficial watershed divides and hydrogeological divides; therefore, the results could be

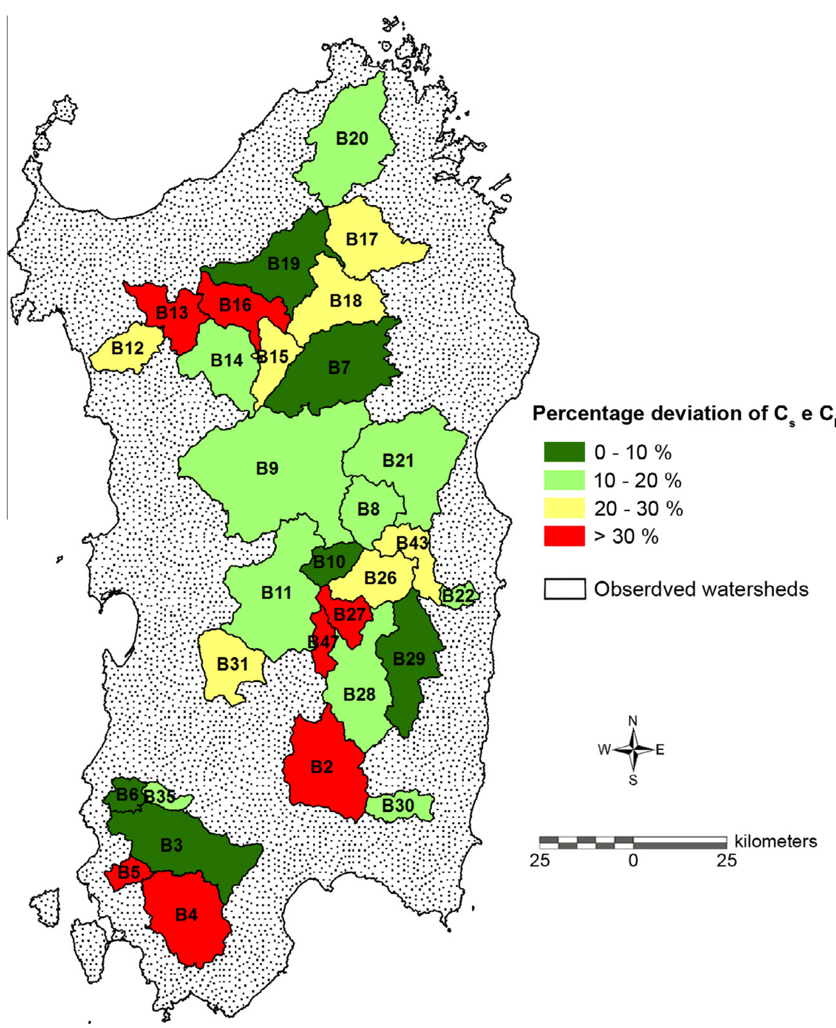

Fig. 5. Schematic representation of the percentage deviation of C_s and C_k in the watersheds.

affected by interbasin flow. Indeed, for some catchments the assumed correspondence of topographic and groundwater divides might not be correct. For example, in crystalline rocks, the structural setting exerts a major influence on groundwater flow at both local and regional scales, whereas in carbonate aquifers, the groundwater flows through a network of large and interconnected fractures. This effect appears to arise in the case of the Flumendosa basin at Villanovatulo (B27) and the Flumendosa basin at Gadoni (B26), which have abnormally high C_s values that are greater than 0.6. Because the limestone that outcrops in the area represents the eastern edge of the extensive Tacco del Sarcidano and dips slightly to the east, the water intake may be derived from inflows from the western part of the Tacco, which lies outside the basins. This water intake would increase the runoff and the measured runoff coefficient (C_s), thus explaining the large discrepancy between these basins and the results of the Kennessey method.

Moreover, the topographic catchment divide might not be representative, because artificial transfers of water by channels, ditches, sewer systems and pumped groundwater can disturb the natural water balance.

In summary, the results appear to indicate that some characteristics may not be identified using an indirect runoff evaluation method such as the Kennessey method.

In the Calich hydrogeological basin, the most representative classes are $C_k < 0.2$ (25.70%), $0.2 < C_k < 0.3$ (26.40%), and $0.3 < C_k < 0.4$ (29.14%) (Fig. 4a and b). The areas with higher runoff coefficients are mainly located in the southeastern part of the catchment. The first class is concentrated almost exclusively in the northern part of the plains area, the second class is primarily located in the eastern part of the plains, and the third is distributed across the entire area but is slightly concentrated in the southern hilly portion of the basin. The runoff coefficient classes corresponding to $0.4 < C_k < 0.5$, which cover 15.57% of the area, are present in the southern part of the study area; the classes with $0.5 < C_k < 0.6$ and $C_k > 0.6$ (3.07% and 0.11% of the area, respectively) appear to correspond with areas of steep slopes.

A statistical analysis of the results was performed to assess the influence of the individual factors on the classification of the runoff coefficients (Fig. 6).

Fig. 6a shows a graphical representation of the distribution of the slope classes for each class of C_k. Slopes of less than 10% have the greatest influence on the classes with the lowest C_k values. Slopes between 10% and 35% account for approximately 50% of the values of C_k between 0.3 and 0.4. Slopes greater than 35% make up 20% of the C_k values between 0.4 and 0.5, 90% of the values between 0.5 and 0.6 values, and 100% of the C_k values greater than 0.6.

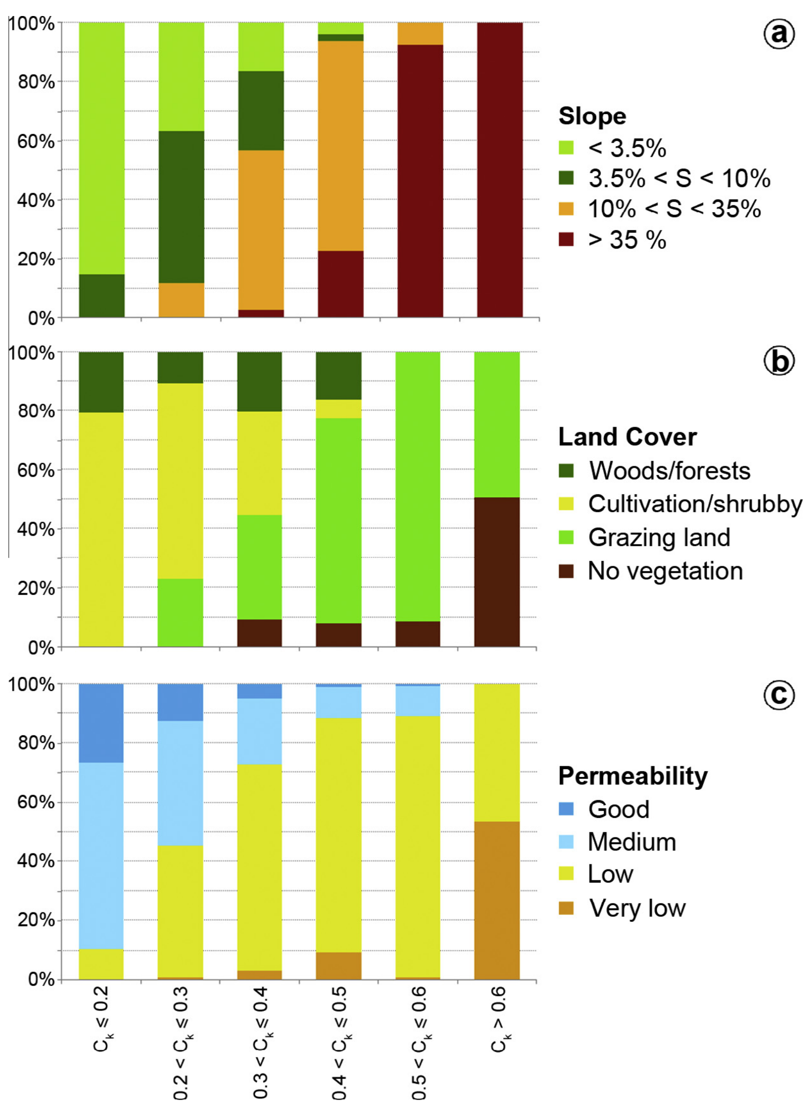

Fig. 6. (a) The distribution of C_a versus C_k; (b) distribution of C_v versus C_k; and (c) distribution of C_p versus C_k in the Calich Basin.

Fig. 6b shows that the cultivated/shrubby land-cover class has a decreasing influence with increasing values of C_k and that the woods/forests class oscillates between 10% and 20% for C_k values up to 0.4. The grazing land class is most common for C_k values greater than 0.4; it represents 90% of C_k values between 0.5 and 0.6 and 50% of values greater than 0.6.

Fig. 6c shows the influence of permeability on C_k. The percentages of the good and medium permeability classes decrease with increasing values of C_k. The low permeability class increases to approximately 90% for values of C_k between 0.5 and 0.6 and decreases to 50% for values greater than 0.6. The very low class, which is present only in the northern part of the basin, generally has a low influence, except for C_k values greater than 0.6, for which it reaches 50%.

The values of effective infiltration calculated by Eq. (3) after applying the Kennessey and standard water balance methods to calculate runoff are compared in Table 9.

The values of I_e obtained using the Kennessey method are approximately 50% higher for all of the reference periods. This disparity can be explained by the fact that the Kennessey method takes into account land cover and surface morphology (slope), whereas the standard method does not. Generally, these two factors strongly influence both the infiltration and runoff.

In the Calich basin, the land cover greatly affects the terms of the water budget; approximately 50% of the catchment area falls within the "cultivated/shrubby" class. The soil in this class exhibits good percolation and thus favours effective infiltration.

The difference between the I_e values calculated with the two methods affects the estimated volume of groundwater recharge for the aquifers (Table 10). In general, the significant mean groundwater recharges are those corresponding to the Jurassic (*(G)-limestone aquifer system*) and Oligo-Miocene (*(OM)-pyroclastic aquifer system*) units. The reserves in all of the hydrogeological units are lower in 2003 than in the 1961–1990 reference period, which may have occurred because the four periods were characterised by low effective precipitation values and consequently low effective infiltration. The reserves increase in 2004 by 50% over the reference period in the Triassic (*(T)-limestone, dolomite and gypsum aquifer system*), Cretaceous (*(C)-limestone sequences aquifer system*), and Miocene (*(Mc)-sandstone and limestone aquifer system*) units and by 80% for the Jurassic unit; on the other hand, the reserves decrease by approximately 10% in the Oligo–Miocene unit. This result can be explained by the fact that compared to the 30-year period, 2004 was characterised by higher effective infiltration in the plains area, with higher values in the Jurassic unit and lower values for the Oligo–Miocene ignimbrite plateau. The reserves in 2005 are not significantly different from those estimated for the 30-year period, except for that of the Oligo–Miocene unit, which decreases by 20% due to the reduction of the effective infiltration values of the ignimbrite plateau.

A comparison between the volumes estimated by the two methods shows that for the entire catchment, the volumes calculated using the Kennessey method are 46–49% higher than those derived from the water balance method. The differences in the individual hydrogeological units range from 27% for the Jurassic units to nearly 200% for the metamorphic complex. These large differences are caused by the less detailed geological and hydrogeological data that are available from the metamorphic complex.

5. Discussion and conclusions

The main objective of this study was the application and validation of the Kennessey method. This empirical, indirect method, which allows for the evaluation of a watershed basin runoff coefficient based on several physiographical parameters, such as slope, land cover, permeability, and climatic conditions, does not require expensive instrumental measurements.

The various datasets of the water-budget are usually determined from data recorded by suitably located instruments; runoff, in particular, is calculated by integrating the discharges measured at the basin outflow point.

Table 9
Comparison of the effective infiltration (I_e) (mm year^{-1}) calculated using the Kennessey method and using the standard water balance method (Calich basin).

	1961–1990	2003	2004	2005
Kennessey method	97.04	76.71	126.43	91.03
Standard water balance method	64.98	51.92	86.11	61.60
Percentage deviation	49.34	47.75	46.82	47.77

Effective infiltration (I_e) is in mm year^{-1}; percentage deviation is in %.

Table 10
Natural recharge of the aquifers (m^3 year^{-1}) calculated using the Kennessey method and using the standard water balance method (Calich basin).

Hydrogeologic complexes	1961–1990 Standard water balance method	1961–1990 Kennessey method	P.D.	2003 Standard water balance method	2003 Kennessey method	P.D.	2004 Standard water balance method	2004 Kennessey method	P.D.	2005 Standard water balance method	2005 Kennessey method	P.D.
(P) – Metamorphic aquifer system	227,024.69	656,165.16	189.0	249,588.55	705,475.21	182.7	463,146.57	1,310,998.98	183.1	264,213.70	744,673.33	181.9
(T) – Limestone, dolomite and gypsum aquifer system	3,388,184.83	5,040,045.48	48.8	2,944,889.75	4,384,769.01	48.9	5,178,866.39	7,723,793.72	49.	3,335,196.48	4,957,446.60	48.6
(G) – Limestone aquifer system	11,382,763.24	14,500,457.05	27.4	10,707,540.79	13,564,570.88	26.7	20,020,084.05	25,433,633.47	27.0	12,652,135.89	16,034,877.96	26.7
(C) – Limestone sequences aquifer system	3,567,414.46	5,306,931.62	48.8	3,168,883.47	4,687,145.12	47.9	5,485,973.69	8,128,811.59	48.2	3,864.086.87	5,729,279.46	48.3
(OM) – Pyroclastic aquifer system	16,491,815.76	26,131,936.61	58.6	10,838,624.34	17,180,046.36	58.5	14,811,685.42	23,562,288.65	59.1	12,813,575.16	20,313,411.94	58.5
(Mc) – Sandstone and limestone aquifer system	2,628,569.57	4,479,259.04	70.4	2,213,782.95	3,720,399.03	68.1	4,004,081.36	6,722,605.29	67.9	2,804,545.72	4,709,277.46	67.9
Hydro – geological basin	37,653,987.51	56,022,449.33	48. 8	30,099,148.01	44,202,474.46	46.9	49,917,741.97	72,849,474.99	45.9	35,709,769.00	52,452,176.54	46.9

P.D. = percentage deviation in %; volumes are in m^3 year^{-1}.

The adopted physiography-based approach is not a substitute for traditional methodologies that rely on extensive field datasets, but it can provide first-order estimates of the basin-scale water balance, particularly for large areas that lack adequate spatial and temporal coverage by field data. In this study, a region-wide approach that uses a Geographic Information System (GIS) was proposed to combine several physiographical spatial data sets into a runoff coefficient map.

To calibrate and validate the methodology, the results were compared to measured streamflow discharge values of 30 basins in Sardinia and with groundwater recharge data from a small catchment (Calich basin) that were obtained during the RIADE Project (Ghiglieri et al., 2006) by applying the water balance method, which is commonly used in hydrogeology (Civita and De Maio, 2001). The results of applying the method to a large number of watersheds that are well differentiated by lithology, morphology, vegetation and weather conditions appear to validate the method and demonstrate that it can generate runoff coefficients that is to be considered a first approximation of water budget, which can then be fine-tuned with other methods as time permits (Allison et al., 1994; Sophocleous, 1991; Essery and Wilcock, 1990; Scanlon et al., 2002; Cherkauer and Ansari, 2005).

Nevertheless, the results of this work reduce the subjectivity of the methodology and indicate that it is a promising technique. The analysis provided good results, although there were significant discrepancies between the results of the methodologies in several cases. Such models can only be calibrated on gauged watersheds, although their results may be extendable to nearby ungauged areas. The method can be used successfully to generate estimates of the magnitude and spatial variability of recharge rates to be applied as input to groundwater flow models (Feinstein et al., 2004; Cherkauer and Ansari, 2005).

The basic shortcoming of the Kennessey method is that it is a "static" procedure that focuses on characteristics of a basin that are nearly invariable over time (the slope and the permeability do not vary over geologic time, and the land cover generally does not change significantly in the short term). Thus, the method cannot interpret changes in the runoff coefficient that occur within a basin over short time scales, such as from year to year.

The only parameter used in the method that is inherently variable is the aridity index, which, because it is a function of rainfall and temperature, should quantify the roles that these parameters play in the formation of runoff. This index actually varies very little between basins that are all in the same climatic region and within a basin from year to year because of the analytical expression that is used to calculate it and because of the effect of the variations attributed to the three classes of aridity proposed by Tardi and Vittorini (1977). Although, several authors (e.g. Barazzuoli et al., 1986; Gazzetti et al., 2005; Spadoni et al., 2010; Grillone et al., 2014) have successfully applied the method considering the range of the aridity index, it appears that I_a still needs improving.

In contrast, the high variability of the annual runoff coefficients in the same basin, as indicated by the calculations performed using the instrumental methods, reflects the extreme variability in the temporal and spatial distributions of precipitation and temperature. In contrast to slope, land cover and permeability, which are relatively stable over time, the variations in precipitation and temperature affect the complex process of surface runoff. Therefore, the runoff coefficient calculated using the Kennessey method should be considered a "potential" runoff coefficient rather than an "average" value; it is a limiting value towards which the real runoff coefficient, as calculated by the instrumental method, approaches when the distributions of temperature and rainfall in a basin are regular and uniform in space and time.

In addition to providing an overview of the runoff dynamics in the various areas of the basin, the runoff coefficient map is a valuable tool for specific quantitative assessments, such as the prevention and mitigation of floods or landslides. It is important to determine not only the hydrological and climatic characteristics of a watershed, but also the influences that various physical and anthropogenic components on the superficial runoff.

The question of whether the weights of the slope, land cover and permeability components are too high, especially compared to the low weights that the meteorological parameters generally have in the Kennessey method, remains to be addressed. In this context, it would be interesting to use mathematical models with the results of this study and a historical dataset to optimise the calculation of the runoff coefficient by varying the numerical weights that are assigned to hydrometeorological, morphological and vegetation data and to further refine the model parameters considered by the method. However, even with the limitations that were discussed previously and even though it requires further validation, the method is a potentially useful tool for a first approximation of hydrologic processes (i.e. water budget), even under data limited environment, such as for water management in areas where instrumental data are not available.

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