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Water Resources Assessment for Karst Aquifer Conditioned River Basins: Conceptual Balance Model Results and Comparison with Experimental Environmental Tracers Evidences

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1. Introduction

Water resources management, more and more limited and poor in quality, represents a present key issue in hydrology. The development of a community is highly related to the management of the water resources available for the community itself and there is a need, for this reason, to rationalize the existing resources, to plan water resources use, to preserve water quality and, on the other hand, to prevent flood risk. The importance of decision support systems tools, such as hydrological models, generating streamflow time series which are statistically equivalent to the observed streamflow time series, is even more important considering the combination of multiple and complex issues concurring in the definition and optimization of water resources management practices.

When river basins with particular features have to be modelled, both traditionally conceptually based models and more recent sophisticated distributed models appear to give not very reliable results. In those cases it is possible to take advantage of a semi-distributed formulation, where every sub-catchment is modelled to account for its features and informations coming from all the sub-catchments are related to each other in order to improve the system description.

In this study, starting from the application of a catchment scale modelling tool, we propose a semi-distributed conceptually based framework, able to describe the sub-catchment scale systems hydrological response. The modelling approach is supported by field measurements collected within several seasonal campaigns, that has been set up for the Bussento river basin, located in Southern Italy, well known to hydrogeology and geomorphology scientists for its karst features, characterized by soils and rocks with highly different hydraulic permeability and above all an highly hydrogeological conditioning. The groundwater circulation is very complex, as it will be later discussed, and groundwater inflows from the outside of the hydrological watershed and groundwater outflows toward surrounding drainage systems frequently occur. With the aim to enhance the knowledge of the interaction between the groundwater and surface water and acknowledged the substantial help given by natural isotope tracers experiments to solve hydrological complex systems circulations problems, radon-in water concentrations have also been collected, in a limited number of cross sections, along the upper Bussento river reach.

Even though the proposed approach has some similarity with a few well known conceptually schemes, based on the existence of linear reservoirs and liner channel to describe the different components the streamflow can be decomposed in, it is valuable because of the possibility, which is in this case the necessity, to join all together hydraulic, hydrological and geological data to achieve reliable results.

2. Hydro-geomorphological setting of the Bussento river basin

The Bussento river basin, located in the Cilento and Vallo di Diano National Park (figure 1), is one of the major and more complex fluvial systems of the southern Campania region (Southern Italy).
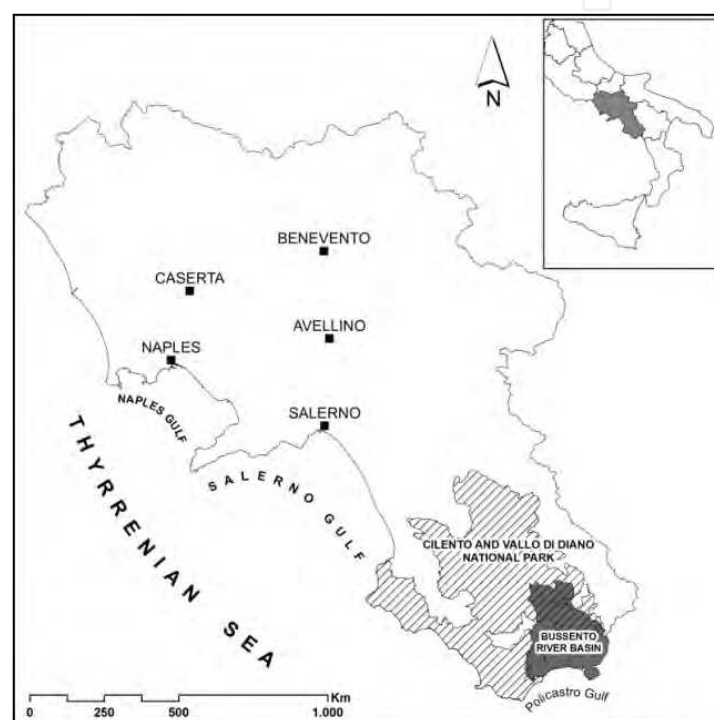

Fig. 1. Location of the Bussento river basin.

The main stream originates from the upland springs of Mt. Cervati (1.888 m), one of the highest mountain ridges in Southern Apennines. Downstream, the river flows partly in wide alluvial valleys (i.e., Sanza valley) and, partly, carving steep gorges and rapids, where a number of springs, delivering fresh water from karst aquifers into the streambed and banks, increase progressively downstream the river discharge.

The hydro-geomorphological setting of the river basin is strongly conditioned by a complex litho-structural arrangement derived from geological, tectonic and morphogenetic events occurred from Oligocene to Pleistocene along the Tyrrhenian Borderland of the southern Apennine chain (Bonardi et al., 1988). The chain is a NE-verging fold-thrust belt derived from an orogenic wedge, accreted by deformation and overthrust shortening of the sedimentary covers of several paleogeographic domains: Internal Sedimentary Domain in the Ligurian oceanic crust on the External Sedimentary Domain of Carbonate Platform-Continental Basin along the passive margin of the African plate (D'Argenio et al., 1973; Ippolito, F. et al., 1975).

The sedimentary basin successions related to the Internal Domain can be grouped in the following tectonic units (Cammarosano et al., 2000, 2004) (figure 2):

Castelnuovo Cilento Unit (Mid Eocene-Lower Miocene), constituted, from the top, by the Pianelli Formation (PNL), micaceous fine sandstone, siltites and shales; Trenico Formation (TNC), marls and calcarenites and Genesio Formation (GSO), argillites and calcilutites. Widely outcroping in the western sector of the basin (Sciaratopamo torrent sub-basin);

North Calabrian Unit (Upper Eocene-Lower Miocene), from the top, the Saraceno Formation (SCE), cherty calcarenites, marls and argillites and Crete Nere Formation (CRN), calciluties, black marls and argillites. The Unit is widely outcroping in the southern sector of the basin and, partially, in the upper and eastern Bussento river basin;

Cilento Group, a torbidite sequence, represented, from the top, by Monte Sacro Formation (SRO), conglomerates and sandstones; San Mauro Formation (MAU), sandstones, marls and conglomerates; Pollica Formation (PLL), sandstones and silty clay.

The tectonic units related to deformation of the above cited passive African continental margin are represented in the study area only by the**:**

Alburno-Cervati - Pollino Unit (Upper Trias-Middle Miocene), constituted from the top by: Bifurto formation (BIF), marls, quarz-sandstones and fine limestone breccias; Cerchiara formation (FCE), glauconite calcarenites; Trentinara formation (TRN), calcirudites and *Spiruline* calcilutite; *Radiolitides* Limestones (RDT); *Requienie* Limestones (CRQ); *Cladocoropsis* and *Clypeina* Limestones (CCM). At the top of the sequence, in disconformity, follows the Piaggine formation, calcirudites, sandstones and wildflysch succession, as low-standing olistostrome, announcing the arrival of Internal Units.

In the Plio-Pleistocene times, the above cited fold-thrust belt is affected by polyphase uplift transtensive and trans-pressive movements, with general lowering toward the Tyrhenian sea and juxtaposition of the clayey-marly successions in the erosional grabens, to the carbonate sequence, as karst summit horsts (Brancaccio et al., 1991; Cinque et al., 1993; Ascione A.&Cinque A., 1999).

In the study area, the main structural features are the overthrust of the Internal Units on the Bifurto/Piaggine formations at the NE piedmont of the M.nt Centaurino and the Sanza trans-tensive line, along the southern piedmont of M.nt Cervati massif.

The complexity of the geological setting gives to river basin an analogous complexity in hydrological response, due to the space-time variability of the river-aquifer interactions, conditioned by the hydro-structural setting and the karst landforms and processes highly affecting hydro-geomorphological behaviour (figure 3).

In general, in the Bussento river basin main and secondary aquifers can be recognized..

The **M.nt Cervati karst carbonate aquifer**, located in the northern side of the river basin, is one of the main aquifer of the southern Apennine; it is delimited at the North and N-E, by regional hydro-tectonic lines and at the SW and South by clayey aquicludes and highly fratured carbonate aquitards; minor hydro-structural lines induces multilayered and compartmented aquifers (sub-aquifers), with centrifugal directions of the groundwater flows (table 1).

M.nt Forcella karst carbonate aquifer, located in the eastern sector of the Bussento river basin, having 75% in area outside of the Upper Bussento, feeds only the 13 Fistole Spring Group, emerging a few hundred meters upstream the end of the river segment, with a M.A.D. 3 m³/s.

M.nt Alta karst carbonate aquifer, located on the N-E sector of the basin feeds only the Farnetani Spring Group, with a M.A.D. 1.5 m³/s, is interconnected with the Sanza Endorheic

Basin and related sinkhole-cave system, feeding the Bonomo Watermill seasonal springs and resurgences.

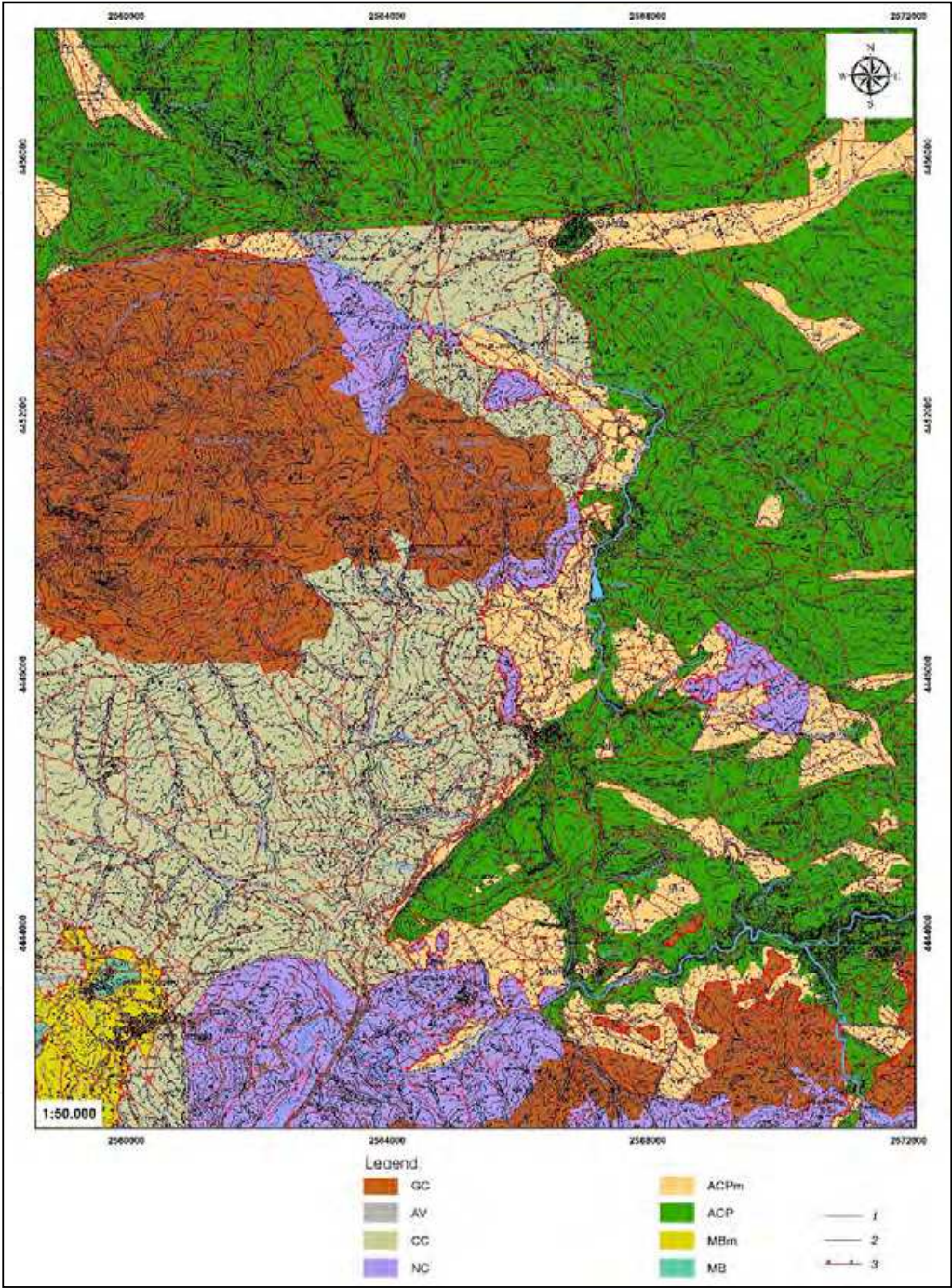**M.nt Centaurino multilayered terrigenous** aquifer feeds several spring with a total M.A.D. $0.1 \ m^3/s$.

Fig. 2. Geological map of the Upper and Middle Bussento river (1:50.000 scale).

Legend: GC. Cilento Group; AV. Sicilide Unit, included in CC. Castelnuovo unit; NC. Nord Calabrian Unit; ACPm. Piaggine formation; ACP. Alburni-Cervati -Pollino Unit; MBm. Bulgheria-Roccagloriosa Unit – clayey marls; MB. Bulgheria-Roccagloriosa Unit- Limestone; 1. Fault; 2. Stratigraphic boundary 3. Overthrust

Spring name	Sub-aquifer name	Elevation (m a.s.l.)	M.A.D. (l/s)	GWFD	Receiving River Basin
Rio Freddo	M.nt Arsano	470	750	East	Tanagro
Fontanelle Soprane	M.nt Arsano	470	800	N-E	Tanagro
Fontanelle Sottane	M.nt Arsano	460	400	N-E	Tanagro
Varco la Peta	Vallivona	1200	40	Southern	Bussento
Montemezzano	Inferno creek	900	100	Southern	Bussento
Sanza Fistole Group	Basal Southern Cervati	550-470	300	Southern	Bussento
Faraone Fistole Group	Pedale Raia	450	400	S-W	Mingardo
Calore Group	Neviera	1150	100	North	Calore
Sant'Elena Group	Rotondo	420	400	N-W	Calore
Laurino Group	Scanno Tesoro	330-400	600	N-W	Calore
Capodifiume Group	Chianiello-Vesole	30-35	2900	N-W	Capodifiume
Paestum-Cafasso Group	Chianiello-Vesole	1-10	750	N-W	Capodifiume
Acqua Solfurea Group	Chianiello-Vesole	5	250	N-W	Capodifiume

Table 1. Hydrogeological characteristics of the springs from Cervati aquifer. M.A.D.: Mean Annual Discharge; GWFD: GroundWater Flow Direction.;

The mainstream originates from south-western summit mountain slope of the Mount Cervati, where many, low discharge springs from shallow aquifer in debris cover laying on marly-clayey bedrock originate ephemeral creek inflowing into the Vallivona Affunnaturo sinkhole. From the Varco la Peta spring-resurgence, the Inferno creek flows southward, carving steep gorges in form of a typical bedrock stream, with cascade and rapids, where further springs (Montemezzano spring), along the streambed, increase progressively the river discharge (table 1), as well as along the piedmont (Sanza Fistole spring groups).
The true Bussento river begins downstream the junction of the above cited Inferno creek and the Persico creek. This last flows at the bottom of an asymmetric valley, characterized at the left side by the above cited southern steep mountain front of M.nt Cervati and at the right by the gentle northern mountain slope of the M.nt Centaurino (1551 m asl). The middle right side of the basin is characterized by marly-arenaceous rocks outcrops (M.nt Marchese hilly ridge), while the left middle side is characterized by karst limestone sequences (M.nt Rotondo and Serra Forcella).
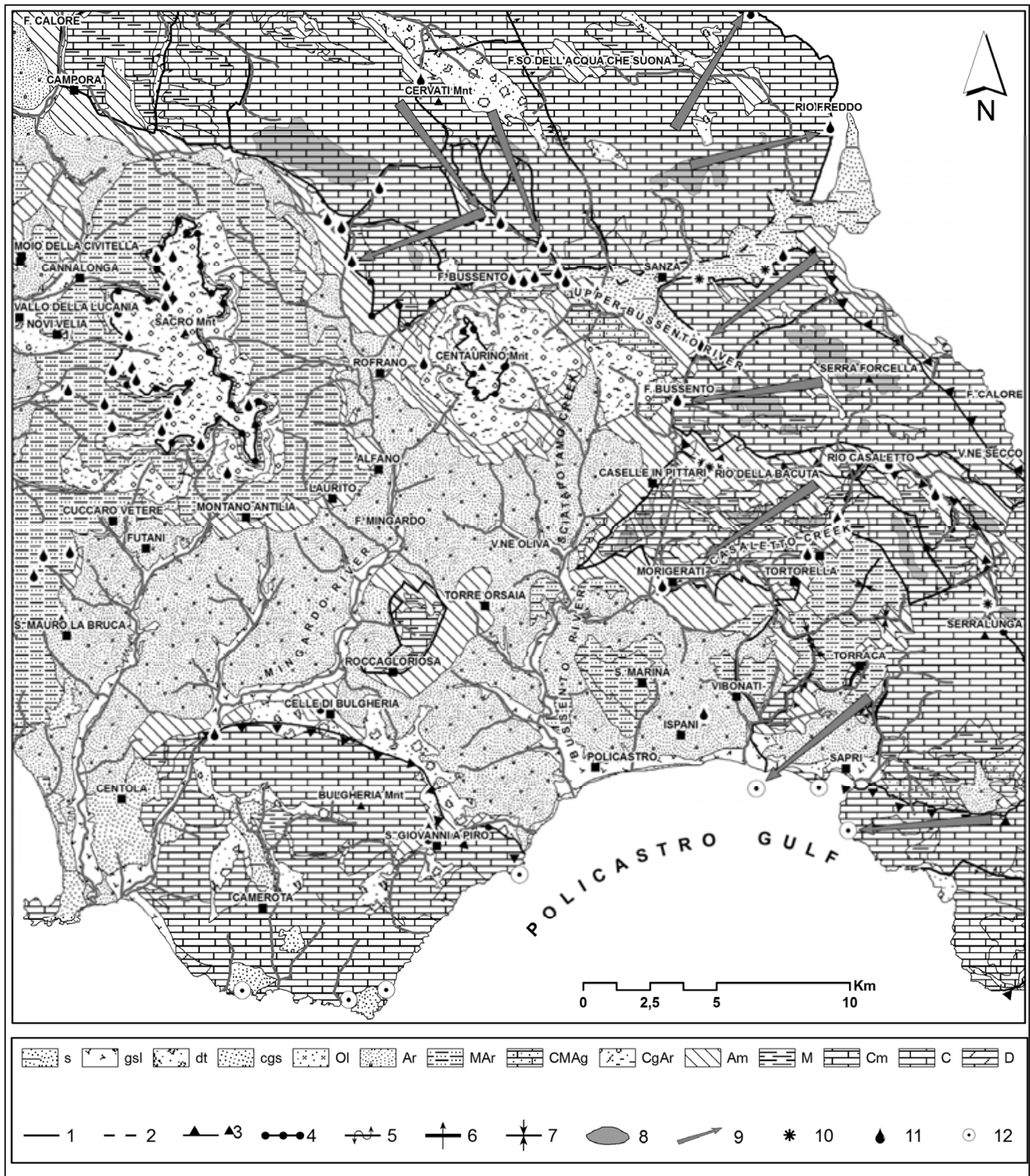
Fig. 3. Hydro-geomorphological map of the Bussento river and related hydro-geomorphological features.

Legend: Hydrogeological complexes: s. Sandy conglomerate; gsl. Gravelly sandy silty; dt. Debris; Ol. Blocky clayey olistostrome; Ar. Sandstone; MAr. Marly sandstone; CMAg. Marly conglomerate sandstone; Am. Silty Sandstone; M. Marly; Cm. Marly limestone; C. Limestone; D. Dolomite. Symbology: 1. Permeability limit; 2. Buried permeability limit; 3. Overtrusth hydro-geological limit; 4. Syncline hydro-geological limit; 5. Overturned strata; 6. Horizontal strata; 7. Sincline; 8. Karst summit; 9. Groundwater flow direction; 10. Sinkhole; 11. Main spring; 12. Submarine spring.

3. The streamflow and geo-chemical database

3.1 Historical streamflow data

Historical streamflow data consist of two short streamflow time series, recorded at the Caselle in Pittari and Sicilì gauging stations, providing daily data, respectively, from 1952-1968 and from 1952-1957.

The lack of historical adequate streamflow time series, both on a temporal and on a spatial point of view, makes even more difficult a realistic calibration of a modelling approach. For this reason, an intensive monitoring campaign, illustrated in the following paragraphs, was planned to temporally and spatially extend the streamflow database.

3.2 The catchment and sub-catchment monitoring campaign

On January 2003, the Sinistra Sele River Watershed Regional Agency, started a monitoring campaign with the aim to measure, in many different cross sections and on a monthly time base, the Bussento river discharge. Based on the above described geomorphological and hydrogeological settings, 25 gauge stations were indicated as significant to define the river and springs hydrological regime (figure 4).

Fig. 4. The Bussento river basin monitoring network. BS is the symbol for streamflow stations whereas PG is the symbol for marine stations, for discharge and radon measurements.

Since December 2009 a further monitoring campaign, focused on the upper Bussento river basin (figure 5 and Table 2), was started and managed by CUGRI (Centro Universitario per la Previsione e Prevenzione dei Grandi Rischi) on behalf of the Regional Agency for the

environmental protection of Campania region (ARPAC), within a more comprehensive study on the radon-222 activity concentration in stream and spring waters. Besides radon concentration, more chemical and physical variables have been measured, such as pH, water temperature, dissolved oxygen, atmospheric pressure, water conductivity and water resistivity.

Monitoring stations locations have been carefully identified to investigate the complex interaction between groundwater and streamflow, caused by the complex karst hydrogeological structure and system hydrodynamics. The monitoring timing of the river discharge was oriented to measure the delayed sub-surface flow and the baseflow component of the hydrograph. For this reason, several recession curves of historical data were analysed, deriving the more appropriate time from the flood peak discharge at which the delayed sub-surface and baseflow occur. Consequently, the monitoring campaigns were planned to measure the stream discharge at least seven days after the end of the rainfall event, while in dry periods the measures were conducted two times a months.
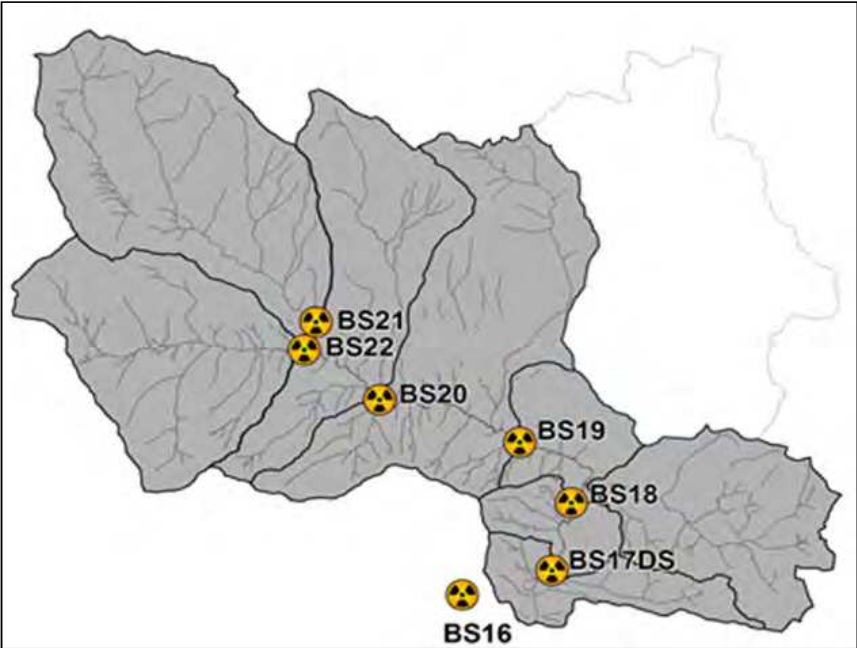

Fig. 5. Monitoring stations in the upper Bussento river basin. In blank Sanza Endorheic Basin.

Station Code	Drainage area (Km²)	Elevation (m.a.s.l.)	Pervious drainage area (Km²)	Impervious drainage area (Km²)
BSU17	85.15	912	64.08	21.07
BSU18	82.13	927	62.43	19.70
BSU19	66.84	927	49.49	17.35
BSU20	47.20	1079	38.74	8.46
BSU22	14.73	926	11.12	3.61

Table 2. Bussento river sub-catchments main characteristics.

4. Conceptual hydro-geological modelling

The hydro-geomorphological settings, above briefly illustrated, induce a very complex surface-groundwater interaction and exchanges, with groundwater inflows, from outside of the hydrological watershed, and groundwater outflows, towards surrounding drainage systems. The hydro-geomorphological domain includes karst and fluvial landforms and processes conditioning groundwater recharge ("karst input control", sensu Ford and Williams, 2007), by means of the infiltration and runoff processes, including: a) allogenic recharge from surrounding impervious drainage basins into deep and shallow sinking stream infiltration points, and fractured bedrock stream infiltration; b) autogenic recharge, including sub-soil and bare diffuse epikarst infiltration, endorheic runoff infiltration in dolines and poljes; c) groundwater discharge ("karst ouput control", sensu Ford and William, 2007), differentiated in the groundwater-river interactions within the aquifer-river domain. The last includes the complex interactions between the streambed-springs system, which generally results in a downstream river discharge increasing, occurring generally in typical bedrock streams, flowing in gorge and canyons carved in enlarged fractured limestone sequences.

Each of the mentioned components corresponds, in the modelling conceptualization of the scheme, to a linear storage, which releases streamflow as a function of the water storage and of a characteristic delay time. The characteristic time indicates that there is a delay between the recharge to the system and the output from the system itself, and this delay is greater for deeper aquifers. The number of storages, each representing, thus, a different process, contributes to the total streamflow through a recharge coefficient, that is a measure of the magnitude of the single storage capacity.

The application of a conceptual model, such as the one briefly described, requires the calibration of the model parameters, and in particular of the characteristic delay time and of the recharge coefficient of each single storage. In complex catchments, such as the Bussento River System, characterized by a large impact of karstic phenomena, raw streamflow data are not sufficient to the quantification of the contribute and magnitude of the single storage, and, therefore, are not sufficient to calibrate the model. To this aim, the use of Radon activity concentration measurements could represent a valuable future perspective.

In this river basin, the results of previous hydrogeological and hydrological studies (Iaccarino G., 1987; Iaccarino G. et al., 1988; Guida D. et al. 2006) indicate a weak correspondence between recorded data and model simulations, due to the strongly conditioning of deep karst circulation on the hydrological response, with an alternation between gaining river reaches from groundwater, and losing river reaches towards the karst aquifers, and also towards external watershed.

Due to these karst-induced features, the surface and groundwater recharge, circulation and discharge turns out to be very complex, and, therefore, a conceptual hydro-geomorphological model has been developed as a physical context in assessing basin and sub-basin water budget by a semi-distributed hydrological model (Todini E, 1996; Franchini M., et al, 1996). Following White (2002), the basic components of the generic karst aquifer flow system can be sketched as in figure 6.

Clearly, not all of these components are present in all aquifers, and their presence and relative importance is a fundamental point of distinguishing one aquifer from another. With reference to Iaccarino et al. (1988) and White (2002), this general conceptual model has been

applied to the Bussento Hydro-geological System (BHS), recognizing the following recharge-discharge components (figure 6).

Starting from the catchment scale characterization and modelling of the Bussento river system, and taking advantage of a consistent long term monitoring campaign, mainly operated over the Upper Bussento river system, it is possible to calibrate an hydro-geological framework to assess the hydrological response at the sub-catchment scale. With the aim to enhance the knowledge and approach a quantification of the interaction between the groundwater and surface water, natural isotope environmental tracers technique have also been used. Radon-in water concentrations have been collected, in a limited number of cross sections, along the upper Bussento river reach, represented, along with the monitoring sections, in the following figure 7. Sub-catchment scale modelling for the upper Bussento river reach will be later compared to experimental environmental tracers evidences, with the intent to set up a modelling framework that, starting from a limited (in space and time) number of observation, concerning hydraulic, hydrological, chemical and geological data, is able to assess water resources systems for karst aquifer highly conditioned river basins.
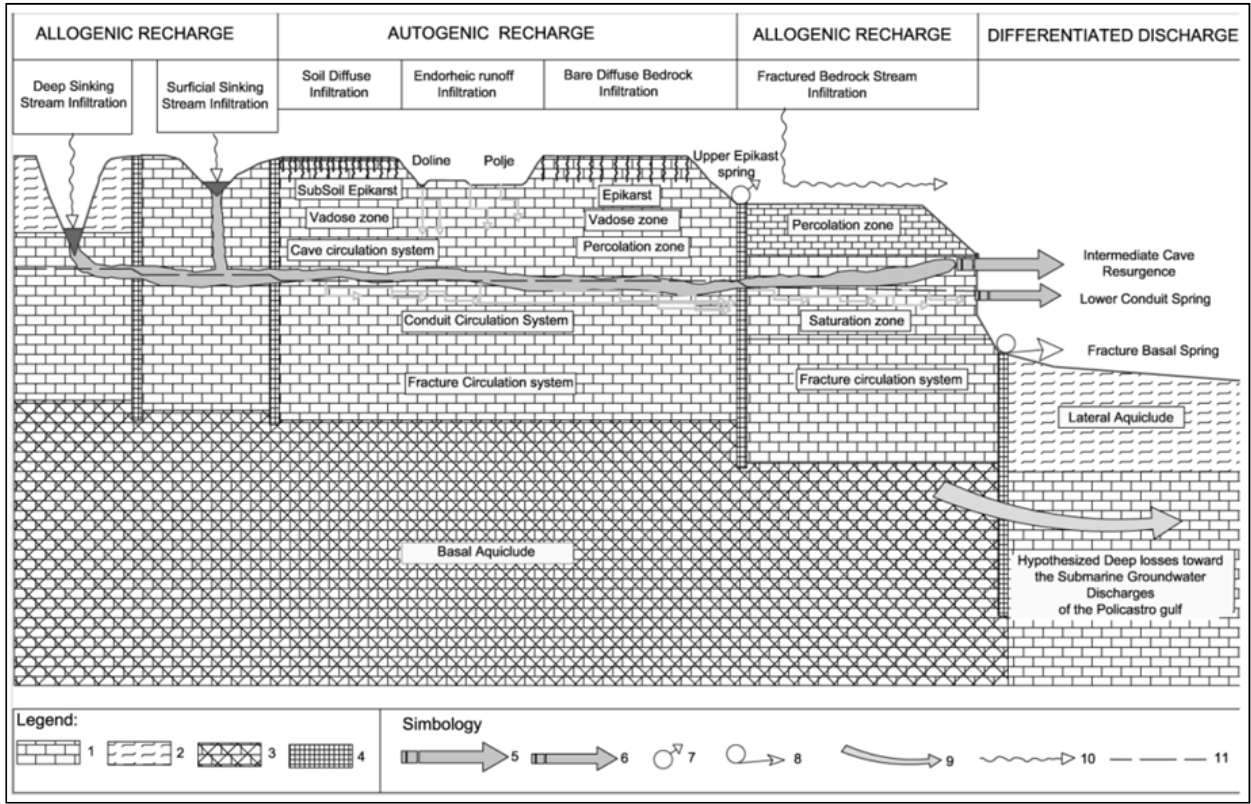

Fig. 6. Specific conceptual model of the karst aquifers in the Bussento Hydrological System (BHS). Legend: 1. Limestone fractured Aquifer; 2. Marly clayey aquitard; 3. Cataclastic Basal Lime-Dolostone Aquitard; 4. Lateral Limestone very fractured aquitard; 5. Intermittent or seasonal growndwater flow from Cave System; 6. Perennial groundwater flow from Conduit System; 7. Secondary springs ; 8. Spring Group; Losses toward
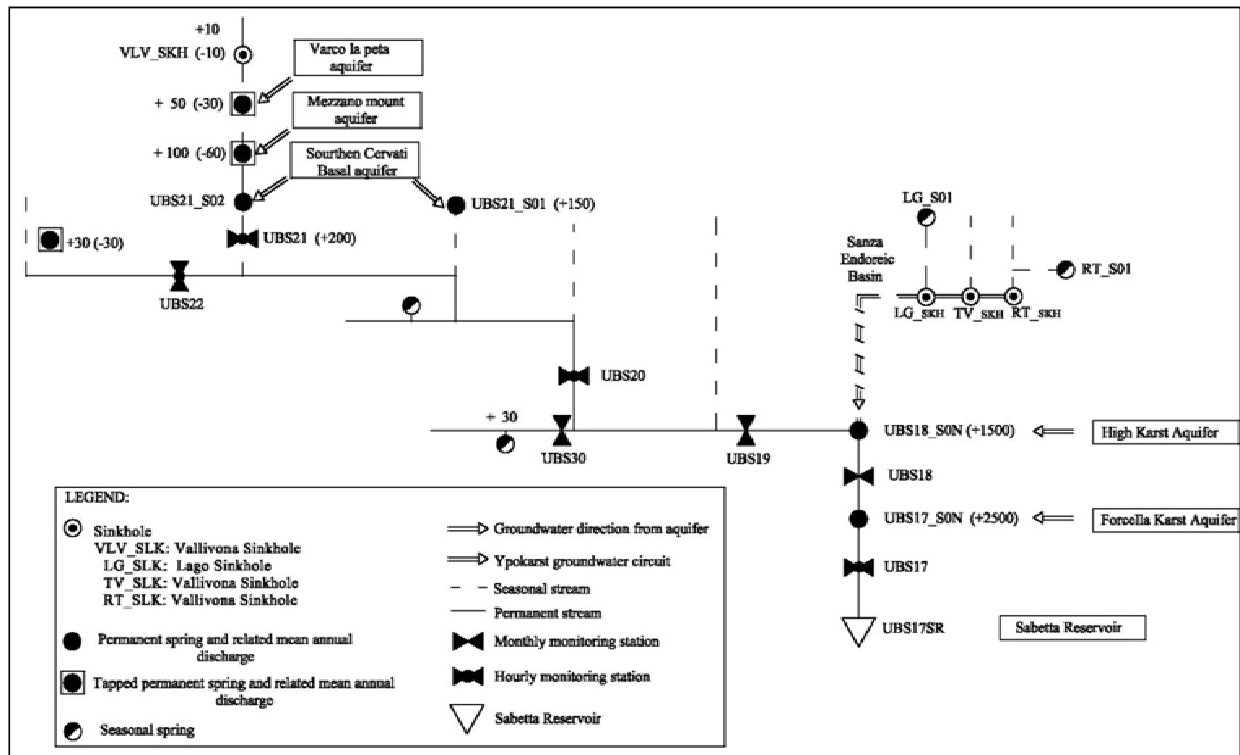
Fig. 7. Upper Bussento river reach network hydro-geological schematization and significant monitoring cross sections.

4.1 Conceptual modelling calibration based on streamflow database

Given the Bussento catchment geomorphological and hydro-geological features described in the previous paragraphs, a lumped model cannot guarantee reliable results. For this reason and taking advantage of the dense monitoring campaign, a semi-distributed formulation, accounting for each sub-basin particular characteristics, seems to be more appropriate.

When dealing with the monthly time scale, each sub-basin can be described (figure 8) as two linear reservoirs in parallel, representing the groundwater flow and the deep subsurface flow, whereas the rainfall contributes, which are characterized by delay times smaller than a month, are supposed to reach the outlet through a linear channel (Claps et al., 1993).

The scheme is also supported by the conceptual hydro-geological model described in the previous paragraph. In this case coupling the linear reservoirs balance equations with the whole system balance equation, total streamflow D at each time step is related to the net input by means of an ARMA (2,2) model, which stochastic formulations corresponds to:

$$D(t) - \Phi_1 D(t-1) - \Phi_2 D(t-2) = \varepsilon(t) - \Theta_1 \varepsilon(t-1) - \Theta_2 \varepsilon(t-2) \qquad (1)$$

where ε is the model residual, related to the net input I, that is then a periodic independent random process, and Θ_1, Θ_2, Φ_1, and Φ_2 are the model stochastic parameters, related to the model conceptual parameters K_1, K_2 (reservoirs response times, respectively of the ground water system and of the subsurface plus surface water system), a and b (recharge coefficients, respectively to the ground water system and to the subsurface plus surface water system) according to the following equations:

In its original formulation the model algorithm, starting from an observed streamflow time series, apply a maximum likelihood procedures to estimates the model parameters and, because of the univariate approach, with an inverse procedure, the net rainfall input is also estimated. As an example, model performance are illustrated for the Bussento at Caselle historical time series, at the monthly scale, in figure 9. The linearity of the quantile - quantile plot entails the good performances of the linear applied model, when historical time series are available.

$$\theta_1 = \frac{e^{-1/k_1} + e^{-1/k_2} - ar_{k1}(1 + e^{-1/k_2}) - br_{k2}(1 + e^{-1/k_1})}{(1 - ar_{k1} - br_{k2})}$$

$$\theta_2 = \frac{ar_{k1}e^{-1/k_2} + br_{k2}e^{-1/k_1} - e^{-1/k1}e^{-1/k_2}}{(1 - ar_{k1} - br_{k2})}$$

$$\Phi_1 = -e^{-1/k_1} + e^{-1/k_2} \quad \Phi_2 = -e^{-1/k_1}e^{-1/k_2} \qquad (2)$$

$$r_{k1} = k_1(1 - e^{-1/k_1}) \quad r_{k2} = k_2(1 - e^{-1/k_2})$$
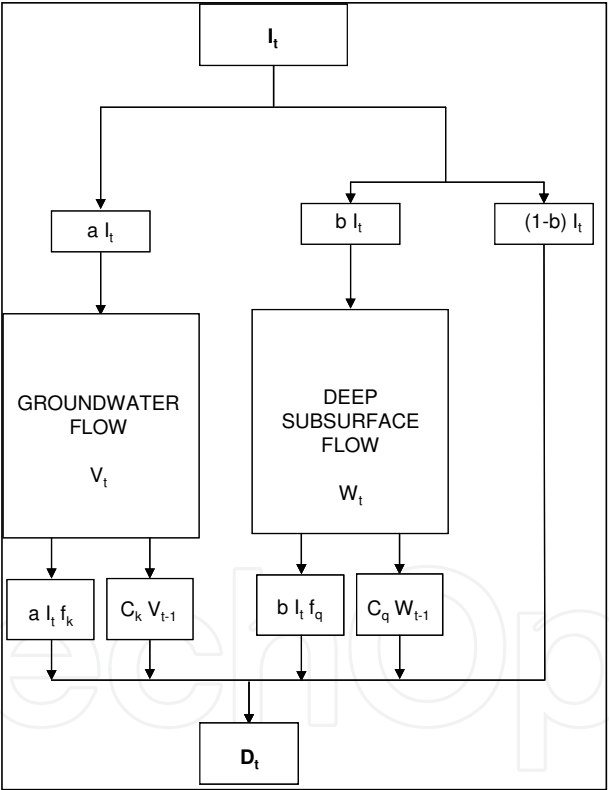

Fig. 8. Linear system for monthly time series.

But to calibrate a semi-distributed model, a number of streamflow recorded time series are needed for a number of nested catchments. Even if the gauging stations planned in the monitoring campaign, resemble a nested catchments scheme, collected streamflow data consist of discharge instantaneous data measured within a month time window, at each section, which does not represent a monthly discharge recorded time series, thus the data are not available to calibrate the ARMA(2,2) model with its inverse procedure at the sub-basin scale.

With the aim to set up a modelling semi-distributed approach able to reproduce observed discharge values along the river network, both short historical streamflow time series and streamflow data collected during the monitoring campaign have been used to a priori estimate the model parameters and net rainfall input.
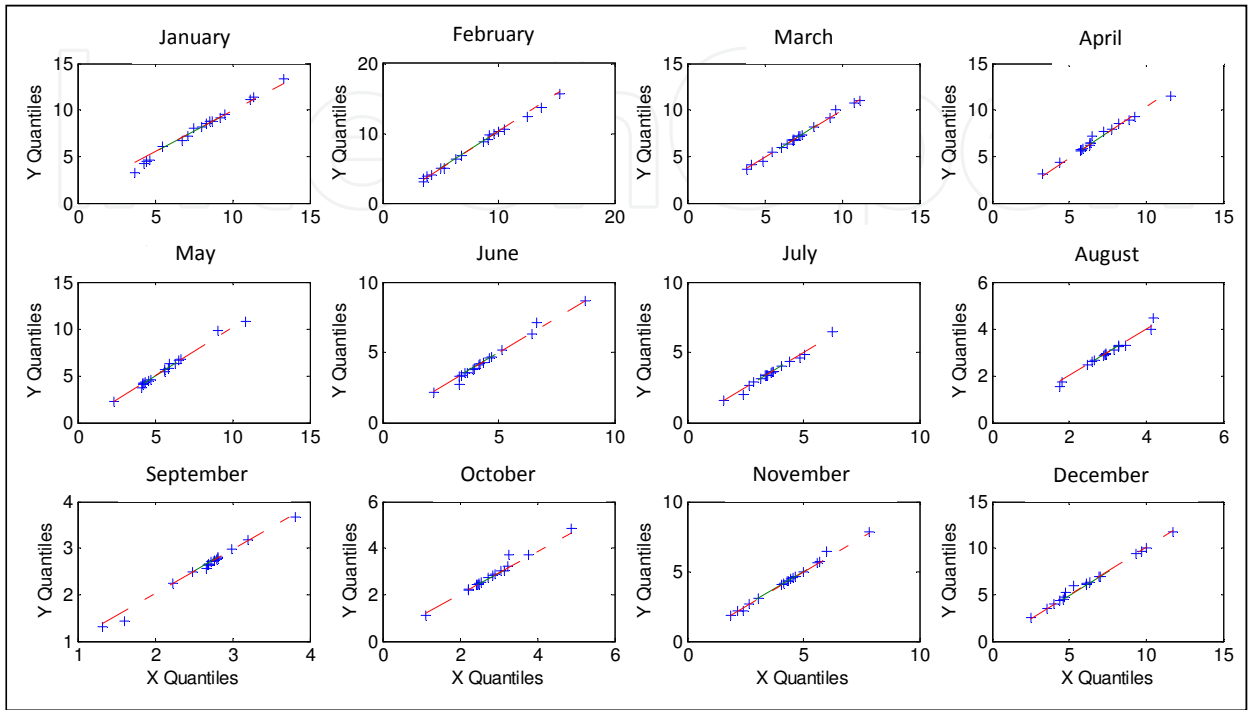

Fig. 9. Modelled and observed discharge data at Bussento at Caselle: quantile – quantile plot.

The recharge coefficients a and b have been estimated on the base of previous studies (Celico, 1978; Iaccarino et al., 1988) focused on the assessment of potential infiltration coefficients based on surface soils properties. The recharge coefficients, initially computed on the base of surface soil properties, are then susceptible to a successive calibration aimed at the optimization of the mean annual water balance. More insights aimed at their calibration would also come from the analysis of radon in water concentration, monitored on a particular river reach as later commented.

The K_1 delay response time has been estimated, during non-raining periods, applying the base flow recession equation:

$$Q(t) = Q_0 e^{-t/K} \tag{3}$$

which describe the event descending hydrograph limb, to two successive events, in order to remove the unknown streamflow data Q_0 at time t_0:

$$Q(t_1) = Q_0 e^{-t_1/K_1} \qquad Q(t_2) = Q_0 e^{-t_2/K_1}$$

$$\frac{Q(t_1)}{Q(t_2)} = \frac{Q_0 e^{-t_1/K_1}}{Q_0 e^{-t_2/K_1}} \Rightarrow K_1 = \frac{(t_2 - t_1)}{\log[Q(t_1)/Q(t_2)]} \tag{4}$$

The K_2 delay response time has been instead estimated during raining periods, when both deep and surface components are detectable in streamflow data. Considering t1 and t2 as two successive time instants for which both streamflow, Q(t1) and Q(t2), and rain values, p1 and p2, are known, and initially retaining that:

$$\frac{Q_0(t_1)}{Q_0(t_2)} = \frac{p1}{p2} \tag{5}$$

then the K_2 response time can be evaluated from the following equation:

$$\ln \frac{Q(t_1)}{Q(t_2)} = \ln \frac{p1}{p2} - \frac{t_1}{K_2} + \frac{t_2}{K_2} \tag{6}$$

The described a-priori estimation procedure set up to compute the fast delay response time, make K_2 the parameter which is likely to be affected by the largest uncertainty, that would in the end also compromise the coupled hydro-geological and hydrological model performances.

Estimated conceptual parameters K_1, K_2, a and b (b = 1-a) are indicated, as an example, for the Upper Bussento river reach gauging stations, in table 32.

Table 3. A priori estimates of delay times and recharge coefficients model parameters, for the Upper Bussento river basin cross sections.

Station Code	K_1 (days)	K_2 (days)	a	1-a
BSU17	288	40	0.70	0.30
BSU18	204	50	0.65	0.35
BSU19	120	39	0.60	0.40
BSU20	123	27	0. 60	0.40
BSU22	115	50	0.60	0.40

4.2 Conceptual modelling simulation results

With regard to the model rainfall net input, the pursued procedure has been to generate it from its probability density distribution, with given parameters. The I(t) probabilistic representation is the Bessel distribution, which is the sum of a Poissonian number of events with exponentially distributed intensity:

$$P[I = 0] = e^{-\upsilon} \qquad\qquad I = 0$$
$$f_I(I) = e^{-\lambda I - \upsilon}(\upsilon\lambda/I)\mathfrak{I}_1[2(\upsilon\lambda I)^{1/2}] \qquad\qquad I > 0 \tag{7}$$

where $\lambda = 1/\beta$ is the exponential parameter, υ is the Poisson parameter and $\mathfrak{I}_1$ is the modified Bessel function of order 1. The rationale for such probabilistic representation is given by the positive values and finite probability at zero that I(t) has to present.

Parameters β and υ are estimated from the existing two streamflow time series. The temporal patterns found for the two series are rather similar, thus we assumed β and υ spatially invariant over the catchment (table 4).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
ν	1.05	1.19	1.21	1.39	1.48	1.82	2.07	1.66	1.28	1.09	1.04	1.03
β mm/ day	5.29	2.65	1.52	1.43	6.33	0.73	0.30	0.86	2.85	2.69	1.77	3.63

Table 4. Net rainfall input distribution β and ν parameters.

Equation (1) as been then used to generate 1000 years monthly streamflow time series at each section, comparing thus the discharge probability distributions, at each section and for each month, with the occurred observed values.

Figure 10 and figure 11 show, as an example, the generated streamflow probability distribution, at cross section BSU19 respectively for the summer (month of august) and the winter season (month of February). If we assume as acceptable the region of data included between the 25° ed il 75° percentile, that is the 50% of data located in the middle of a sorted sample data, the proposed conceptual bivariate hydro-geological modelling approach shows reasonable performances both during the summer season (observed discharge corresponds to the 50° percentile) and the winter season (observed discharge corresponds to 56° percentile).
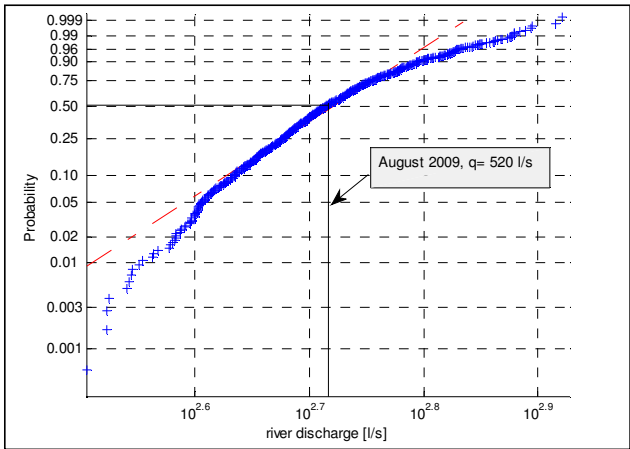

Fig. 10. Generated streamflow probability distribution compared with occurred value, cross section BSU19, for the summer season (August).
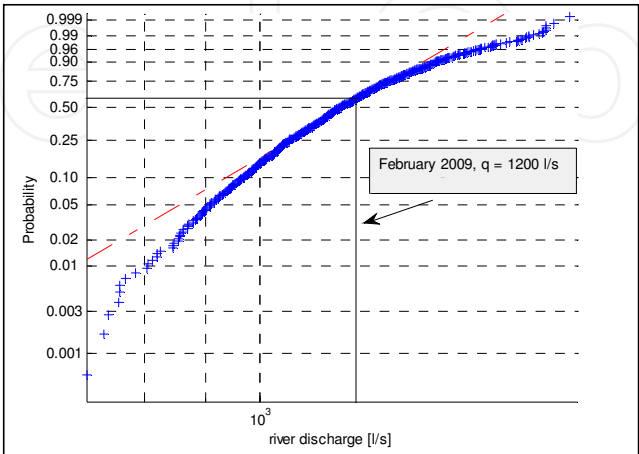

Fig. 11. Generated streamflow probability distribution compared with occurred value, cross section BSU19, for the winter season (February).

5. Environmental tracers experimental evidences

Isotopic tracers studies was introduced into catchment hydrology research in the 1960s as a complementary tools to conventional hydrological methods, to address questions about the pathways taken from precipitation infiltrating water to the stream network and about the water residence times within the catchment boundary (McDonnell, 2003). Especially in the Mediterranean environments, where karst aquifer groundwater represents more than 98% of the available fresh-water supply, the study of the interaction between groundwater and surface water is particularly important and difficult, at the same time, because of the complex hydraulic interconnections between fractured carbonate rocks and watershed network (Brahana and Hollyday, 1988). Deep water resources system discharge is of particular importance during the summer period, when, because of the rainfall deficiency, it contributes to the total streamflow in a measure of 70% (Dassonville and Fé d'Ostiani, 2003; Tulipano et al., 2005; Longobardi and Villani, 2008).

In the last decades, the use of isotopic tracers has been of substantial need in many problems concerning the decomposition of total streamflow into its main components, such as the surface, the sub-surface and deep flows, both in experimental and laboratory experiments (Levêque et al., 1971; McDonnell, 2003; Solomon et al. 1993, 1995, 1997; Goldscheider and Drew, 2007). Besides the traditional and long time use of natural isotopes in hydrology and hydrogeology (Flora and Longinelli, A., 1989; Emblanch et al., 2003), one of the most interesting, promising and innovative approach to quantitatively assess the groundwater contributions to streamflow and seawaters in natural environments, consists in measuring radon-in-water activity concentrations (Andrews and Wood, 1972; Shapiro, 1985). The principle at the base of this technique is the larger concentration of Radon in groundwater compared to surface waters (Rogers, 1958).

Radon-222 (simply 'radon' in the following) is a volatile gas with a half-life of 3.8 days, moderately soluble in water and atmosphere. It is released to groundwater from Radium-226 alpha decay, by means of permanent alpha recoil in micro-pore or fracture walls (Rama and Moore, 1984) and progressive dissolution of the aquifer-forming-material that supplies more and more soluble Ra-226, subsequently decaying to radon (Ellins et al., 1990). Due to its volatility, radon gas quickly degasses into the atmosphere producing a significant disequilibrium between concentrations in groundwater and surface water.

From the seminal work of Rogers (1958), the assessment of spatial-temporal variations in radon concentrations between surface and groundwater (Ellins, 1990; Lee and Hollyday, 1987, 1991) have provided insights in: i) testing infiltration-filtration models (Genereaux and Hemond, 1990; Genereaux et al., 1993; Gudzenko, 1992; Kraemer and Genereux, 1998), ii) performing hydrograph separation (Hooper and Shoemaker, 1986), iii) calculating water residence times (Sultankhodzhaev et al., 1971), iv) interpreting the role of "old water" in non-linear catchments hydrological response, v) estimating shallow and deep water mixing (Hoehn and von Gunten, 1989; Hamada, 2000; Hakl et al., 1997; Semprini, 1987; Gainon et al., 2007), and vi) calculating flow velocities in homogeneous aquifers (Kafri, 2001).

In addition, the use of radon enables the researchers to trace groundwater migration pathways (Hoehener and Surbeck, 2004), and to assess the time dependence of groundwater migration processes (Schubert et al., 2008). Infiltration of surface waters from a river to groundwater (Hoehn and von Gunten, 1989) as well as flow dynamics in a karst system (Eisenlohr and Surbeck, 1995) are just a few examples of applications where radon-based methodology has been used successfully to gain additional information on environmental processes.

In the current project, the general objectives of the radon in-water monitoring program are (i) to localize and quantify the contributions of groundwater along the main stream riverbed and banks, (ii) to set up an adaptive methodology, based on monthly radon activity concentration measurements in streamflow and springs, for the baseflow separation from other streamflow components; (iii) to verify the hydro-dynamical behaviour of the karst circuits and their influence on streamflow and iv) to calculate the downstream groundwater influence on streamflow. The project has been also planned in order to implement and improve this approach in the conventional regional public practice, to compliance the suggestions given from the European Water Framework Directive (EWFD, 2000) and to apply the methodology to other similar karst-conditioned river basin in Southern Italy.

5.1 Illustration of radon-in-water concentration collected data

The monitoring campaign of Rn-222 concentration is oriented to investigate the variability of radon gas in stream water and stream inflowing springs water and to separate the total streamflow in the subsurface and baseflow components.

Rn-222 concentration in stream water in a particular cross section along the river network is tightly related to the residence times of water collected at that particular section: the longer is the journey made by each drop of water through the rock formations, the larger is the Radon-in water concentration. According to this criteria, waters flowing from different source systems are characterized by different isotopic labels, that allow then distinguishing waters from different origins. As an example, in figure 12, the temporal variability of radon concentration is given for a number of gauging stations along the upper Bussento river network. It is interesting to highlight how radon concentration temporal variability can be dramatically different in different cross sections. For the particular river reach under consideration, it is possible to observe that there exist two significantly different temporal patterns: a first behavioural pattern, that records a temporal large fluctuation of radon concentration around a mean value and a second behavioural pattern, that records a mainly constant radon concentration during the time. The existence of these two patterns is strictly related to the presence or not of significant inflowing springs water contributions in particular gauging stations. Opposite to stations BSU17 and BSU18, where substantial stream inflowing springs water occur, stations BSU19, BSU20 and BSU22 are indeed featured by the absence of springs feeding the streams along the correspondent river reach. This physical characterization would explain the larger and constant concentration of radon for the first two stations and the lower and fluctuating radon concentration for the remaining stations. Radon concentration fluctuation detected for the stations BSU19, BSU20 and BSU22 can be explained by the fact that, in these particular sections, surface flow component, which is the results of the fastest transformation of rainfall and is the poorest radon concentration stream water fraction, is significantly contributing to the total discharge.

The effect of the increase in the surface component respect to total discharge is also detectable for stations significantly affected by springs feeding, as a function of the proportion of groundwater versus surface water: stations BSU18, compared to station BSU17, receives a large fraction of groundwater contributing to total streamflow and is not thus affected from rainfall events, only increasing the surface component of total discharge.

As a proof, in figure 13, the temporal pattern of radon concentration measured in sections BSU17 and BSU18, is compared to the temporal pattern of radon concentration in spring water feeding the stream, in cross sections BS17S0N and BS18S0N, immediately upstream

sections BSU17 and BSU18. It is evident, in particular for the station BSU18 for the same reasons previously indicated, that the temporal pattern of radon concentration in stream water (BSU18) strongly resembles the temporal pattern of radon in spring water (BS18S0N).
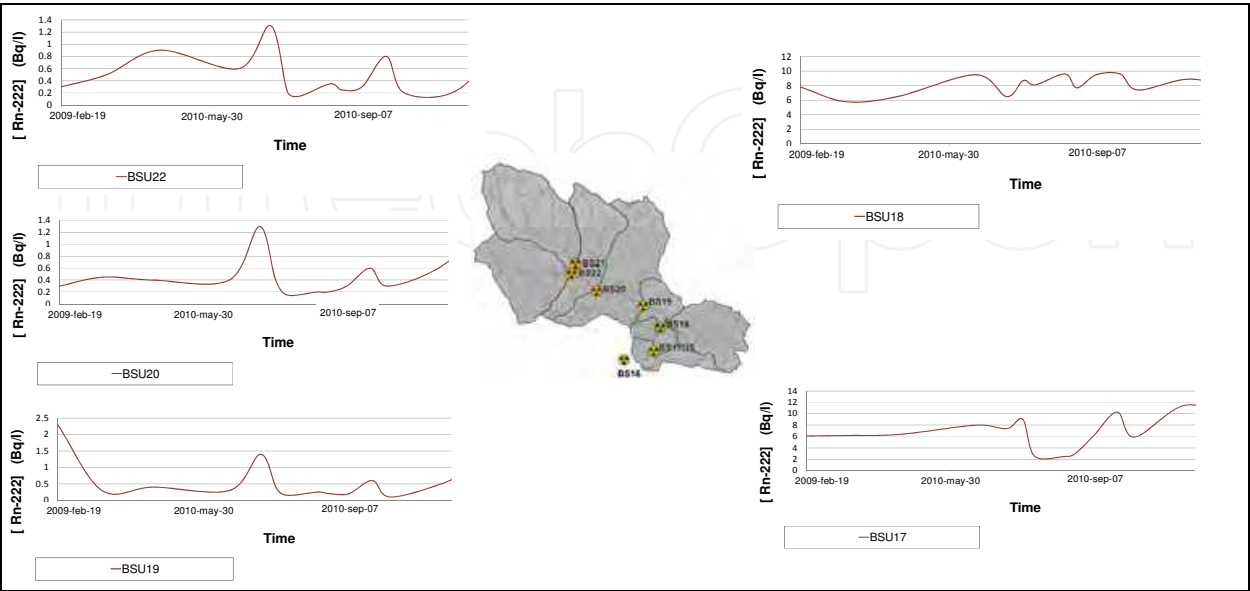

Fig. 12. Temporal variation of radon concentration measured in the gauging stations along the river network.
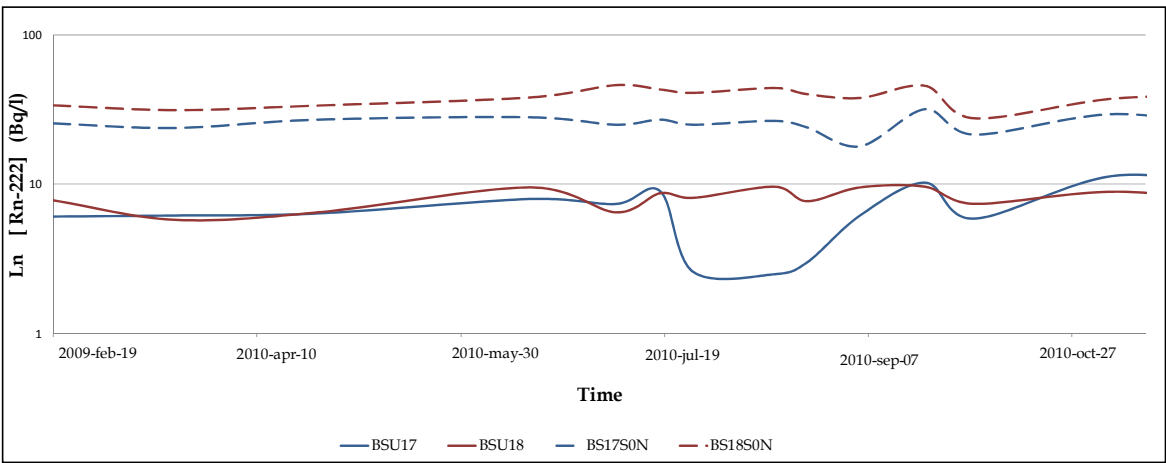

Fig. 13. Temporal pattern of radon concentration in stream water (BSU17 and BSU18) and in spring water feeding the stream (BS17S0N and BS18S0N).

More insights about the radon concentration dynamics could be achieved by comparing, at the annual scale, the temporal pattern of precipitation, discharge and radon concentration (figure 14).

During the winter season, the abundant precipitations recharge the deep water resources system and at the same time produce a significant surface component of total streamflow (flood conditions), with radon concentration approaching a rather constant and average value during the whole period. During the summer dry season, instead, when low flow conditions occur, the river discharge is mainly sustained by the baseflow, that is the outflow

of deep water resources systems, characterized by the larger radon concentration because of the long residence times. Measured data confirm indeed that, in the period from May to September, the river discharge decrease and a consequent increment in radon concentration is instead detected.
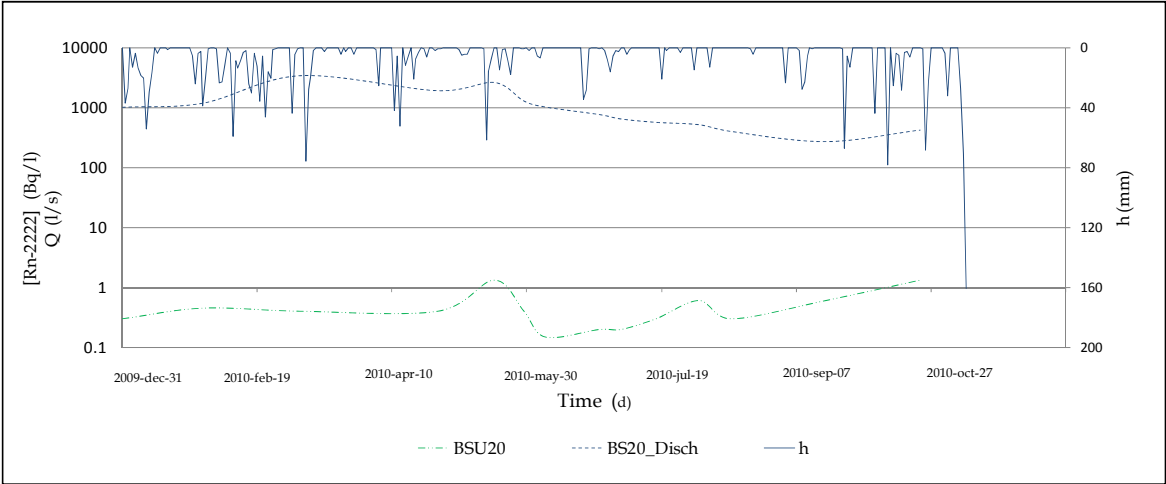

Fig. 14. Precipitation, discharge and radon concentration temporal patterns vs. daily rainfall.

5.2 Preliminary combined analysis of radon data and hydro-geological modelling

Starting from the well-known assumption that water is composed of a set of well mixed end members, the collected data of radon concentration are used to illustrate an example of hydrograph separation into different flow components. To this aim, mass balance and mixing equations can be written, as described in Kendall and McDonnell (1998):

$$Q_T = Q_{SSF} + Q_{GW}$$
$$C_T Q_T = C_{SSF} Q_{SSF} + C_{GW} Q_{GW}$$

(8)

where:

Q_T is the total streamflow, Q_{SSF} is the sub-surface delayed flow, Q_{GW} is the groundwater flow, C_T is the Rn-222 value in total streamflow, C_{SSF} is the Rn-222 value in sub-surface delayed flow, C_{GW} is the Rn-222 value in groundwater flow.

As an example, the mixing equations (8) are applied at cross section BSU18, which is one of the gauging sections where groundwater contributions are extremely large, to derive the Q_{SSF} and Q_{GW} components of total discharge. If Q_{SSF} and Q_{GW} are the unknown variables, application of equations (8) requires observation and measures of all other variable. Q_T and C_T are indeed the only measured variables, whereas values for C_{SSF} and C_{GW} are inferred from measurements referred to different cross sections.

The Rn-222 content of river water is strongly affected by volatilization to the atmosphere, and this must be accounted for in using radon data to estimate a possible groundwater influx from subsurface water sources (Kies A., 2005). If C_{DS} and C_{US} are the radon concentration measured in a downstream and upstream cross sections, and L is the length of the river segment between the mentioned cross sections, the relationship between radon concentrations is described by the following equation (9), from (Wu Y. et al., 2004):

$$C_{DS} = C_{US} \times e^{-\alpha L}$$

(9)

Model equation (9) is applied between sections BS18_S0N and BSU18, assuming C_{US} as the radon concentration in section BS18_S0N, which is the river inflow spring water section, and determining the C_{DS} as the radon concentration in section BS18, at a distance of about 1 Km, also representing the C_{GW} concentration in section BSU18. Application of the volatilization model requires a value for the parameter α, previously calibrated on a specific river reach of the Bussento network (Guadagnuolo D., 2009), whose hydro-geomorphological settings are similar to the one of the river reach investigated in this report and resulting in an α ccoefficient equal to 0.9 (l/km). CSSF radon concentration at cross section BSU18, that is the concentration of sub-surface flow, is computed as the mean value of radon concentration measure in sections BSU22, BSU20 and BSU19, where deep water resources contribution are negligible and representative of the sub-surface flow. Results are illustrated in figure 15.
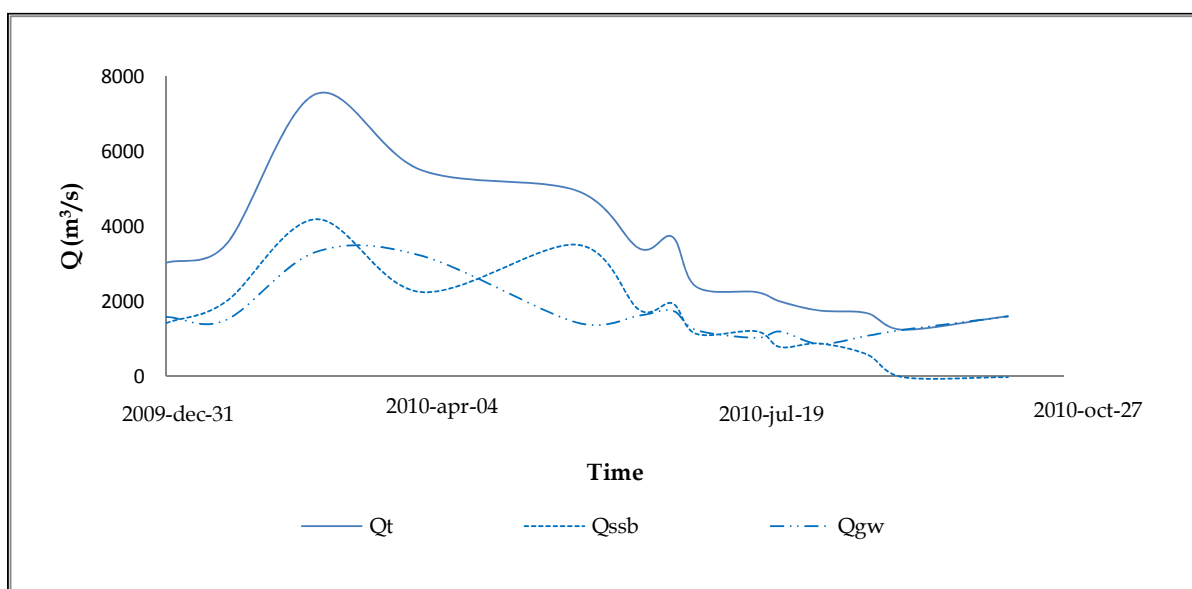
Fig. 15. Hydrograph separation based on mixing equation solution and environmental tracers measurements.

Total streamflow components hydrograph patterns appear realistic: groundwater component has a smoother pattern compared to subsurface flow, the most responsive component to rainfall event between the two, and essentially represents total streamflow during the summer season, when rainfall contribution are negligible or absent. With regard to the quantification of the deep water resources, the mixing equations separation performance, based on the number of hypothesis at the base of the application, lead to quite comparable volume of total groundwater and subsurface flow. For the same cross section, instead, the hydro-geological conceptual approach would indicate a larger contribution of groundwater to total streamflow, of about 60-70%, as indicated from the a-priori estimation of the a model parameter, representing the groundwater coefficient of recharge and, approximately, also the proportion of groundwater flow versus total streamflow. Similar quantifications are moreover confirmed by the analysis of observed streamflow time series for the Bussento river catchment. As already stressed, the qualitative and quantitative results of hydrograph separation based on the use of environmental tracers rely on a number of assumptions (e.g. the impossibility to measure radon concentration relative to the

single hydrograph component and calibration of the volatilization model) obviously impacting the assessment uncertainty. Besides its potential capability then, attempts to achieve an improvement in the calibration of the technique are to be found. With reference to the illustrated modeling conceptual approach, major concernments has to be focused on a more realistic hydrograph separation, preserving a weight of the different streamflow components, in the water balance, which would tightly fits the system hydro-geological characteristics. Further data analysis and collection could also be planned to estimate the residence times of total streamflow components, which would give a quantitative assessment of delay times K_1 and K_2 model parameters.

6. Conclusion

In this paper modelling difficulties that have to be faced when water basins with particular hydro-geological features are under investigation have been highlighted and suggestions of alternative, and in somehow integrated, approaches have been proposed in order to assess the potentiality of water resources systems. The presented case study is the Bussento river basin, located in Southern Italy, which is well known to hydrogeology and geomorphology scientists for its karst features, characterized by soils and rocks with highly different hydraulic permeability and, above all, an highly hydrogeological conditioning.

Traditional hydrological modelling relies on the existence of, at least, recorded streamflow time series, but when dealing with complex system watershed, lumped modelling, at the catchment scale, would not be satisfactory and a semi-distributed methodology, at the sub-basin scale, would be more appropriate. But such an approach would require even more data, that is even more streamflow time series in many different cross sections along the river network, enabling model calibration for homogeneous sub-catchment areas.

The methodology we have presented, has undoubtedly some similarity with a few well known conceptually hydrological and hydrogeological schemes, based on the existence of linear reservoirs and liner channel to describe the different components the streamflow can be decomposed in. However, it benefits from the coupling of hydraulic, hydrological and geological data, to set up a parsimonious model which, based on an a-priori calibration procedure requiring poorly dense time sampled data, is able to reasonable simulate total discharge.

The hydro-geological conceptual modelling approach has been compared to a water resources assessment methodology based on the use of environmental tracers, in particular of radon in water concentration. The preliminary hydrograph separation, into main components, performance based on radon concentration sampled data is affected by a number of assumptions (e.g. the impossibility to measure radon concentration relative to the single hydrograph component and calibration of the volatilization model) at the base of the application of the mixing equation model. At this stage, water resources assessment results from geo-chemical method, even though reasonable, is not indeed really comparable to the results of the conceptually modeling technique, which results, at the sub-basin scale, are instead confirmed by time series analysis at the catchment scale. Geo-chemical methods have however a great potential to be a fast and poorly dense time sampled data requirement method for water resources assessment and major attempts to achieve an improvement in the calibration of the technique are then to be found.

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8. References

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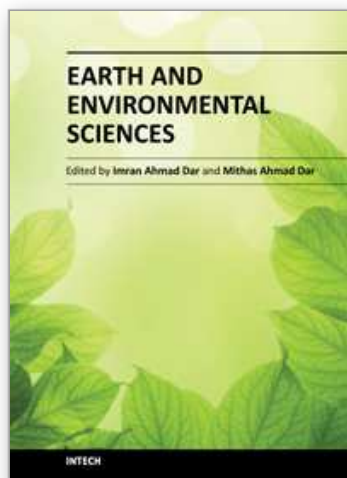
We are increasingly faced with environmental problems and required to make important decisions. In many cases an understanding of one or more geologic processes is essential to finding the appropriate solution. Earth and Environmental Sciences are by their very nature a dynamic field in which new issues continue to arise and old ones often evolve. The principal aim of this book is to present the reader with a broad overview of Earth and Environmental Sciences. Hopefully, this recent research will provide the reader with a useful foundation for discussing and evaluating specific environmental issues, as well as for developing ideas for problem solving. The book has been divided into nine sections; Geology, Geochemistry, Seismology, Hydrology, Hydrogeology, Mineralogy, Soil, Remote Sensing and Environmental Sciences.

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